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# Monitoring of firefighters exposure to smoke during fire experiments in Portugal

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A B S T R A C T

Forest fires represent a serious threat to public security in Europe due to the large burned area. Moreover, smoke pollution due to forest fire events is an important public health issue for the communities directly affected, and particularly for the personnel involved in firefighting operations. Aiming to contribute to the scientific knowledge concerning firefighters exposure to forest fires smoke, data of individual exposure to carbon monoxide, nitrogen dioxide, volatile organic compounds, and particulate matter were obtained during experimental field fires for a group of 10 firefighters equipped with portable "in continuum" measuring devices. Measured values are very high exceeding the Occupational Exposure Standard limits, in particular for peak limit thresholds. These are the first measurements and analysis of firefighter's individual exposure to toxic gases and particles in fire smoke experiments in Europe. However, they already indicate that urgent measures to avoid these levels of exposure are needed.



## 1. Introduction

There is a general agreement on the importance of forest fires as a major emission source of air pollutants to the atmosphere with several environmental and human impacts either at local, regional or global scales. Among the most significant air pollutants one can refer particulate matter (PM), carbon dioxide ($CO_2$), carbon monoxide (CO), methane ($CH_4$), non-methane hydrocarbons (NMHC), nitrogen oxides ($NO_x$), and nitrous oxide ($N_2O$). Smoke pollution due to forest fire events can potentially represent an important public health issue for the communities directly affected, and particularly for the personnel involved in firefighting operations (Brustet et al., 1991; Ward et al., 1993; Miranda et al., 1994; Reinhardt et al., 2001; Miranda et al., 2005a). However, the current state of knowledge about the potential health impacts on firefighting personnel is still scarce, in particular within the European context. The difficulty involved in the collection of data on human exposure to smoke during firefighting activities has largely contributed to this scientific gap.

Although some studies have shown that firefighters can experience acute, subchronic, and chronic effects resulting from the exposure to smoke, associated to acute decrements in respiratory functions resulting from an increasing exposure (Rothman et al., 1991; Materna et al., 1992; Liu et al., 1992; Bergstrom et al., 1997; Mustajbegovic et al., 2001), other works led to the conclusion that the respiratory effects on firefighters are not so significant (Betchley et al., 1997; Slaughter et al., 2004). This disagreement suggests that there is not a complete understanding about this problematic. Therefore, the knowledge on the occupational exposure profile of firefighters is a necessary step towards an improved understanding of the cause/effect relations between the air pollutants contained in smoke and the potential outcomes on fire workers health.

The most extensive measurements of smoke exposure among wildland firefighters were conducted in the United States of America (USA) and Australia (Reinhardt and Ottmar, 2004; Reisen and Brown, 2009; De Vos et al., 2009). In these studies it was shown that firefighters can be exposed to high levels of CO and respiratory irritants, including formaldehyde, acrolein, and respirable PM during firefighting activities at wildfires and prescribed burns. Work activity was identified as a major factor influencing exposure, and peak exposure situations were found to be several times higher than the recommended occupational exposure limits for short-term exposures.

However, due to the differences in vegetation, meteorology, and firefighting practices, which are known to affect smoke composition and human exposure (Reinhardt and Ottmar, 2004; Reisen and Brown, 2009; De Vos et al., 2009), the exposure data obtained in the USA and Australia may not be applicable to the European conditions. The relevance of assessing individual exposure levels for the Mediterranean conditions is stressed by the fact that forest fires represent a serious threat to public security in Europe due to the large burned area, nearly 500,000 ha $year^{-1}$, in average, in the last 29 years

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(European Commission, 2009), and the increased risk associated to wildland–urban interface fires in Southern Europe, especially in Greece and Portugal.

With this purpose, the authors have been carrying out, for the last 10 years and under the scope of several National and European research projects, measurements of the individual exposure of firefighters to nitrogen dioxide ($NO_2$), using passive samplers, during real scale fire experiments (Miranda et al., 2005b). Notwithstanding the small size of the burning plots when compared to wildfires, the measured exposure levels were considered significant. However, the use of this type of sampling devices did not allow measuring the peak values of exposure, and was limited to only one pollutant. Aiming to go further and to better contribute to the firefighters smoke exposure knowledge, the current work presents and analyze the data on individual exposure to CO, $NO_2$, volatile organic compounds (VOC), and PM2.5 obtained during experimental field burnings for a group of 10 firefighters equipped with portable "in continuum" measuring devices.

## 2. Methodology

The measurement of the individual exposure of firefighters was conducted during the fire experiments of Gestosa 2008 and 2009, in


**Fig. 1.** Plots layout from Gestosa 2008 (A) and Gestosa 2009 (B) study areas.

Central Portugal. The experiments were done at the end of the spring, just before the beginning of fire season.

### 2.1. Study area characteristics

The study area is located in the region of Gestosa site, and has been used since 1998 to obtain fire behavior data (Miranda and Borrego, 2002; Viegas et al., 2002; Miranda et al., 2005b; Valente et al., 2007). The Gestosa site is located in the mountain range of Lousã, Central Portugal (at an altitude between 900 and 1100 m) in the municipality of Castanheira de Pêra, at a distance of 70 km from Coimbra by road. It offers very good conditions to perform this type of experiments such as: good road accessibility, visibility to the burning area from different positions, fuel bed and slope homogeneity and safety conditions to perform the experiments. These were the main requirements to select the place where the experiments took place.

The major part of Gestosa area is composed by the lythologic complex (schist–grauvaquic) with Cambi soils. The annual average temperature is 11.0 °C, January being the coolest month (in average 2.5 °C) and August the warmest (in average 18.0 °C). Annual mean precipitation is 760 mm, and a water deficit in the soil exists from July to September. Following Thornthwaite (1948) climatological classification, the climate in the region is moderately humid, mesotermic, with water deficit during summer and superavit in winter time.

Before the experiments and during several weeks, fuel bed sampling, and fire breaks opening with the support of local firefighters and forest workers were carried out. The plots were marked on the field and, in order to define the plots borders and guarantee the access to the firefighters and water lines, firebreaks were opened using manual techniques complemented with prescribed burn to widen the fire breaks, and therefore to create larger safety zones between the test plots and the surrounding area. This preparatory work was very important to ensure the safety conditions during the burns. An extensive survey of the terrain with a precision GPS was made. The experimental burning plots, represented in Fig. 1 were established within Forest Service lands, and within the Gestosa forestry perimeter.

A detailed fuel sampling in each plot was done before the burns. The vegetation cover was composed by a continuous mass of shrubs and some isolated maritime pine trees (*Pinus pinaster*). The shrub species composition can be considered homogeneous, and the dominant species were *Erica umbellata*, *Erica australis*, and *Chamaespartium tridentatum*.

The characteristics of the experimental plots and available fuel are presented in Table 1. The main slopes in the study area vary between 14° and 27° and the prevailing aspect is NW. In the experiments of 2008 seven plots with a rectangular shape and of various sizes, covering approximately a total area of 7 ha were prepared. In the experiments of 2009, four plots were prepared also with a rectangular shape and with different sizes, with an approximately area of 2 ha.

During one month before the experiments, hourly data related with wind speed, wind direction, precipitation, air temperature and relative humidity were recorded by a Geolog S meteorological station. This information allowed assessing the best period of the day to burn with the advisable wind conditions. Table 2 presents the start of the plots ignition and the finish of the experimental fire for each plot.

The duration of the burns in Gestosa 2008 is rather small (10–15 minutes) when compared to wildfires. In wildfire situations the exposure may last for several hours or even longer. Although the fire duration during Gestosa 2009 is higher than during Gestosa 2008, the

**Table 1**
Main characteristics of the experimental plots (Gestosa 2008 and 2009).

| Plot | Area ($m^2$) | Slope (°) | Fuel cover (%) | Fuel height (cm) | Fuel bulk density ($kg\ m^{-3}$) | Fuel load ($ton\ ha^{-1}$) |
|---|---|---|---|---|---|---|
| *Gestosa 2008* | | | | | | |
| P01 | 820 | 20 | 100.00 | 83.25 | 2.04 | 24.79 |
| P02 | 959 | 27 | 100.00 | 93.00 | 2.06 | 26.69 |
| P03 | 1228 | 24 | 98.20 | 85.95 | 2.11 | 26.31 |
| P04 | 1493 | 22 | 86.00 | 70.40 | 2.26 | 22.41 |
| P05 | 2642 | 20 | 100.00 | 66.53 | 2.23 | 33.58 |
| P06 | 1089 | 23 | 100.00 | 83.00 | 2.28 | 31.17 |
| P07 | 1049 | 17 | 100.00 | 66.25 | 2.34 | 29.15 |
| *Gestosa 2009* | | | | | | |
| P11 | 2552 | 19 | [a] | [a] | [a] | [a] |
| P12 | 1800 | 17 | [a] | [a] | [a] | [a] |
| P13 | 6057 | 14 | [a] | [a] | [a] | [a] |
| P14 | 2990 | 19 | [a] | [a] | [a] | [a] |

[a] Plots are safety areas with little vegetation.

**Table 2**
Plots ignition in Gestosa 2008 and 2009.

| Plot | Start (hh:mm) | End (hh:mm) | Remarks |
|---|---|---|---|
| *Gestosa 2008* | | | |
| P07 | 10:48 | 11:00 | One linear ignition at the top for safety and then a linear ignition at the bottom; very fast propagation. |
| P06 | 11:15 | 11:38 | Two linear ignitions made on both sides of the plot. After that a linear ignition was made at the bottom. |
| P04 | 13:02 | 13:17 | A linear ignition to create a safety area on the top of the plot. A second linear ignition was made at the bottom of the plot. |
| P05 | 13:57 | 14:12 | A linear ignition to create a safety area on the top of the plot. A second linear ignition was made at the bottom of the plot. |
| P01 | 15:53 | 16:10 | Suppression exercise for the firefighters with FUMEXP Sensors. |
| P02 | 16:34 | 16:42 | Two linear ignitions on the top left side of the plot to create a safety area. Third ignition was made on the bottom of the plot (linear ignition). |
| P03 | 17:30 | 17:40 | A linear ignition to create a safety area on the top of the plot. A second linear ignition was made at the bottom of the plot. |
| *Gestosa 2009* | | | |
| P11 | 10:17 | 11:25 | Safety plot. |
| P12 | 11:46 | 12:43 | Safety plot. |
| P13 | 14:43 | 15:31 | Safety plot. |
| P14 | 16:25 | 17:00 | Safety plot. |

**Fig. 2.** Firefighters with the exposure monitoring equipment.

**Table 3**
Summary of pollutant measurement techniques.

| Pollutant | Type of data | Equipment | Characteristics | |
|---|---|---|---|---|
| | | | Range | Resolution |
| VOC | Continuous measurement: 5 s interval | GasAlertMicro 5 PID from BW Technologies | 0–1,000 ppm | 1 ppm |
| $NO_2$ | | | 0–99.9 ppm | 0.1 ppm |
| CO | Continuous measurement: 5 s interval | GasAlertMicro Clip from BW Technologies | 0–500 ppm | 0.1 ppm |
| | | GasAlertextreme from BW Technologies | 0–1,000 ppm | 1 ppm |
| PM2.5 | Continuous measurement: 1 min interval | Personal Aerosol Monitor SidePack AM510 from TSI | 0–20 mg $m^{-3}$ | 0.001 mg $m^{-3}$ |

plots had little vegetation and that limited the firefighter's exposure to smoke.

### 2.2. Measuring equipment and techniques

Ten firefighters were selected from four different brigades to monitor their individual exposure to smoke emitted during the Gestosa fire experiments. The selection was made by the commanders of each corporation, based on the available human resources and taking into account the firefighter's age, work developed during the firefight, years of experience as a firefighter, respiratory diseases, and smoking habits.

The selected firefighters were equipped with sampling devices monitoring CO, PM2.5, VOC, and $NO_2$. Also a GPS instrument per corporation was provided with the purpose of tracking their firefighters position when exposed to smoke. The basic criterion for the use of this monitoring equipment was its toughness, lightness, possibility of continuous data acquisition and the easiness of operation. Fig. 2 shows some firefighters with the exposure monitoring equipment.

VOC and $NO_2$ were monitored continuously with a 5 s time-step using the integrated photo-ionization detector GasAlertMicro 5 PID from BW Technologies. The rechargeable battery allows a continuous operation up to 12 h and with the memory card it is capable of recording two months of data. The Micro 5 PID measures VOC levels in air up to 1000 ppm with a resolution of 1 ppm and $NO_2$ up to 99.9 ppm with a resolution of 0.1 ppm. The VOC and $NO_2$ sensors were calibrated before the burning experiments using a 100 ppm isobutylene and 10 ppm $NO_2$ calibration gas, respectively.

CO was also monitored continuously at a 5 s intervals, using a CO GasAlertMicroClip and CO GasAlertextreme from BW Technologies, in Gestosa 2008 and 2009, respectively. The detector measures CO in air up to 500 ppm or 1000 ppm with a resolution of 0.1 ppm or 1 ppm. The CO detector was calibrated before the fire experiments using a 100 ppm CO calibration gas.

PM2.5 monitoring was performed using the monitor SidePack AM510 Personal Aerosol Monitor from TSI Inc. fitted with a built in 2.5 µm cut off impactor at a constant flow rate of 1.7 L $min^{-1}$. Before the fire experiments the flow rate was calibrated and the monitor was zeroed using a zero filter. Data were logged continuously at a 1 min interval. The SidePack AM510 measures particulate matter in air up to 20 mg $m^{-3}$.

Table 3 summarizes the characteristics of the equipments.

During the experimental fires, air temperature, air relative humidity, wind speed and direction were also continuously monitored near the fire plots with an acquisition period of 1 min, in order to foresee possible issues resulting from the interaction between the fire and the wind measured by the anemometers. Wind speed and direction sensors were located 6 m from the ground, temperature and moisture measurements were made at 4 m height.

### 2.3. Occupational exposure standard (OES) values

The assessment of the exposure of firefighters to smoke requires the comparison with occupational exposure standard (OES) values defined for different air pollutants. According to the American Conference of Governmental Industrial Hygienists (ACGHI), OES are presented as the: (i) threshold limit value (TLV) of the time-weighted average (TWA); (ii) TLV of the short-term exposure limit (STEL); and (iii) peak limit. The TWA is calculated over a normal 8-hour working day and a five days working week. The TLV-STEL corresponds to a 15-minute time-weighted average exposure that should not be exceeded at any time during a workday, even if the 8-hour TWA is under its TLV. The TLV-STEL is the higher concentration to which it is believed that workers can be exposed continuously for a short period of time without suffering from: (i) irritation; (ii) chronic or irreversible tissue damage; (iii) dose-rate dependent toxic effects; or (iv) narcosis of sufficient degree to increase the likelihood of accidental injury, impaired self-rescue or materially reduced work efficiency. Moreover, for an 8-hour working day, 15 min averaged exposure values between the TLV-TWA and the TLV-STEL can occur, but only four times per day and with at least 60 min interval between successive exposures in this range.

In Portugal, OES values for occupational activities are established by Occupational Health and Safety (OHS) regulations, namely through the Portuguese Regulation NP, 1796:2007. In the case of CO, $NO_2$ and PM TLV-TWA values are established by the NP 1796:2007. The PM TLV-TWA value was defined for different types of particles and is not specific for smoke constituents.

This NP also includes the TLV-STEL value for $NO_2$. These regulations tend to follow those established by the ACGIH. Table 4 presents the OES values for the different air pollutants analyzed under this study.

For the CO TLV-STEL and peak limit we considered the exposure limits set by the Australian Safety and Compensation Council (1995). Due to the lack of a $NO_2$ peak limit in the Portuguese OHS regulation, a value of 20 ppm was considered. This value is proposed by the National Institute for Occupational Safety and Health (NIOSH) taking into consideration recommendations derived from acute inhalation

**Table 4**
OES limit values for different air pollutants contained in biomass burning smoke. For some air pollutants these values are not available (n.a.) in National or International regulations.

| Air pollutant | TLV-TWA | Reference | TLV-STEL | Reference | Peak Limit | Reference |
|---|---|---|---|---|---|---|
| CO | 25 ppm | NP 1796:2007 | 200 ppm | Australian legislation | 400 ppm | Australian legislation |
| $NO_2$ | 3 ppm | | 5 ppm | NP 1796:2007 | 20 ppm | NIOSH |
| Respirable particles without other classification | 3 mg $m^{-3}$ | NP 1796:2007 | n.a. | n.a. | n.a. | n.a. |
| VOC | n.a. | | n.a. | n.a. | n.a. | n.a. |

**Table 5**
Meteorological data for Gestosa 2008 and Gestosa 2009.

| Plot | Wind speed ($m s^{-1}$) | Wind direction (−) | Temperature (°C) | Humidity (%) |
|---|---|---|---|---|
| *Gestosa 2008* | | | | |
| P01 | 1.5 | S | 19.4 | 32.8 |
| P02 | 2.2 | W | 20.2 | 35.0 |
| P03 | 3.8 | NW | 20.2 | 48.2 |
| P04 | 3.3 | SE | 17.0 | 58.5 |
| P05 | 2.8 | SE | 17.7 | 57.6 |
| P06 | 0.9 | SE | 17.6 | 19.2 |
| P07 | 2.2 | W | 17.8 | 15.6 |
| *Gestosa 2009* | | | | |
| P11 | 2.2 | SE | 21.0 | 31.0 |
| P12 | 1.9 | SE | 22.0 | 28.4 |
| P13 | 6.2 | NE | 24.6 | 21.6 |
| P14 | 7.8 | NW | 22.3 | 22.3 |

toxicity data (Patty, 1963), which indicate this limit value as immediately dangerous to life or health (IDHL).

## 3. Presentation and analysis of results

In addition to the exposure data monitored along the experiments, several meteorological parameters were continuously acquired. Table 5 presents the averaged values measured near each plot (P01–P07 and P11–P14), for 2008 and 2009, respectively.

In general winds were not strong (which was a pre-requisite for the experiments) varying between 0.9 and 3.8 m $s^{-1}$. Only plots 13 and 14 were burnt with higher wind speeds, which reached 7.8 m $s^{-1}$. This was possible because of the low fuel load of the burned plots. Wind direction was mainly from South-East. For 2008 air temperatures were higher during the afternoon burning plots. Relative humidity was generally low.

During the Gestosa 2008 and 2009 campaigns ten firefighters were monitored. In Gestosa 2008 the numbers 1 to 10 were attributed to the involved firefighters, while in 2009 11 to 20 were the allocated numbers. A statistical analysis of the exposure concentration measurements is presented in Fig. 3. The box plot summarizes the information on the data distribution in terms of the median, extreme values, 5th and 95th percentiles. One minute averages are analysed in order to uniform the temporal resolution of CO, VOC, $NO_2$, and PM2.5 measurements since the exposure monitoring equipment were programmed with different acquisition times. For all the pollutants, non-normal distribution with positive skew is identified, which is related with the higher concentration values but short exposure duration observed along the experimental burnings.

Firefighting is considered an occupational activity. Therefore it is recommended to evaluate their exposure in terms of TWA, STEL, and peak limit values. The experimental buns were carried out during an 8 h work shift to be considered representative of a regular working

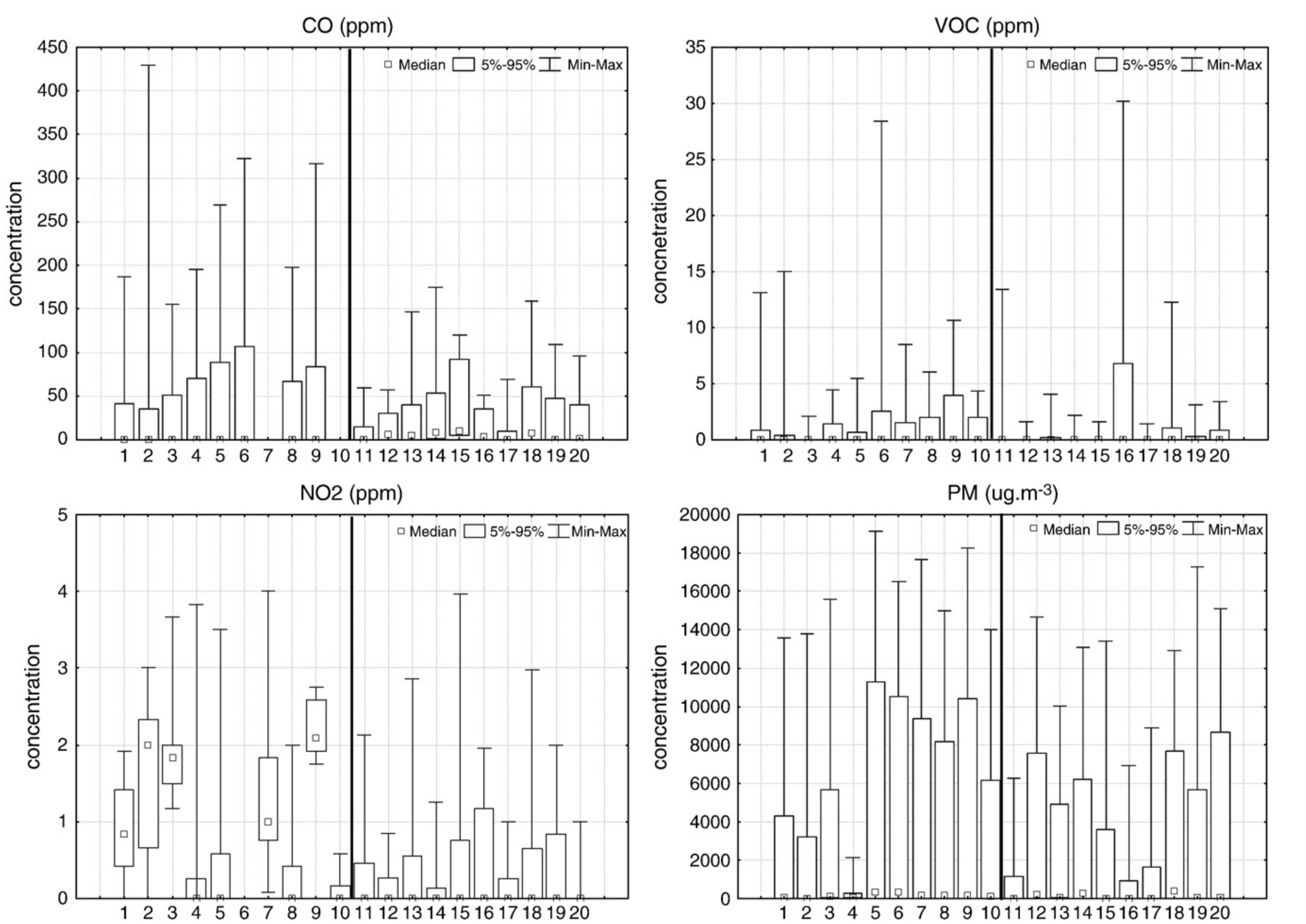


**Fig. 3.** Statistical parameters for 1 min averages for CO, VOC, $NO_2$, and PM2.5 for the monitored firefighters. The data for firefighters 1–10 correspond to the 2008 campaign and the data for firefighters 11–20 correspond to the 2009 campaign.

day. To assess firefighters exposure to smoke pollutants, 8 h and 15 min time-weighted averages were calculated. Peak limits values were also analyzed. Table 6 shows, for each firefighter and each pollutant, the TWA values, the number of exceedances of the peak limit (and the maximum value), and indicates if the TLV-STEL criteria were fulfilled or not. There were some situations when the batteries of the individual sampling devices did not last for the period of 8 h; in these situations, when determining the 8 h time-weighted averages, an exposure of zero was considered for the time periods during which data were not available.

For 2008 CO data from firefighters 7 and 10 are not presented due to problems with the CO sensors; the same happened with firefighter 6 regarding $NO_2$.

From the analysis of the results presented in Table 6, it can be seen that there are no exceedances of the TLV-TWA for any of the monitored pollutants. However, TWA was calculated considering time

**Table 6**
TWA, number of peak (*n*), peak values, and TLV-STEL fulfilment for CO, $NO_2$, VOC, and PM2.5.

| Firefighter | Parameter | CO (ppm) | $NO_2$ (ppm) | VOC (ppm) | PM2.5 (ug $m^{-3}$) |
|---|---|---|---|---|---|
| 1 | TWA | 7.60 | 0.90 | 0.19 | 773.40 |
| | *n* (peak value) | **1 (493.30)** | 0 (3.00) | (88.00) | (13,593.00) |
| | Fulfilment of TLV-STEL criteria | **No** | Yes | n.a. | n.a. |
| 2 | TWA | 9.60 | 1.90 | 0.28 | 551.00 |
| | *n* (peak value) | **9 (486.60)** | 0 (9.00) | (35.00) | (13,768.00) |
| | Fulfilment of TLV-STEL criteria | **No** | Yes | n.a. | n.a. |
| 3 | TWA | 10.70 | 1.80 | 0.03 | 917.10 |
| | *n* (peak value) | 0 (198.80) | 0 (8.00) | (4.00) | (15,590.00) |
| | Fulfilment of TLV-STEL criteria | **No** | Yes | n.a. | n.a. |
| 4 | TWA | 13.10 | 0.10 | 0.16 | 1439.60 |
| | *n* (peak value) | 0 (386.60) | **1 (33.00)** | (11.00) | (19,953.00) |
| | Fulfilment of TLV-STEL criteria | **No** | Yes | n.a. | n.a. |
| 5 | TWA | 14.80 | 0.10 | 0.12 | 2196.40 |
| | *n* (peak value) | **2 (499.80)** | **1 (22.00)** | (12.00) | (19,134.00) |
| | Fulfilment of TLV-STEL criteria | **No** | Yes | n.a. | n.a. |
| 6 | TWA | 19.80 | n.d. | 0.47 | 2187.50 |
| | *n* (peak value) | **6 (454.40)** | n.d. | (63.00) | (16,516.00) |
| | Fulfilment of TLV-STEL criteria | **No** | n.d. | n.a. | n.a. |
| 7 | TWA | n.d. | 1.10 | 0.22 | 2052.80 |
| | *n* (peak value) | n.d. | 0 (10.00) | (23.00) | (17,635.00) |
| | Fulfilment of TLV-STEL criteria | n.d. | Yes | n.a. | n.a. |
| 8 | TWA | 11.80 | 0.10 | 0.19 | 1435.40 |
| | *n* (peak value) | 0 (376.70) | 0 (4.00) | (15.00) | (14,969.00) |
| | Fulfilment of TLV-STEL criteria | **No** | Yes | n.a. | n.a. |
| 9 | TWA | 13.70 | 2.20 | 0.69 | 1829.30 |
| | *n* (peak value) | **2 (421.00)** | 0 (5.00) | (20.00) | (18,286.00) |
| | Fulfilment of TLV-STEL criteria | **No** | Yes | n.a. | n.a. |
| 10 | TWA | n.d. | 0.02 | 0.25 | 618.50 |
| | *n* (peak value) | n.d. | 0 (4.00) | (15.00) | (13,989.00) |
| | Fulfilment of TLV-STEL criteria | n.d. | Yes | n.a. | n.a. |
| 11 | TWA | 2.60 | 0.06 | 0.00 | 131.90 |
| | *n* (peak value) | 0 (112.00) | 0 (16.8) | (68.00) | (6257.00) |
| | Fulfilment of TLV-STEL criteria | Yes | Yes | n.a. | n.a. |
| 12 | TWA | 6.80 | 0.03 | 0.03 | 1201.60 |
| | *n* (peak value) | 0 (248.00) | 0 (2.60) | (7.00) | (14,663.00) |
| | Fulfilment of TLV-STEL criteria | **No** | Yes | n.a. | n.a. |
| 13 | TWA | 5.80 | 0.05 | 0.03 | 371.50 |
| | *n* (peak value) | **1 (422.00)** | 0 (5.90) | (29.00) | (10,049.00) |
| | Fulfilment of TLV-STEL criteria | **No** | Yes | n.a. | n.a. |
| 14 | TWA | 12.50 | 0.02 | 0.02 | 943.70 |
| | *n* (peak value) | 0 (295.00) | 0 (5.00) | (15.00) | (13,055.00) |
| | Fulfilment of TLV-STEL criteria | **No** | Yes | n.a. | n.a. |
| 15 | TWA | 19.30 | 0.11 | 0.03 | 456.40 |
| | *n* (peak value) | 0 (287.00) | 0 (9.70) | (9.00) | (13,390.00) |
| | Fulfilment of TLV-STEL criteria | Yes | Yes | n.a. | n.a. |
| 16 | TWA | 5.70 | 0.12 | 0.86 | 120.10 |
| | *n* (peak value) | 0 (323.00) | 0 (5.10) | (76.00) | (6934.00) |
| | Fulfilment of TLV-STEL criteria | Yes | Yes | n.a. | n.a. |
| 17 | TWA | 1.30 | 0.03 | 0.01 | 198.00 |
| | *n* (peak value) | 0 (155.00) | 0 (5.70) | (5.00) | (8896.00) |
| | Fulfilment of TLV-STEL criteria | Yes | Yes | n.a. | n.a. |
| 18 | TWA | 12.70 | 0.09 | 0.17 | 1188.30 |
| | *n* (peak value) | **1 (614.00)** | 0 (12.00) | (59.00) | (12,929.00) |
| | Fulfilment of TLV-STEL criteria | **No** | Yes | n.a. | n.a. |
| 19 | TWA | 6.10 | 0.09 | 0.04 | 528.90 |
| | *n* (peak value) | 0 (236.00) | 0 (3.70) | (12.00) | (17,290.00) |
| | Fulfilment of TLV-STEL criteria | **No** | Yes | n.a. | n.a. |
| 20 | TWA | 4.10 | 0.09 | 0.06 | 1072.9 |
| | *n* (peak value) | (286.00) | (8.50) | (6.00) | (15,071.0) |
| | Fulfilment of TLV-STEL criteria | Yes | Yes | n.a. | n.a. |

In bold are the situations in which limit values are exceeded or criteria not fulfilled.
*n* — number of exceedances to the peak limit.
n.a. — Not applicable.
n.d. — No data.

periods which are non-burning periods and with very low exposure or even zero values. The authors believe that the eight hours time weighted averages may not be suitable for this kind of occupation, due to the high variations of concentrations in relatively short term exposure periods. For instance, the peak limits were surpassed for the pollutants with available limit values (see Table 4), namely CO and $NO_2$.

During Gestosa 2008 the CO peak value was exceeded for five firefighters (ranging from 1 to 9 times each). The highest recorded peak was 499.80 ppm, near the maximum value of the working range of the equipment (0–500 ppm). This working interval of the measurements was increased in the 2009 experiments, when the CO peak value was surpassed for two firefighters and the highest CO peak was 614 ppm. Concerning the TLV-STEL, one of its criterion (according to the definition given in section 2.3) was not fulfilled by any of the firefighters in 2008 and by half of them (five) in 2009, since there were less than 60 min between successive exposures in the range TLV-TWA up to TLV-STEL.

When analyzing the $NO_2$, only two values higher than the peak limit value are observed, in 2008, with a maximum of 33 ppm.

There is no National or International legislation that sets TLV-TWA, TLV-STEL or peak limits for the total VOC but for the specific compounds only. Thus, it is not possible to compare the monitored concentrations with any limit value. Previous studies (Reinhardt et al., 2001; Reinhardt and Ottmar, 2004) have identified formaldehyde, and acrolein as the main toxic VOC emitted by bushfire; other studies (De Vos et al., 2009; Reisen and Brown, 2009) have also identified those compounds as well as acetaldehyde, benzene, toluene, xylene, and phenol. Those authors found that these compounds were in concentrations below 1 ppm. We measured total VOC peak concentrations as high as 88 ppm; further research would be interesting for identifying the concentrations and speciation of VOC. The experimental conditions during Gestosa 2008 and 2009 are different from the previous studies, namely the fuel load. Therefore, it is possible that other VOC, different from those previously identified, might occur in higher concentrations or at least might be present.

Since there is not a specific value of TLV-TWA for particles emitted by wildfires or prescribed burns, the ACGHI's TLV-TWA of 3 mg $m^{-3}$ for respirable particles was selected for the analysis However, because ACGHI assumes respirable particles as PM3.5 (sampled with a 50% efficiency at 3.5 µm), and this study considers PM2.5 (sampled with a 50% efficiency at 2.5 µm), the ACGHI's TLV-TWA will only be used as a reference value. All the monitored firefighters are within the allowed OES for particulate matter; the highest calculated TWA was 2.196 mg $m^{-3}$ and occurred in 2008.

In the following Figures continuum measurements of PM2.5, CO, VOC, and $NO_2$ concentrations are presented for firefighters 1 and 5 during Gestosa 2008, and firefighters 16 and 18 along Gestosa 2009. The selection of these firefighters was based on the representativeness of the data. In each graphic the duration of the fire in each plot is represented by the horizontal bars. The OES limit values defined by the National and International regulations are also indicated (according to Table 4) for a better understanding of the attained exposure values.

In terms of PM2.5, the instantaneous exposure concentration values acquired during the Gestosa 2008 fire experiments were very

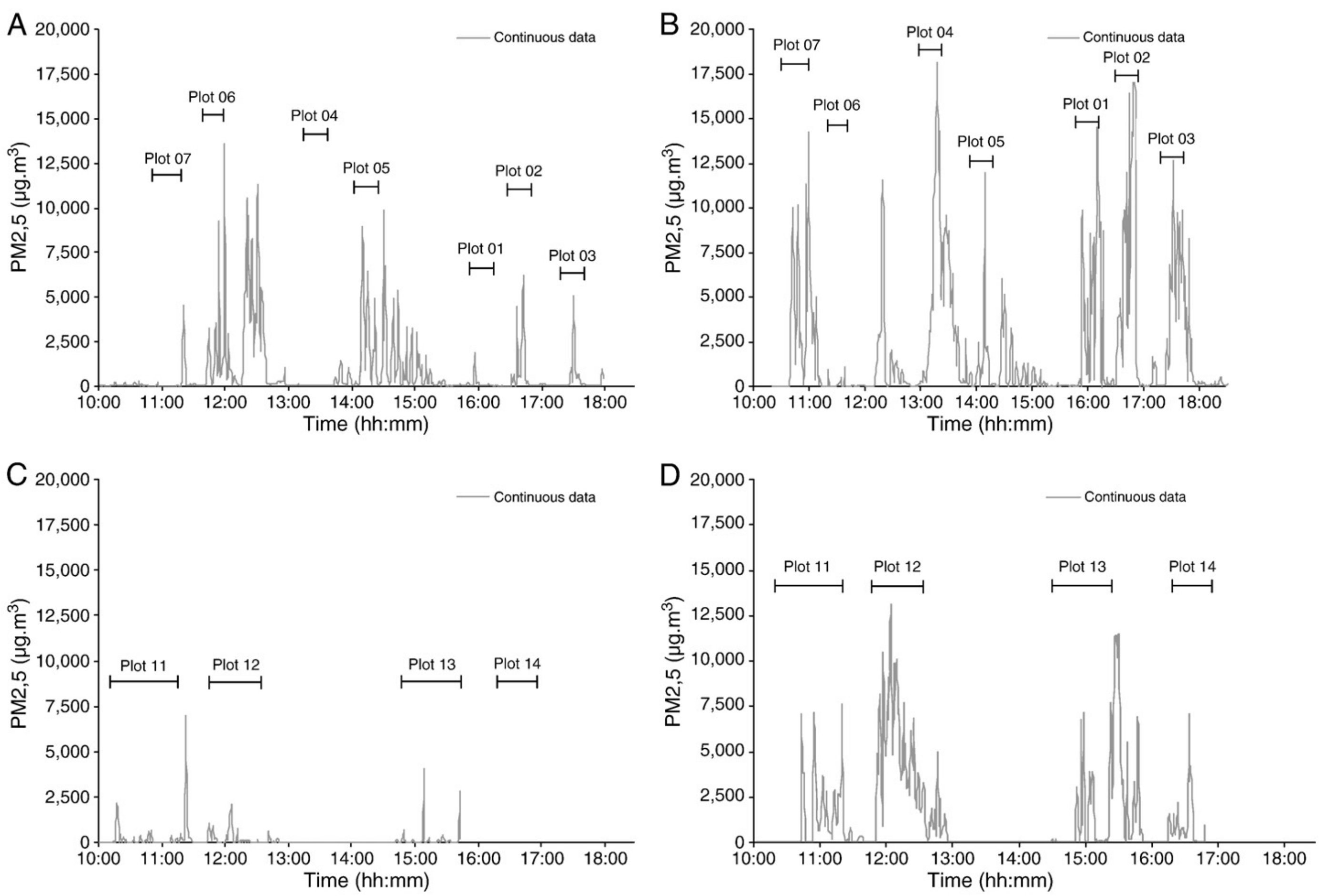


**Fig. 4.** PM2.5 concentrations for firefighters 1, 5, 16, and 18 (A, B, C, and D, respectively).

high, reaching a maximum of approximately 18000 μg $m^{-3}$ (image B) during the burning of plot 04, when firefighter 5 was near the fire front. As expected, there is a good agreement between the burning periods and the observed concentration peaks. For the same burning plots the maximum measured values were different between firefighters 1 and 5 in Gestosa 2008 (Fig. 4 A and B), and between firefighters 16 and 18 in Gestosa 2009 (Fig. 4 C and D), showing the influence of the positioning in relation to the smoke plume and of the job task of the firefighter. In fact, while firefighters 1 and 16 were near the trucks during the fire experiments; firefighters 5 and 18 were close to the burning plots, which explain the higher PM2.5 exposure values of the latter. For each plot concentrations tend to increase along the duration of the burn, because of the higher emission of fine particles during the smouldering phase (when compared to flaming) (e.g. Ward, 1999) and the close proximity of the firefighters to the emission source due to the decrease on fire intensity at this stage. This behaviour is more evident in the Gestosa 2008 fire experiments (images A and B). In some cases it can be noticed that concentrations attain significant values although there is not an active fire anymore. This is particularly explicit in the peaks observed for the time periods between plots 06 and 04, and between plots 05 and 01, for both firefighters (images A and B) in Gestosa 2008. The explanation relies on the fact that after the fire, suppression and mopping operations are carried out in order to guarantee the extinction.

The time evolution of instantaneous CO concentrations is shown in Fig. 5.

The data represented in Fig. 5 show that the acquired instantaneous concentration values were frequently very high. The knowledge of the CO concentration peaks to which firefighters are exposed is very important due to the risk of asphyxia. It can be seen that, for the four firefighters here analysed, the CO peak limit is exceeded four times. The surpassing of the recommended occupational exposure standard values by peak exposures agrees with the conclusions taken from the works of Reinhardt and Ottmar (2004), Reisen and Brown (2009), and De Vos et al. (2009). As in PM2.5, the CO levels present some agreement with the burning of the plots, corresponding to direct attack and fireline holding activities. Again, and because CO is a smouldering-derived pollutant (e.g. Andreae and Merlet, 2001) high concentrations were measured outside the flaming periods, which means that mop-up exposure can be important.

Examples of the continuum measurement of VOC concentrations are shown in Fig. 6 for the same firefighters.

From the analysis of Fig. 6 it can be concluded that the magnitude of VOC values is clearly distinct among the different periods, especially before and during the experiments in plot 4, and before plot 14. While in PM2.5 and CO there is a certain agreement between the exposure of firefighters 1 and 5, in the case of VOC the magnitude of the acquired concentrations has major differences. Similar conclusion can be taken from the analysis of Fig. 7, which shows the time evolution of continuum $NO_2$ concentrations for the selected firefighters.

In the case of $NO_2$ values, only for firefighter 5 (image B) the peak exposure limit is exceeded. Nevertheless, significantly high instantaneous concentration values were acquired during the Gestosa 2008 and 2009 experimental fires.

Concerning the relation between the job task and the magnitude of the exposure values it was concluded that firefighters 5 and 18, who were close to the burning plots, had higher exposure to CO and PM2.5 in terms of peak value and TWA. On the other hand, firefighters 1 and

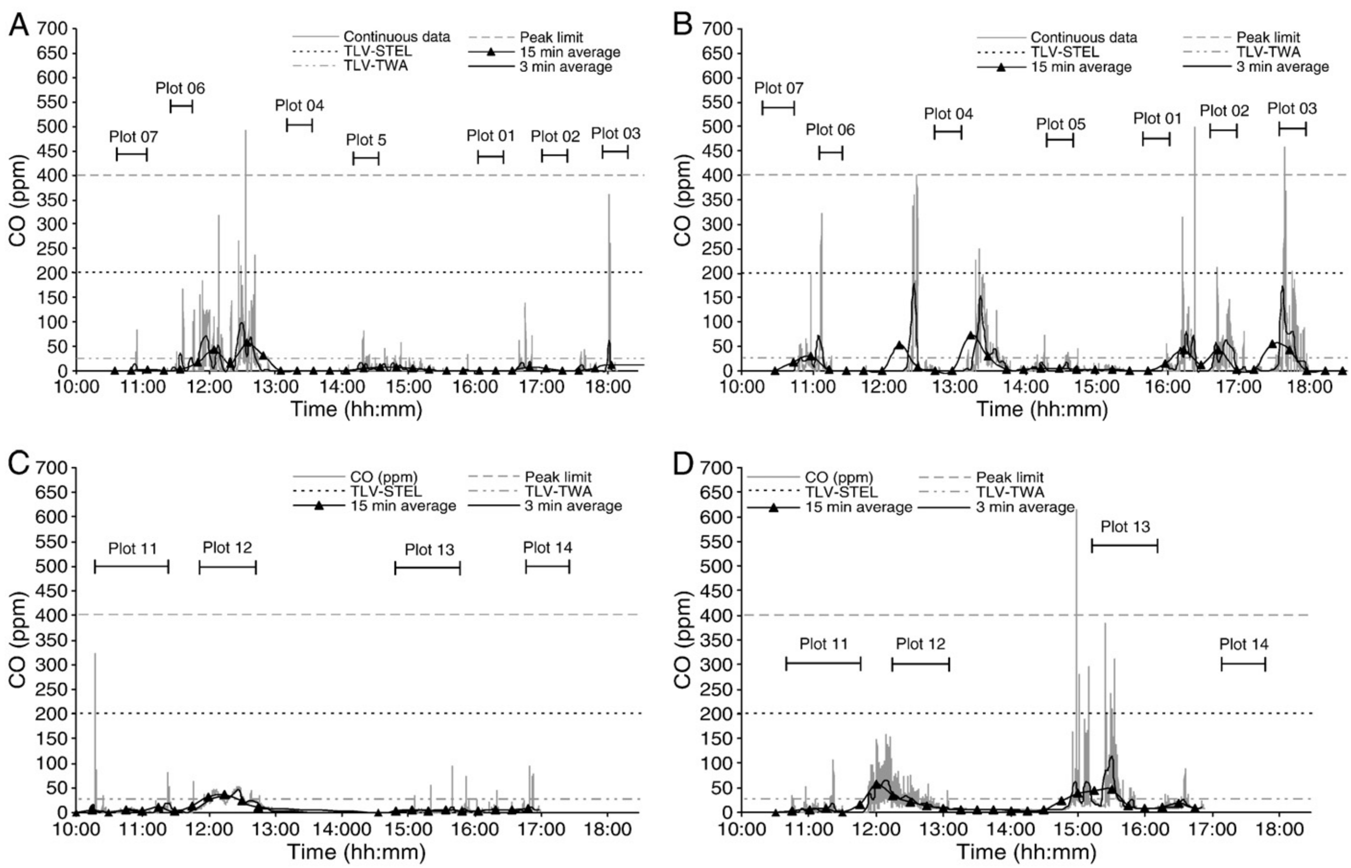


**Fig. 5.** CO concentrations for firefighters 1, 5, 16, and 18 (A, B, C, and D, respectively).

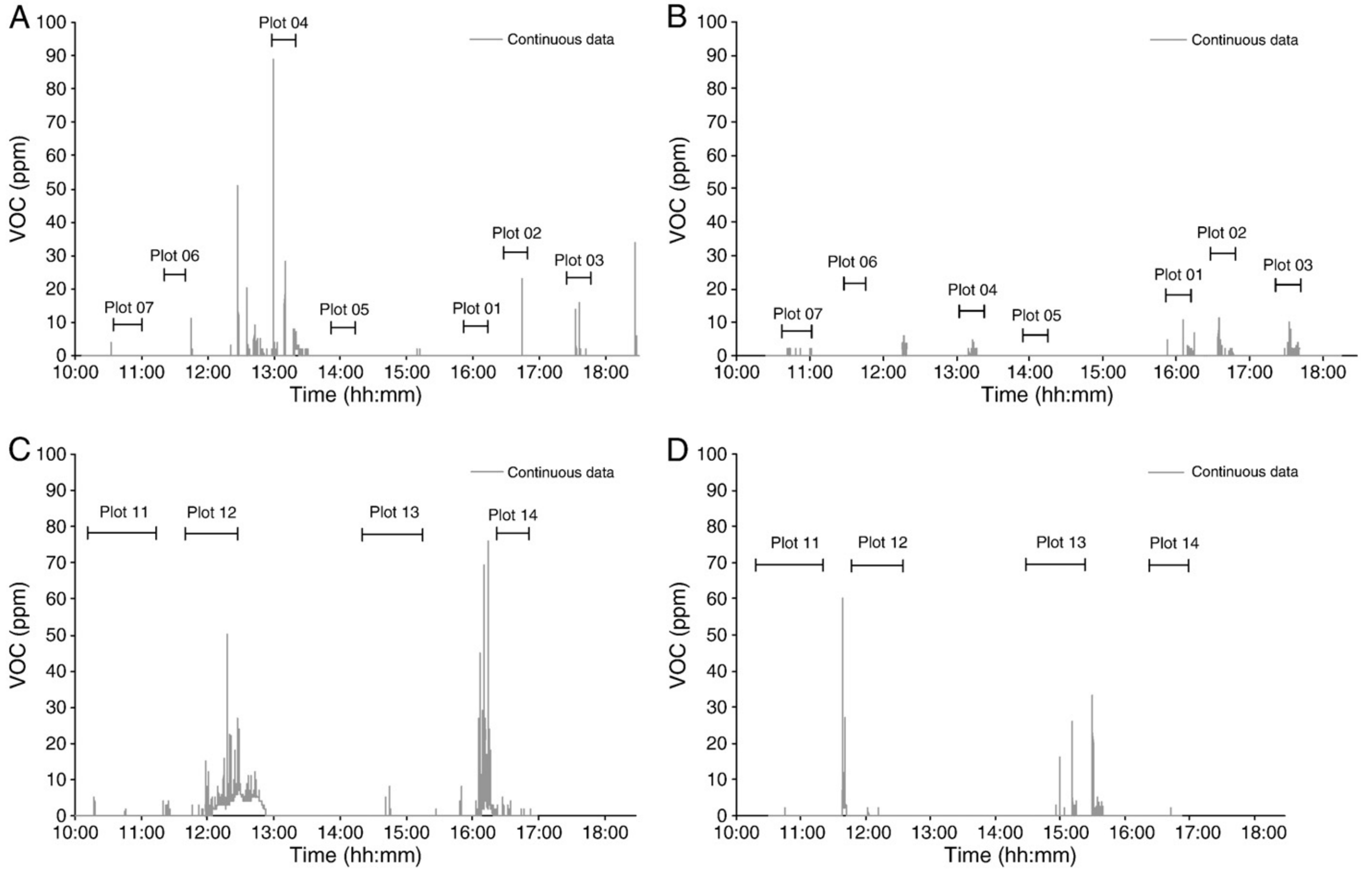


**Fig. 6.** VOC concentrations for firefighters 1, 5, 16, and 18 (A, B, C, and D, respectively).

16 were close to the water-pumps and the engines of the trucks leading to higher VOC exposures. For $NO_2$ a distinct behaviour was detected: for the firefighters near the trucks higher TWA exposures were found, while higher peak values were acquired by the ones near the fire.

Within this study the exposure values are compared with OES values. Nevertheless, it is interesting to notice that the World Health Organization (WHO) air quality guidelines, which are also defined for the protection of human health, present quite lower limit values. As an example, according to WHO, the daily-averaged concentration of PM2.5 in ambient air should not surpass 25 μg $m^{-3}$, while in working environments, and according to the OES values, a worker can be exposed to an averaged concentration value of respirable particles up to 3000 μg $m^{-3}$ during a 8 h work shift. Further research is needed to clarify why air quality and occupational exposure, which are strongly related concepts, have such different limit values.

## 4. Conclusions

Usually, the amount and characteristics of noxious exposure of wildland forest firefighters are not widely recognized; more attention has been drawn upon the risks of indoor firefighting. Our work indicates that firefighting operations can lead to the exposure to very high concentrations of CO, VOC, $NO_2$ and PM2.5, with potential harmful effects on human health.

Several exceedances to the OES values for CO were observed, meaning that firefighters are exposed to levels higher than the allowed limits of current legislation. $NO_2$ values are within the OES, except for some peak values exceedances. PM2.5 is also within the OES value. However, according to the figures, the measured exposure to PM2.5 is very high and could affect human health. Regarding VOC and taking into consideration that values reaching 88 pm were measured, some further research will be needed to determine the specific compounds and their individual concentrations. The firefighter task was found to have an important impact on the exposure. It was concluded that higher exposure values for CO and PM2.5 were monitored by firefighters near the fire, and higher VOC exposures were acquired near the trucks. It was also found that the emissions from the engines can increase the mean exposure (TWA) to $NO_2$, but peak values of this pollutant are mostly affected by the biomass-burning smoke.

The results presented in this paper are the first measurements of firefighter's personal exposure to toxic gases and particles in fire smoke experiments in Europe. They highlight that urgent measures to avoid these levels of exposure are needed. Those can be related to the use of adequate protecting devices, to a correct planning of firefighting shifts, and/or to the operational availability of information regarding the areas of higher pollutants levels that can be obtained through modelling of exposure.

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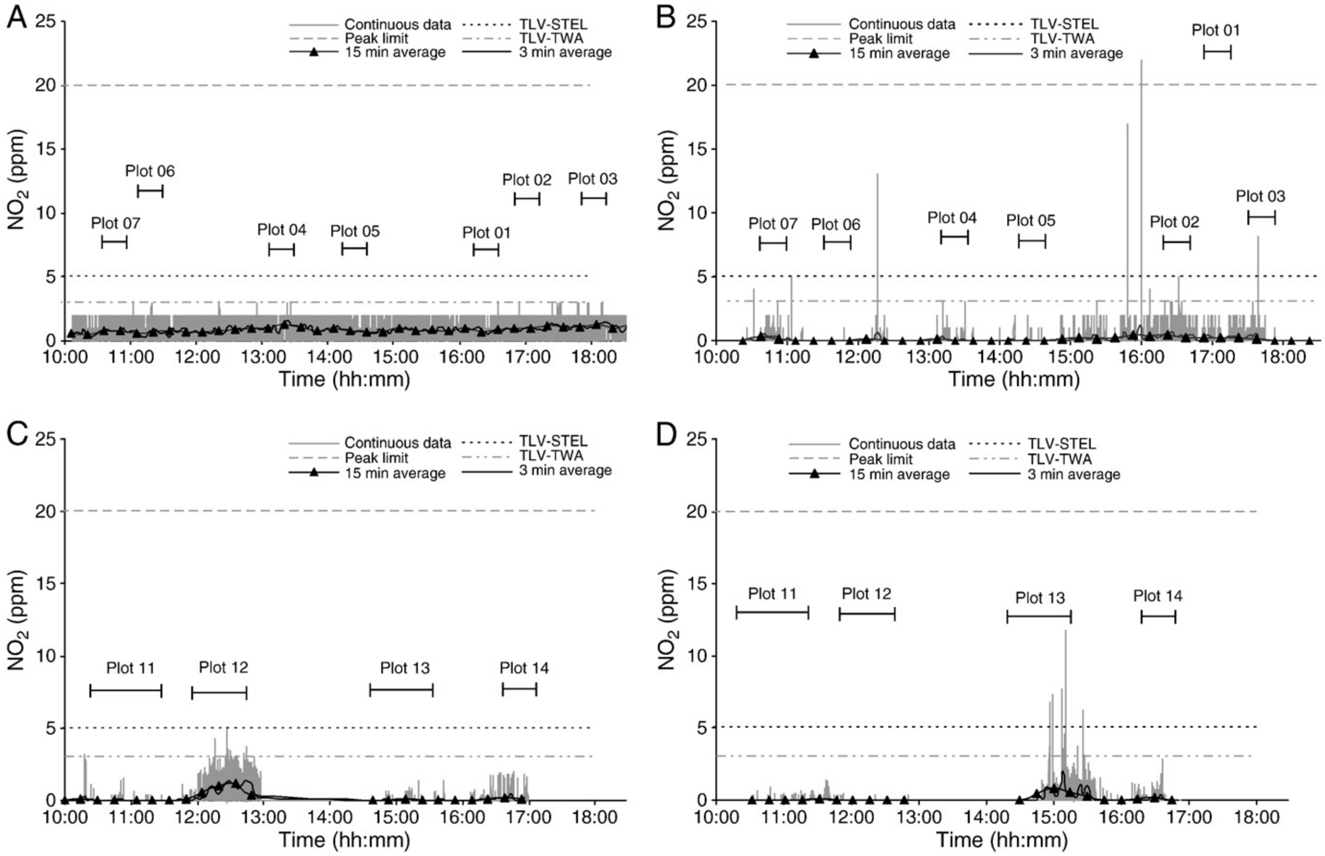


**Fig. 7.** $NO_2$ concentrations for firefighters 1, 5, 16, and 18 (A, B, C, and D, respectively).

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