11A.3

MONITORING FIREFIGHTERS EXPOSURE TO SMOKE DURING FIRE EXPERIMENTS AND WILDFIRES

Ana Isabel Miranda[1], Vera Martins*[1], Pedro Cascão[1], Jorge Humberto Amorim[1], Joana Valente[1], Richard Tavares[1], Carlos Borrego[1], Oxana Tchepel[1], António Jorge Ferreira[2], Carlos Robalo Cordeiro[2], Domingos Xavier Viegas[3], Luís Mário Ribeiro[3] and Luís Paulo Pita[3]

[1] CESAM & Department of Environment and Planning, University of Aveiro, 3810-193 Aveiro, Portugal.
[2] Centre of Pulmonology of Coimbra University Medical School, 3000-075 Coimbra, Portugal.
[3] Association for the Development of Industrial Aerodynamics & University of Coimbra, 3031-601 Coimbra, Portugal.

Abstract. The main objective of the research project FUMEXP is to study the potential effect of forest-fire smoke emissions on forest firefighter's health. FUMEXP implied an extensive number of measurements of individual exposure to smoke pollutants and of medical parameters, for a group of firefighters during fire experiments and wildfires. For the smoke exposure monitoring, ten firefighters from four different fire brigades were selected. The firefighters' individual exposure to gaseous compounds and particulate matter was monitored with portable devices, and their location in time was registered with GPS equipment. For all the monitored firefighters, air pollutants concentration values acquired during their activity, both in the wildfires and in the fire experiments, were beyond the limits recommended by the World Health Organization (WHO), namely for PM2.5, CO, NO_2 and VOC. Daily averages of PM2.5 concentration values as high as 470 $\mu g.m^{-3}$ 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 4,670 $\mu g.m^{-3}$, once again much higher than the recommended value of 200 $\mu g.m^{-3}$. For VOC, a maximum hourly average of 5,300 $\mu g.m^{-3}$ was registered for one of the firefighters; however, due to the lack of recommended or legislated values it is not possible to establish a comparison. The medical tests conducted on the firefighters, before and after the exposure to smoke, also indicate a considerable effect on the measured medical parameters, in particular an expressive increase of CO and a decrease of NO in the exhaled air of the majority of the firefighters.

1 INTRODUCTION

There is a general agreement about the importance of forest fires as a major emission source of air pollutants to the atmosphere. However, the current state of knowledge on the potential health impacts on the affected population and, in particular, on the personnel involved in firefighting operations is still scarce. Wildland firefighters are exposed to a complex mixture of combustion products including carbon monoxide (CO), irritant gases and vapours, carcinogen substances, respirable particles, and nanoparticles. Firefighters engage in heavy exercise levels while fighting fires, many times during long shifts that are extended to more than 16 hours (Austin, 2008).

The most extensive measurements of smoke exposure among wildland firefighters were conducted in the United States of America (USA) and Australia (Materna *et al.*, 1992, 1993; McMahon and Bush, 1992; Reh and Deitchman, 1992; Kelly, 1992a, 1992b; Reh *et al.*, 1994; Reinhardt and Ottmar, 2000, 2004; Reinhardt *et al.*, 2000). From these field studies it was possible to conclude that firefighters can be exposed to significant levels of CO and respiratory irritants, including formaldehyde, acrolein, and respirable particles (Reinhardt and Ottmar, 2000; Reinhardt *et al.*, 2000). 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 up for 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

* *Corresponding author contact*: V. Martins, University of Aveiro, Dep. of Environment and Planning, Campus Universitário, 3810-193, Aveiro, Portugal; e-mail: veram@ua.pt

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 firefighter, the exposure duration, exertion levels, and individual susceptibility such as pre-existing lung or heart diseases (Reisen and Brown, 2009).

In Europe, where an average annual value of 500,000 hectares of forest was consumed by fire in the last 29 years (EC, 2009), 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 air pollutants exposure to smoke and firefighters health effects.

Exposure results from the USA and Australia experiments may not be applicable to the European wildland firefighters due to differences in vegetation, fire conditions and firefighting operations. The composition of smoke depends on the type of vegetation being burned, fuel moisture content, temperature of the fire and wind conditions (Reisen and Brown, 2009). Additionally, a major factor influencing exposure is the type of work activities that the firefighters 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.

In this scope, the research project FUMEXP, developed in a south European country, Portugal, aims to evaluate the effects of forest fire emissions on firefighters health for typical south European conditions. FUMEXP is based on three complementary approaches: measurements of exposure to smoke, along experimental and wildfires conditions; exposure modelling; and medical tests. Hence, FUMEXP activities involved an extensive number of measurements of environmental indicators, individual exposure to smoke pollutants and medical parameters for a group of firefighters along wild fires and experimental field burnings. This paper presents results from the 2008 and 2009 measuring campaigns.

2 METHODS AND EQUIPMENT

Different measuring methods and equipment have been used along the field campaigns, aiming to collect information about smoke effects on the air and on the firefighters health. Both field campaigns occurred at spring time, just before the fire season starting in Portugal.

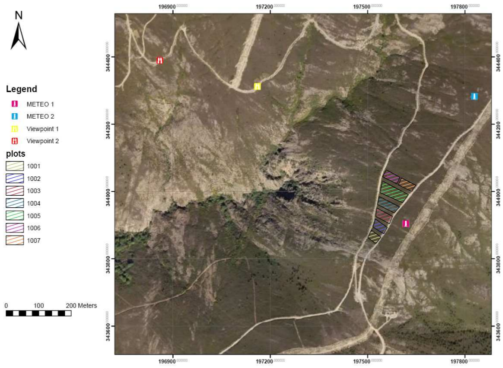
2.1 *Study area characteristics*

The study area is located in Central Portugal (40º15'N, -8º10'W), in a hillside of "Serra da Lousã" with altitudes between 800 and 950 meters. 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.

Figure 1. Image from Gestosa-2009 study area.

The experimental area was divided into 7 and 12 plots in 2008 and 2009, respectively, with regular shapes and variable dimensions. For 2008 plots varied between 874 and for 2,820 m^2 for 2009 plots varied between 1,632 for 1,933 m^2. These experimental burning plots, represented in Figure 2, were established within Forest Service lands, and within the Gestosa forestry perimeter.

A



B

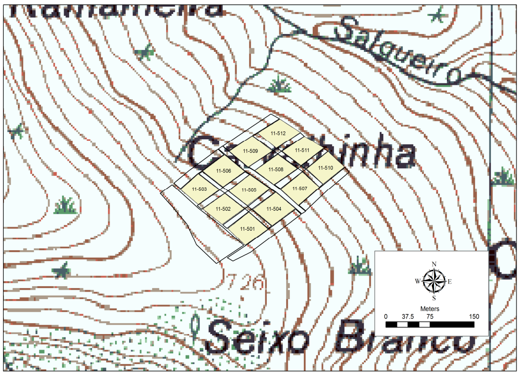


Figure 2. Map and schematic view of 2008 (A) and 2009 (B) burning plots.

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

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

Plot	Fuel Cover (%)	Fuel Height (cm)	Fuel Bulk Density (kg.m^{-3})	Fuel Load (ton.ha^{-1})
Gestosa-2008				
1001	100.00	83.25	2.04	24.79
1002	100.00	93.00	2.06	26.69
1003	98.20	85.95	2.11	26.31
1004	86.00	70.40	2.26	22.41
1005	100.00	66.53	2.23	33.58
1006	100.00	83.00	2.28	31.17
1007	100.00	66.25	2.34	29.15
Gestosa-2009				
11501	100.00	79.85	2.26	35.66
11502	94.60	38.50	1.78	28.28
11503	77.00	50.32	1.90	28.40
11504	93.40	52.91	2.27	33.86
11505	104.60	67.57	2.38	35.50
11506	66.80	30.62	2.20	32.49
11507	97.40	76.52	2.40	37.92
11508	100.00	93.98	2.83	43.75
11509	66.67	136.03	2.73	41.02
11510	98.40	72.63	2.51	38.55
11511	100.00	151.25	2.71	43.14
11512	94.60	124.83	2.77	42.37

2.2 *Data acquisition*

The Gestosa experimental field fires occurred on warm and dry days in May, and air quality and meteorological values were measured, as well as individual firefighters exposure to pollutants and some health indicators.

Air quality

During the experimental fires, temperature, humidity and wind speed and direction were measured near the fire plots. Furthermore, specific equipment was used to obtain the concentrations of different air pollutants, namely particles with an aerodynamic diameter lesser than 10 µm (PM10), CO, nitrogen dioxide (NO_2), nitric oxide (NO) and ozone (O_3). A mobile laboratory located near the burning plots, was equipped with the meteorological apparatus and the air quality analysers. Table 2 summarises the used air pollutant measuring equipments.

Table 2. Summary of air pollutant measurement techniques during Gestosa-2008/2009 experiments.

Pollutant	Type of data (continuous measurement)	Equipment
PM10	15 minutes average	*Environnement* MP101M™
NO_x	15 minutes average	*Environnement* AC31M™
CO	1 minute average	*Environnement* CO11M™
O_3	1 minute average	*Environnement* O341M

The continuous acquisition of NO and NO_2 concentrations in air was performed using the automatic equipment Environnement AC31M™ (dual chamber chemiluminescent nitrogen oxides; Environnement S.A., Poissy France). CO was measured continuously with the Environnement CO11M analyzer, whose functioning principle is based on the selective absorption of infrared radiation by the CO molecules. To monitor PM10, one MP101M analyzer was used with adequate sampling inlet. A ß-gauge mass monitor determines the particles mass. CO and O_3 were continuous measured with 1 minute average, while PM10 was measured with a 15 minutes average.

Aiming to better understand the effects of these experimental fires on the air quality, the measured results were compared to the European air quality legislation values, which are also the Portuguese standards, and to the values recommended by the World Health Organization (WHO) (see Table 3).

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

Pollutant	European Legislation	WHO
PM10	50 µg.m^{-3} (24 hours) 40 µg.m^{-3} (1 year)	50 µg.m^{-3} (24 hours) 20 µg.m^{-3} (1 year)
PM2.5	25 µg.m^{-3} (1 year)	25 µg.m^{-3} (24 hour) 10 µg.m^{-3} (1 year)
NO_2	200 µg.m^{-3} (1 hour) 40 µg.m^{-3} (1 year)	200 µg.m^{-3} (1 h) 40 µg.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)
O_3	240 µg.m^{-3} (1 hour) Alert threshold 180 µg.m^{-3} (1 hour) Information threshold 120 µg.m^{-3} (8 hours) Health protection	100 µg.m^{-3} (8 hours)

Smoke exposure

For the smoke exposure monitoring, 10 firefighters were selected from four different fire brigades, while for the medical tests the sample was composed by 38 firefighters. Firefighters were chosen based on predefined criteria that took into account the age, gender, smoking habits, function in the fire brigade, etc. Individual exposure to CO, volatile organic compounds (VOC), nitrogen dioxide (NO_2), and particles with an aerodynamic diameter lesser than 2.5 µm (PM2.5) was monitored with portable devices (Table 4). Moreover, the location of each firefighter in time was registered with GPS equipment.

Table 4. Characteristics of the equipments.

Pollutant	Equipment	Weight	Range	Resolution
VOC	GasAlertMicro 5 PID – BW Technologies	370 g	0-1,000 ppm	1 ppm
NO_2	GasAlertMicro 5 PID – BW Technologies		0-99.9 ppm	0.1 ppm
CO	GasAlertextreme – BW Technologies	82 g	0-1,000 ppm	1 ppm
PM2.5	SIDEPAK AM510 – TSI	460 g	0.001-20 mg.m^{-3}	0.001 mg.m^{-3}

For the selection of the monitoring equipment some important aspects were considered, namely their weight and the robustness, as well as the measuring ranges.

Medical tests

The respiratory function of the 38 firefighters sample was evaluated, prior to any exposure, during April 2008. They also answered the SF -36 questionnaire, which regards the general quality of health. These data will again be collected and statistically compared for the same sample after the ending of the forest fire season, probably at end-October 2009.

An initial subgroup of 14 non smoker firefighters was tested during 2008, before and after firefighting, regarding to their exhaled nitric oxide (eNO) and CO. Exhaled nitric oxide, CO and % carboxy-haemoglobin, were also registered for a similar sub-group of 14 firefighters, pre and post smoke exposure, during the May 2009 Gestosa experiments.

At 2009, a sample of Exhaled Breath Condensate was also collected before and after smoke exposure, for determination of lung inflammatory patterns.

3 RESULTS AND DISCUSSION

3.1 *Meteorological data*

During the fire experiments of Gestosa 2008 and 2009 several meteorological parameters were continuously measured, namely, wind speed and direction, humidity and temperature.

Table 5 presents the averaged values measured near each plot, for 2008, and Table 6 presents the hourly-averaged values measured along the 2009 experiments

Table 5. Meteorological data for Gestosa-2008.

Plot	Wind Speed (m.s^{-1})	Wind Direction (-)	Temperature (ºC)	Humidity (%)
1	1.5	S	19.4	32.8
2	2.2	W	20.2	35.0
3	3.8	NW	20.2	48.2
4	3.3	SE	17.0	58.5
5	2.8	SE	17.7	57.6
6	0.9	SE	17.6	19.2
7	2.2	W	17.8	15.6

Table 6. Meteorological data along Gestosa-2009.

Time (hh:mm)	Wind speed (m.s^{-1})	Wind direction (-)	Temperature (ºC)	Humidity (%)
09:00	1.4	SE	18.3	40.4
10:00	2.3	SE	19.1	37.2
11:00	2.2	SE	20.3	33.5
12:00	1.9	SE	22.0	28.4
13:00	1.7	SE	23.3	27.2
14:00	3.3	NE	24.2	25.6
15:00	6.2	NE	24.6	21.6
16:00	7.8	NW	22.3	22.3
17:00	8.4	NE	22.0	21.1
18:00	7.4	NW	21.6	23.8
19:00	7.7	NW	20.6	30.4

For 2008 wind speed was in general low. The humidity of the air varied among the burning plots from 16% to 60%.

Regarding 2009, at morning hours wind speed was low and coming from SE. With the afternoon higher wind speeds were registered and the wind changed coming now from NE and NW.

3.2 *Air quality data*

Figure 2 depicts the measured concentrations of PM10, O_3, NO_2 and CO during the two fire experiments.

A

B

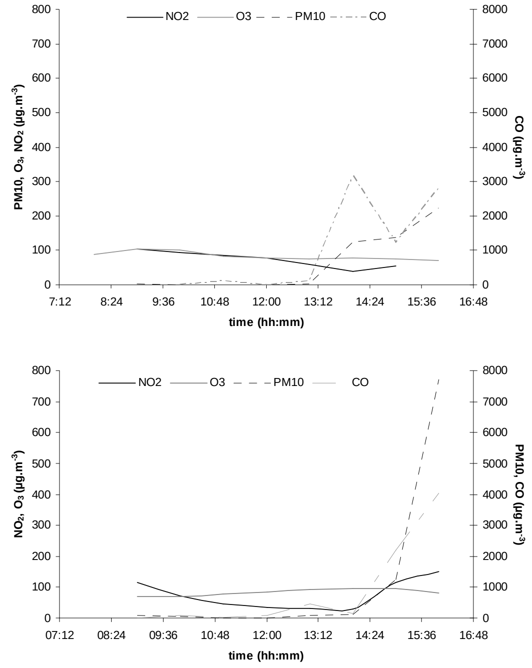


Figure 2. Hourly averaged PM10, O_3, NO_2 and CO concentration values (µg.m^{-3}) measured in ambient air in Gestosa-2008 (A) and Gestosa-2009 (B)

In both cases (2008 and 2009) air quality equipment registered the effect of fire emissions in the afternoon period, when the wind was in a favourable direction, and the plume was measured by the equipment installed in the mobile laboratory. From the analysis of Figure 2 it is identifiable the effect of smoke on the measured concentration values for all measured pollutants, with the exception of ozone, which is a secondary pollutant and therefore for this scale of experiments without discernible increases.

3.3 *Smoke exposure data*

As previously mentioned, the measurement of the firefighters exposure to air pollutants was conducted during the Gestosa field burning experiments. Figure 3 shows firefighters with the exposure monitoring equipment. In addition the 10 selected fire fighters were also monitored along the wildfire 2008 and 2009 seasons.

Figure 3. Firefighters with the exposure monitoring equipment.

Figure 4 and 5 present the instantaneous registered data along the 2008 Gestosa experiments and fire season, respectively, for a particular firefighter. The European air quality thresholds and the values recommended by the WHO are also indicated (see Table 3) for a better understanding of the attained exposure values.

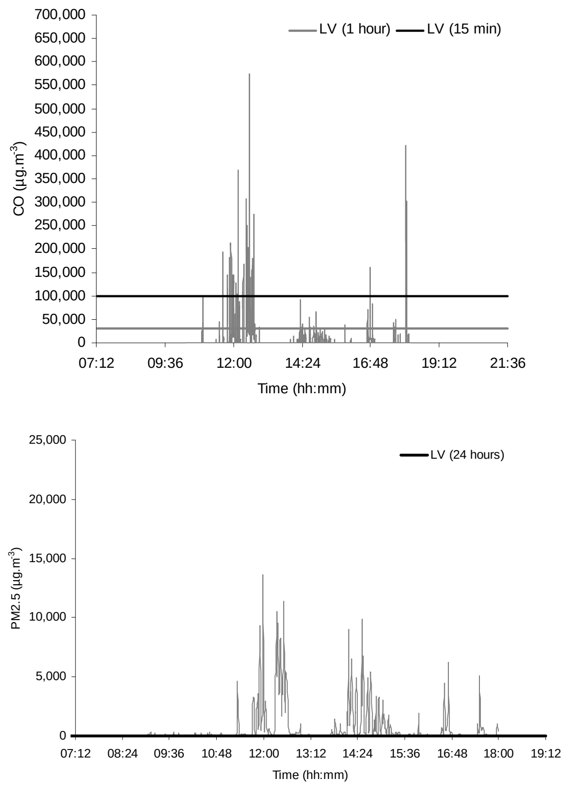


Figure 4. CO and PM2.5 exposure values measured during Gestosa-2008

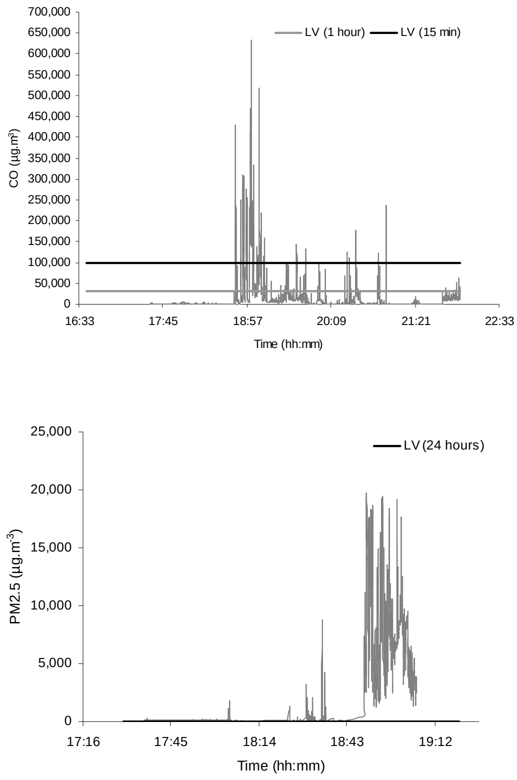


Figure 5. CO and PM2.5 exposure values measured during wildfires 2008.

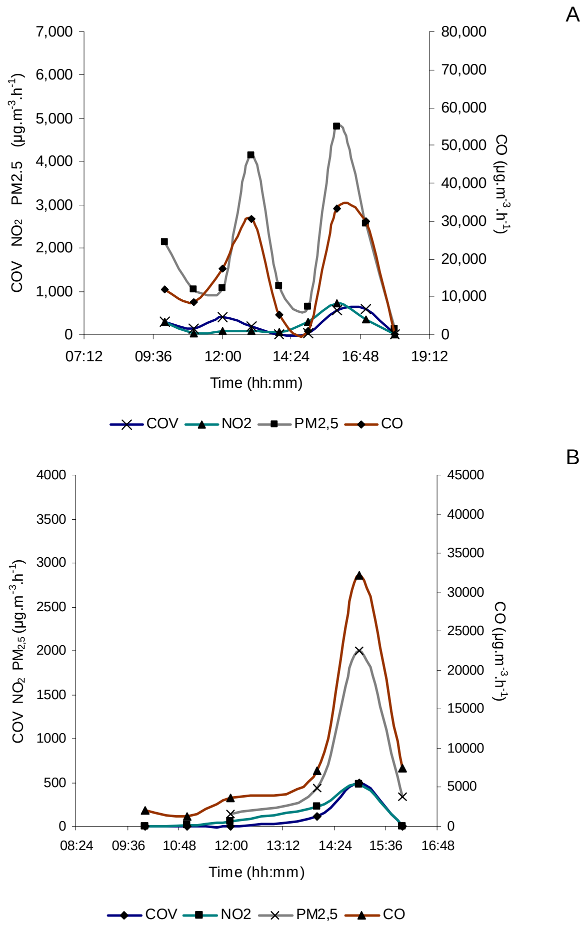


Figure 6. Hourly averaged exposure values in Gestosa-2008 (A) and Gestosa-2009 (B).

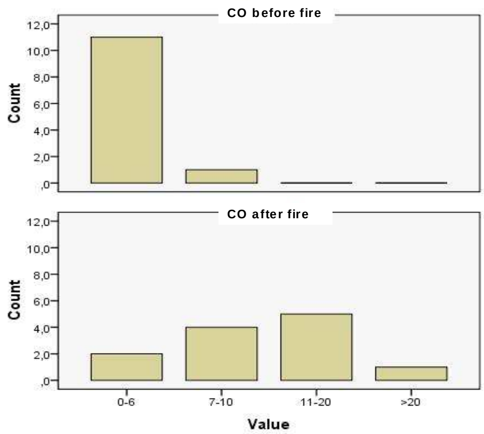
The instantaneous CO concentration values acquired during the 2008 wildfires were very high, reaching a maximum value above 600,000 µg.m^{-3}. PM2.5 values were also very high (20,000 µg.m^{-3}). These data show the magnitude of the exposure peaks occurred during regular firefighting operations. The knowledge of the CO concentration peaks to which firefighters are exposed is quite important, since high concentrations of this gas can cause death by asphyxia. Comparatively, the values registered in wildfires are higher than the ones at Gestosa.

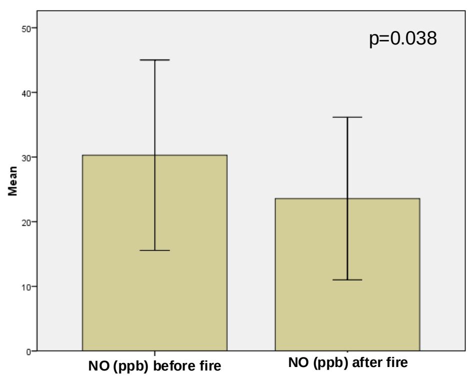
The hourly averaged exposure values for the measured pollutants during Gestosa 2008 and 2009, for a particular firefighter, were calculated and are presented in Figure 6A and 6B, respectively.

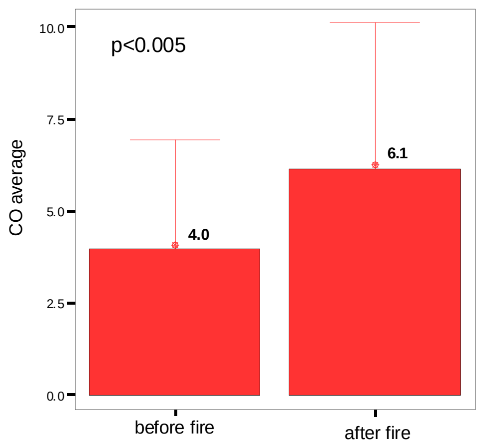
For all the monitored firefighters, a considerable number of the air pollutants concentration values acquired during their activity, both in the wildfires and in the fire experiments, is beyond the limits recommended by the WHO, namely for PM2.5, CO, NO_2 and VOC. Daily averages of PM2.5 concentration values as high as 470 µg.m^{-3} were obtained, well above the recommended limit of 25 µg.m^{-3}, even considering that during the rest of the day the concentration was 0 µg.m^{-3}. In terms of CO, hourly averaged values higher than 73,000 µg.m^{-3} were monitored, clearly above the 30,000 µg.m^{-3} recommended by the WHO. The highest NO_2 hourly averaged measured value was 4,670 µg.m^{-3}, once again much higher than the recommended value of 200 µg.m^{-3}. For VOC, a maximum hourly average of 5,300 µg.m^{-3} was registered for one of the firefighters; however, due to the lack of recommended or legislated values it is not possible to establish a comparison.

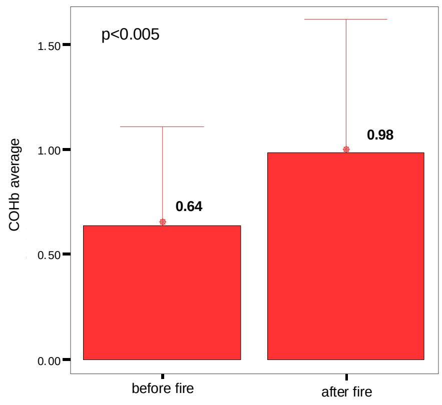
3.4 *Health assessment*

The medical tests conducted on the firefighters at 2008, before and after the exposure to smoke, indicate a considerable effect on the measured parameters: there was a significant decrease (p=0.038) on the exhaled NO (similar to the effect observed on smokers) and a very significant increase on % carboxy-haemoglobin and exhaled CO (p=0.004), pre and post firefighting. Similar data were again observed in May 2009, with statistical significance. Figure 7 illustrates these increases in the medical measured parameters.









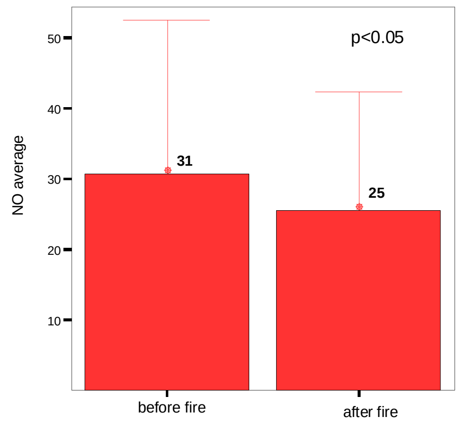


Figure 7. Medical tests results for 2008 and 2009 pre and post fire exposure.

4 CONCLUSIONS

Usually, the amount and characteristics of noxious exposure of forest wild firefighters are not widely recognized; more attention has been drawn upon the risks of indoor firefighting. Our work indicates that wildland firefighting can expose firefighters (and probably also civilian population) to very high concentrations of CO, VOC's, 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 firefighting shifts, and/or to the operational availability of information regarding the areas of higher pollutants levels that can be obtained through modeling of exposure, which is the next step of the FUMEXP project.

Acknowledgements

The authors would like to acknowledge the financial support of the Portuguese Ministry of Science, Technology and Higher Education, through the Foundation for Science and Technology (FCT), for the PhD grants of V. Martins (SFRH/BD/39799/2007), J. Valente (SFRH/BD/22687/2005), R. Tavares

(SFRH/BD/22741/2005) and the Post-Doc grant of J.H. Amorim (SFRH/BPD/48121/2008). Also FCT is acknowledged for the funding of the national research project FUMEXP (PTDC/AMB/66707/2006).

5 REFERENCES

Austin, C. 2008. Wildland firefighter health risks and respiratory protection. Studies and Research Projects REPORT R-572.

European Commission, 2009. Forest Fires in Europe 2008. EUR 23971 EN. ISSN 1018-5593.

Kelly, J. 1992b. Health hazard evaluation report, U.S. Department of Interior, National Park Service, New River Gorge National River, West Virginia. HETA 92-045-2260. U.S. Department of Health and Human Services, Public Health Service, Centres for Disease Control and National Institute for Occupational Safety and Health. Cincinnati, OH.

Kelly, J. 1992a. Health hazard evaluation report, U.S. Department of Interior, National Park Service, Gallatin National Forest, Montana. HETA 91-312-2185. U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and National Institute for Occupational Safety and Health. Cincinnati, OH; 1992a.

Materna, B.L., Jones, J.R., Sutton, P.M., Rothman, N., Harrison, R.J. 1992. Occupational Exposures in California Wildland Fire Fighting. Am Ind Hyg Assoc J 1992; 53(1):69–76.

Materna, B.L., Koshland, C.P., Harrison, R.J. 1993. Carbon monoxide exposure in wildland firefighting: a comparison of monitoring methods. Appl Occup Environ Hyg 1993;8(5):479–87.

McMahon, C.K., Bush, P.B. 1992. Forest worker exposure to airborne herbicide residues in smoke from prescribed fires in the southern United-States. Am Ind Hyg Assoc J 1992;53(4):265–72.

Reh, C.M., Deitchman, S.D. 1992. Health hazard evaluation report, U.S. Department of Interior, National Park Service, Yellowstone National Park, Wyoming. HETA 88-320-2176. U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and National Institute for Occupational Safety and Health. Cincinnati, OH; 1992.

Reh, C.M., Letts, D., Deitchman, S. 1994. Health hazard evaluation report, U.S. Department of Interior, National Park Service, Yosemite National Park, California. HETA 90-0365-2415. U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and National Institute for Occupational Safety and Health. Cincinnati, OH.

Reinhardt, T.E., Ottmar, R.D. 2000. Smoke exposure at western wildfires. USDA Forest Service Pacific Northwest Research Station Research Paper(525).

Reinhardt, TE, Ottmar, RD, Hanneman, A. 2000. Smoke exposure among firefighters at prescribed burns in the Pacific Northwest. USDA Forest Service Pacific Northwest Research Station Research Paper (526); 2000. p. U1–45

Reinhardt, T.E., Ottmar, R.D. 2004. Baseline measurements of smoke exposure among wildland firefighters. J Occup Environ Hyg 2004;1(9):593–606.

Reisen, F., Brown, S.K. 2009. Australian firefighters' exposure levels to air toxics during bushfire burn of autumn 2005 and 2006. Environment International 35 (2009) 342-352.

Viegas, D.X., Cruz, M.G., Ribeiro, L.M., Silva, AJ, Ollero, A, Arrue, B, Dios, R, Gómez-Rodríguez, F., Merino, L., Miranda, A.I., Santos, P. 2002. Gestosa fire spread experiments. In 'Proceedings of IV International Conference on Forest Fire Research', Luso-Coimbra, Portugal, 18-23 November 2002. Forest Fire Research & Wildland Fire Safety. (Ed. DX Viegas), Millpress, Rotterdam, Netherlands. pp. 121