Monitoring fire-fighters' smoke exposure and related health effects during Gestosa experimental fires

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Abstract

The main objective of this study is to contribute to the scientific knowledge regarding fire-fighters' exposure to smoke and its related health effects. Forest fire experiments were developed with an extensive number of measurements of individual exposure to smoke pollutants and of medical parameters for a group of fire-fighters. For the smoke exposure monitoring, ten fire-fighters from four different fire brigades were selected. The fire-fighters' individual exposure to toxic gases and particulate matter was monitored with portable devices, and their location in time was registered with GPS equipment. For all the monitored fire-fighters, air pollutant concentration values acquired during the fire experiments were beyond the limits recommended by the World Health Organization (WHO), namely for PM2.5, CO and NO_2. Daily averages of PM2.5 concentration values as high as 738 $\mu g.m^{-3}$ were obtained, well above the recommended limit of 25 $\mu g.m^{-3}$. In terms of CO, hourly averaged values higher than 73,000 $\mu g.m^{-3}$ were monitored, clearly above the 30,000 $\mu g.m^{-3}$ recommended by the WHO. The highest NO_2 hourly averaged measured value was 4,571 $\mu g.m^{-3}$, once again much higher than the recommended value of 200 $\mu g.m^{-3}$. For VOCs, a maximum hourly average of 10,342 $\mu g.m^{-3}$ was registered for one of the fire-fighters; however, due to the lack of recommended

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or legislated values it is not possible to establish a comparison. The medical tests conducted on the fire-fighters, before and after the exposure to smoke, also indicate a considerable effect on the measured medical parameters, in particular an expressive increase of CO concentration and a decrease of NO concentration in the exhaled air of the majority of the fire-fighters.

Keywords: smoke exposure, fire experiments, carbon monoxide, particulate matter, nitrogen dioxide, medical tests.

1 Introduction

Nowadays there is a growing awareness that smoke produced during forest fires can expose individuals and populations to hazardous concentrations of air pollutants. However, the current state of knowledge about the potential health impacts on fire-fighting personnel is still scarce, in particular within the European context. The most extensive measurements of smoke exposure among wild land fire-fighters were conducted in the United States of America (USA) and Australia [1–5]. From these field studies it was possible to conclude that fire-fighters can be exposed to significant levels of carbon monoxide (CO) and respiratory irritants, including formaldehyde, acrolein, and respirable particles [3, 5]. As a result, adverse health effects occur with acute, instantaneous eye and respiratory irritation and shortness of breath, developing into headaches, dizziness and nausea enduring for up to several hours. Additionally, long-term health effects, such as impaired respiratory function or increased risk of cancer, may be caused by these pollutants. Special concern is raised by exposure to respirable particles and potentially toxic compounds adsorbed to them (e.g. polycyclic aromatic hydrocarbons (PAHs) and semivolatile organic compounds, some of which may be carcinogenic), as well as to aldehydes, compounds that are known as probable human carcinogens. There are a number of factors that affect the impacts of smoke on health, including the concentration of air pollutants within the breathing zone of the fire-fighter, the exposure duration, exertion levels, and individual susceptibility, such as pre-existing lung or heart diseases [6].

In Europe, where an average annual value of 500,000 hectares of forest was consumed by fire in the last 29 years [7], there is a considerable lack of data on personal smoke exposure. These data are of vital importance for the establishment of cause/effect relationships between the exposure to air pollutants from smoke and fire-fighters' health effects.

Exposure results from the experiments in the USA and Australia may not be applicable to European wild land fire-fighters due to differences in vegetation, fire conditions and fire-fighting operations. The composition of smoke depends on the type of vegetation being burned, fuel moisture content, temperature of the fire and wind conditions [6]. Additionally, a major factor influencing exposure is the type of work activities that the fire-fighters carry out. Therefore it is crucial to assess exposure at the individual level and within the European context to determine whether exposure could result in health damage and what primary factors influence exposure.

The main purpose of this paper is to contribute to the fire-fighters' smoke exposure and related health effects knowledge. The current work presents and analyzes the data on individual exposure to CO, nitrogen dioxide (NO_2), volatile organic compounds (VOCs), and particles with an aerodynamic diameter lesser than 2.5 µm (PM2.5), which were obtained during field burning experiments for a group of ten fire-fighters equipped with portable "in continuum" measuring devices. A group of 14 fire-fighters were also tested before and after fire-fighting regarding their exhaled nitric oxide (eNO) and CO.

2 Methodology and equipment

The measurement of fire-fighters individual exposure and of the medical parameters was conducted during the Gestosa 2008 and 2009 fire experiments, in Central Portugal, at the end of spring season.

2.1 Study area characteristics

The study area is located in the mountain range of Lousã, Central Portugal, at an altitude between 900 and 1,100 m. The vegetation was mainly composed by continuous shrubs of three dominant species: *Erica umbellata*, *Ulex minor* and *Chamaespartium tridentatum*. In Figure 1 it is possible to have a perspective of the study area general characteristics, for 2008 and 2009 fire experiments.

The study areas were divided into 7 and 4 plots in 2008 and 2009, respectively, with regular shapes and variable dimensions. For 2008 plots varied between 874 and 2,820 m^2 and for 2009 plots varied between 1,800 and 6,057 m^2. These experimental burning plots were established within Forest Service lands, and within the Gestosa forestry perimeter.

Before the experiments the burning plots were prepared and the vegetation properties analysed. The characteristics of the experimental plots and available fuel are presented in Table 1.

During one month before the experiments, hourly data related with wind speed, wind direction, precipitation, air temperature and relative humidity were

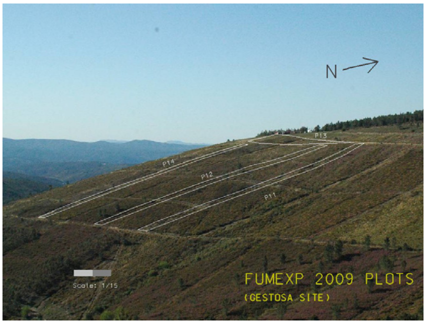

Figure 1: Plot layouts from the Gestosa 2008 and Gestosa 2009 study areas.

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	1,228	24	98.20	85.95	2.11	26.31
P04	1,493	22	86.00	70.40	2.26	22.41
P05	2,642	20	100.00	66.53	2.23	33.58
P06	1,089	23	100.00	83.00	2.28	31.17
P07	1,049	17	100.00	66.25	2.34	29.15
Gestosa 2009						
P11	2,552	19	*	*	*	*
P12	1,800	17	*	*	*	*
P13	6,057	14	*	*	*	*
P14	2,990	19	*	*	*	*

* Plots are safety areas with little vegetation.

recorded by a Geolog S meteorological station. This information allowed assessing the best period of the day to burn with the advisable wind conditions.

The duration of the burns in Gestosa 2008 was rather small (10-15 minutes) when compared to wildfires. Although the fire duration during Gestosa 2009, which lasted for almost one hour for a specific plot, is higher than during Gestosa 2008, the plots had little vegetation and that limited the fire-fighter's exposure to smoke.

2.2 Smoke exposure

For the smoke exposure monitoring, 10 fire-fighters were selected from four different fire corporations. Fire-fighters were chosen based on predefined criteria that took into account the age, smoking habits, respiratory diseases and function in the fire brigade. The selected fire-fighters were equipped with sampling devices monitoring individual exposure to CO, VOC, NO_2 and PM2.5. Moreover, the location of each corporation in time was registered with GPS equipment. For the selection of the monitoring equipment some important aspects were considered, namely their weight and the robustness, as well as the measuring ranges. Figure 2 shows some fire-fighters with the exposure monitoring equipment.

VOC and NO_2 were monitored continuously using integrated photo-ionization detector GasAlertMicro 5 PID from BW Technologies. The rechargeable battery allows a continuous operation up to 12 hours and with the memory card is capable of recording two months of data. The VOC and NO_2 sensors were calibrated before the burn using a 100 ppm isobutylene and 10 ppm NO_2 calibration gas, respectively.

Figure 2: Fire-fighters with the exposure monitoring equipment.

Table 2: Characteristics of the equipment.

Pollutant	Type of data	Equipment	Characteristics	
			Range	Resolution
VOC	Continuous measurement: 5 seconds 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 seconds interval	GasAlertMicroClip from BW Technologies	0-500 ppm	1 ppm
		GasAlertextreme from BW Technologies	0-1,000 ppm	1 ppm
PM2.5	Continuous measurement: 1 minute interval	Personal Aerosol Monitor SidePack AM510 from TSI	0-20 $mg.m^{-3}$	0.001 $mg.m^{-3}$

CO was also monitored continuously using a CO GasAlertMicroClip and CO GasAlertextreme from BW Technologies, in Gestosa 2008 and 2009, respectively. 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. Table 2 summarizes the characteristics of the equipments.

2.3 Air quality limit values

Aiming to better understand the effects of these experimental fires on the fire-fighters health, the measured results were compared to the European air quality legislation values and to the values recommended by the WHO (Table 3).

Both the air quality legislation limit values as well as the WHO standards were established aiming to protect the human health from the air pollution effects. In general, the proposed limit values agree with only one exception regarding PM2.5, for which WHO is more demanding. Moreover, the WHO recommends limit values for other time periods than those considered by the European Directive.

2.4 Medical tests

The respiratory function of a 38 fire-fighters sample was evaluated, prior to any exposure, during April 2008. They also answered the SF-36 questionnaire, which regards the general quality of health. An initial subgroup of 14 non smoker fire-fighters was tested during 2008, before and after fire-fighting, regarding to their eNO and CO. During the Gestosa 2009 experiments, eNO, CO and % carboxy-haemoglobin (COHb) were also registered for a similar sub-group of 14 fire-fighters, pre and post smoke exposure. In 2009, a sample of exhaled breath condensate was collected too, before and after smoke exposure, for the determination of lung inflammatory patterns. Table 4 summarizes the characteristics of the medical equipments.

Table 3: Air quality limit values for the protection of human health established by European legislation and recommended by the WHO.

Pollutant	European Legislation (2008/50/CE)	WHO
PM2.5	25 $\mu g.m^{-3}$ (1 year)	25 $\mu g.m^{-3}$ (24 hour)
		10 $\mu g.m^{-3}$ (1 year)
NO_2	200 $\mu g.m^{-3}$ (1 hour)	200 $\mu g.m^{-3}$ (1 hour)
	40 $\mu g.m^{-3}$ (1 year)	40 $\mu g.m^{-3}$ (1 year)
CO	10 $mg.m^{-3}$ (8 hours)	100 $mg.m^{-3}$ (15 minutes)
		60 $mg.m^{-3}$ (30 minutes)
		30 $mg.m^{-3}$ (1 hour)
		10 $mg.m^{-3}$ (8 hours)

Table 4: Characteristics of the medical equipment.

Parameter	Equipment	Characteristics	
		Range	Resolution
eNO	Nioxmino from Aerocrine	5-300 ppb	1 ppb
Alveolar CO	MICRO CO/Smoke-check from Micromedical	0-500 ppm	1 ppm

3 Results and discussion

3.1 Smoke exposure

To assess fire-fighters exposure to smoke pollutants and taking into account the recommended limit values (see Table 3), 1 hour averages for CO, VOC and NO_2 and 24 hours averages for PM2.5 were calculated for every monitored fire-fighter. Table 5 presents the maximum hourly-averaged values for CO, NO_2 and VOC and the daily averages for PM2.5. This last one was calculated considering zero PM2.5 values for the non-exposure time periods.

For all the monitored fire-fighters, a considerable number of the air pollutants concentration values acquired during their activity is beyond the limits recommended by the WHO (see bold values in Table 5), namely for PM2.5, CO

Table 5: Highest hourly averages of CO, NO_2 and VOC and 24 hour averages for PM2.5.

Fire-fighter	CO	NO_2	VOC	PM2.5
	($\mu g.m^{-3}.h^{-1}$)			($\mu g.m^{-3}.day^{-1}$)
Gestosa 2008				
1	**32,479**	**2,163**	1,585	**260**
2	**73,033**	**4,172**	3,934	**184**
3	**47,223**	**3,641**	415	**306**
4	**50,881**	**274**	1,789	**240**
5	**33,178**	**709**	599	**738**
6	**49,078**	n.d.	2,917	**735**
7	n.d.	**2,599**	1,838	**684**
8	**35,847**	**609**	1,520	**479**
9	**48,259**	**4,571**	5,302	**610**
10	n.d.	82	2,097	**206**
Gestosa 2009				
1	12,586	**344**	54	**44**
2	22,814	**332**	526	**400**
3	**32,222**	**485**	496	**124**
4	**39,090**	142	343	**315**
5	**36,199**	**884**	337	**152**
6	**30,669**	**1,544**	10,342	**40**
7	4,903	132	62	**66**
8	**41,9389**	**788**	1,377	**396**
9	**42,023**	**802**	376	**176**
10	17,899	**1,091**	1,076	**358**

n.d. – No data

and NO_2. Daily averages of PM2.5 concentration values as high as 738 $\mu g.m^{-3}$ were obtained, well above the recommended limit of 25 $\mu g.m^{-3}$, even considering that during the rest of the day the concentration was 0 $\mu g.m^{-3}$. In terms of CO, hourly averaged values higher than 73,000 $\mu g.m^{-3}$ were monitored, clearly above the 30,000 $\mu g.m^{-3}$ recommended by the WHO. The highest NO_2 hourly averaged measured value was 4,571 $\mu g.m^{-3}$, once again much higher than the recommended value of 200 $\mu g.m^{-3}$. For VOC, a maximum hourly average of 10,342 $\mu g.m^{-3}$ was registered for one of the fire-fighters; however, due to the lack of recommended or legislated values for total VOC it is not possible to establish a comparison.

Aiming to have the time evolution of exposure values along the experiments, hourly averaged values for the measured pollutants during Gestosa 2008 and Gestosa 2009, for two particular fire-fighters, are presented in Figure 3.

The hourly averages for the pollutants show a similar pattern in terms of concentration variation, which is related to the smoke exposure. PM2.5 and CO are the pollutants that present the highest concentrations.

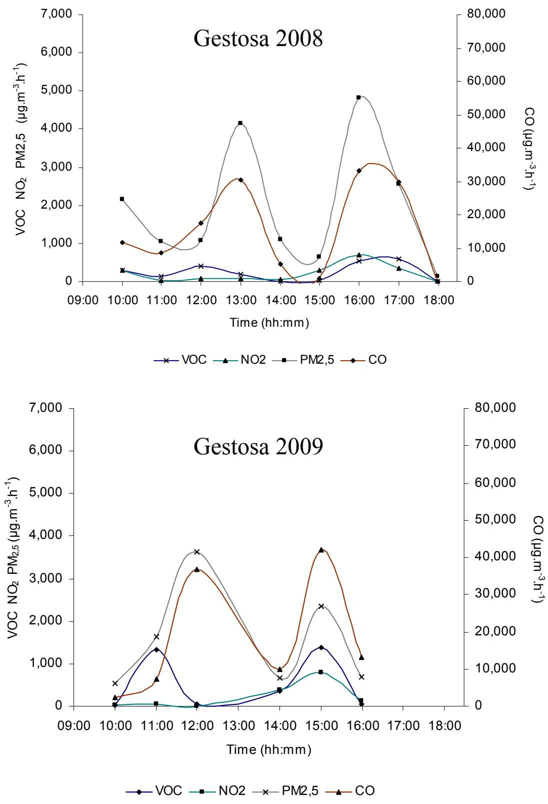

Figure 3: Hourly averaged exposure values in Gestosa 2008 and 2009 for fire-fighters 5 and 8.

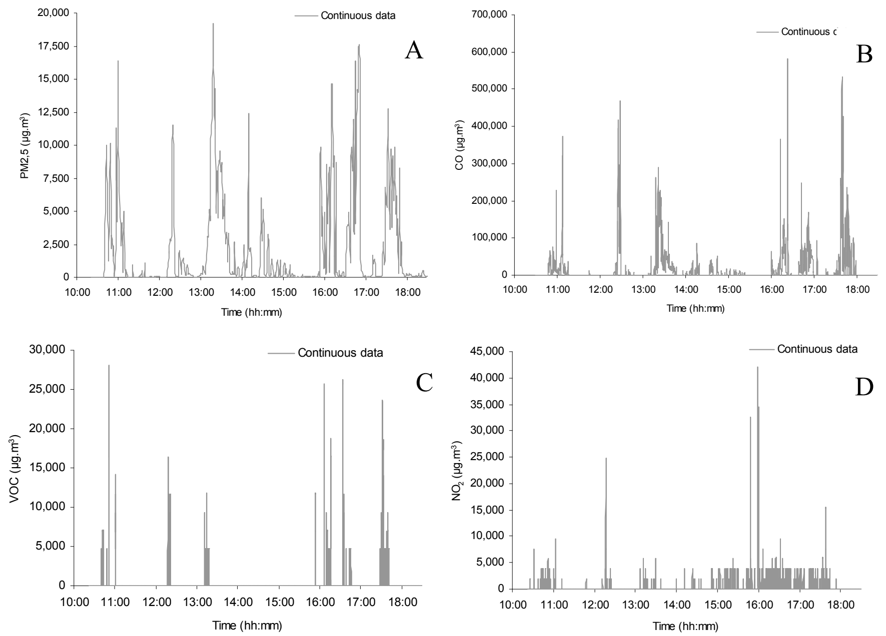

Figure 4: PM2.5, CO, VOC and NO_2 concentrations measured during Gestosa 2008 for fire-fighter 5 (A, B, C and D respectively).

Figure 4 also shows the instantaneous registered data along the Gestosa 2008 experiments, for the fire-fighter 5.

The instantaneous CO concentration values acquired during the Gestosa 2008 were very high, reaching a maximum value above 600,000 $\mu g.m^{-3}$. PM2.5 values were also very high (19,953 $\mu g.m^{-3}$). These data show the magnitude of the exposure peaks occurred during regular fire-fighting operations. For instance, the knowledge of the CO concentration peaks to which fire-fighters are exposed is quite important, since high concentrations of this gas can cause death by asphyxia. The same type of results was obtained for Gestosa 2009.

3.2 Health assessment

Figures 5 and 6 illustrate the changes in the medical measured parameters in Gestosa 2008 and 2009, respectively.

The medical tests conducted on the fire-fighters in 2008, before and after the exposure to smoke, indicate a considerable effect on the measured parameters. Regarding CO concentration in the exhaled air: (i) there was a higher number of fire-fighters with concentration values above 7 ppm after fire (20 ppm were even registered for one fire-fighter); (ii) before fire 11 fire-fighters had CO levels in the [0-6] ppm range, and after fire only 2 remained in the same interval.

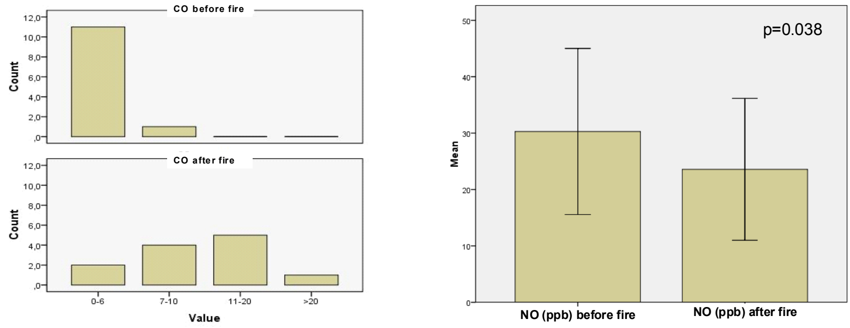

Figure 5: Medical test results for Gestosa 2008 before and after fire exposure, for CO (ppm) and NO (ppb).

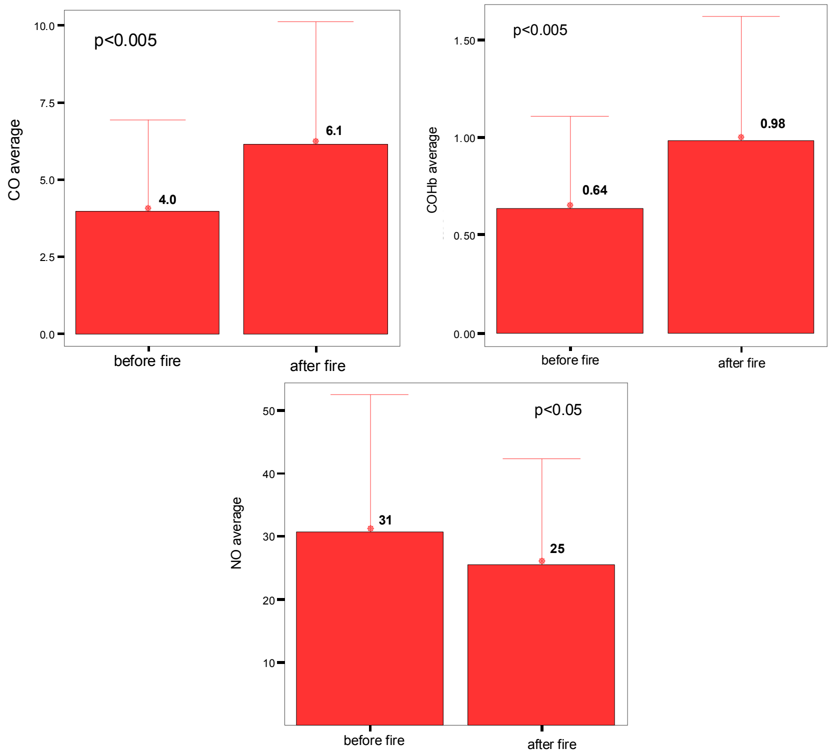

Figure 6: Medical tests results for Gestosa 2009 before and after fire exposure (CO and COHb in ppm, NO in ppb).

In what concerns the exhaled NO, there was a significant decrease ($p=0.038$) between the values measured before and after the exposure to smoke, achieving 5 ppb. This could indicate an effect similar to the exposure to cigarette smoke. Indeed, in current smokers, it is usually observed a decrease on exhaled nitric oxide, probably related to the inhibition of nitric oxide synthetase [8].

Figure 6 shows, for CO, COHb and NO, the averaged values for the 14 monitored fire-fighters. In the scope of the previously observed, there was a strong increase ($p<0.005$) of the exhaled CO and COHb after fire, reaching 2.10 ppm and 0.34 ppm, respectively. In terms of NO in the exhaled air, there was a decrease ($p<0.05$) in the order of 6 ppb.

4 Conclusions

Usually, the amount and characteristics of noxious exposure of forest fire-fighters are not widely recognized; more attention has been drawn upon the risks of indoor fire-fighting. Our work indicates that forest fire-fighting can expose individuals to very high concentrations of CO, VOC, NO_2 and PM2.5, with potential harmful effects on human health. Urgent measures to avoid these levels of exposure are needed. They can be related to the use of adequate protecting devices, to a correct planning of fire-fighting 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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