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SMOKE MEASUREMENTS DURING EXPERIMENTAL FIELD FIRES

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1. INTRODUCTION

Concern associated to smoke from forest fires has been increasing during the last past years. The severe air pollution episodes caused by fires in Amazonia, Indonesia and Philippines in 1997/98 and, more recently, in Australia, drawn worldwide attention to the problem. Currently, there is a growing awareness that smoke from forest fires can expose individuals and populations to hazardous air pollutants. This concern is also associated to the use of prescribed fires, namely in Australia and North America where this fire management technique is frequent. The World Health Organization have developed policies and guidelines to reduce the health impacts of smoke generated during vegetation burning (Schwela *et al*., 1999) and some legislation requirements regarding air quality should be attained to perform prescribed burns in North America (Riebau and Fox, 2001). However, air quality data acquired during forest fires and accompanied with other important information, like meteorology, visibility, fire and combustible characteristics, is still reduced and it is not possible to completely evaluate the effects of forest fires on air quality. The main purpose of this work is to contribute to a better understanding of forest fires as a source of pollutants to the atmosphere.

Smoke production, transport, and dispersion depend of several related features. The combustion process that involves the chemistry, the phases, and the efficiency of combustion is of fundamental importance for estimating emissions from forest fires. Besides the combustion process, emission products from fires vary greatly with the type of fuel, fire line intensity, fuel moisture, wind and the temperature of the fire. Therefore, to estimate the emission rate of a pollutant, at least the following variables are needed: fuel load, combustion rate, and the emission factor. Ward and Radke (1993) reviewed the methods to measure emissions from vegetation fires, which range from satellite techniques to very small controlled combustion experiments.

The emission production calculation is not sufficient to estimate the effects of smoke in the air quality. Air pollution assessment requires estimates of the concentration of a pollutant some distance from sources of known emission characteristics, and the role of the atmospheric flow in the smoke transport and dispersion is very important. This concentration estimation can come from measurements or from simulations.

The burning experiments performed in Central Portugal, Gestosa, since 1998 till 2003, aim to collect experimental data to support the development of new concepts and models and to validate existing methods or models in various fields of fire management (Viegas *et al*., 1999, Viegas *et al*., 2000). These experiments involving several research teams and covering a very extensive characterization of variables related to the fire behaviour constituted a great opportunity to analyse and measure air pollutants concentrations during experimental field fires.

This paper presents the concentration values measured during the Gestosa-2002 experimental fires and analyses the acquired values in an integrated way, taking into account also other involved variables, like the fire type and the meteorology, and identifying the possible correlation between them in order to contribute to a better understanding of the air pollution phenomenon associated to forest fires. This work was performed in the scope of SPREAD (a research project funded by the European Commission) and several other teams were involved. Part of the data used in the paper comes from these teams work.

The particular location of this study, South Europe, should be stressed, because the information concerning forest fires effects on the air quality (from emissions to ambient concentrations) is mainly available from other parts of the world.

2. METHODOLOGY

From the first field campaign (1998) till the last one (2002) it is possible to notice a clear evolution of measurement approaches and techniques aiming to optimise the procedures (Miranda and Borrego, 2002). The knowledge acquired during the previous burning experiments was fundamental to the organization of Gestosa-2002 experiments and, during the main burns, on the 30th and 31st of May, measurements of atmospheric emissions and air quality concentrations have been taken.

2.1 Study Area Characteristics

The study area is located in Central Portugal (40°15'N, 8°10'W) in a hillside of Serra da Lousã at

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altitudes between 800 and 950 m. To safeguard the safety of the burns and to assure a good organization of the experimental program, the area was divided into plots with regular shape and dimensions separated by fuel breaks to limit fire spread and to keep it inside desired boundaries in each burn. The width of the fire-breaks is between 5 and 15 m, depending on their location. These experimental burning plots were established in Forest Service lands, in Gestosa forestry perimeter. Figure 1 presents a photo of the experimental plots.

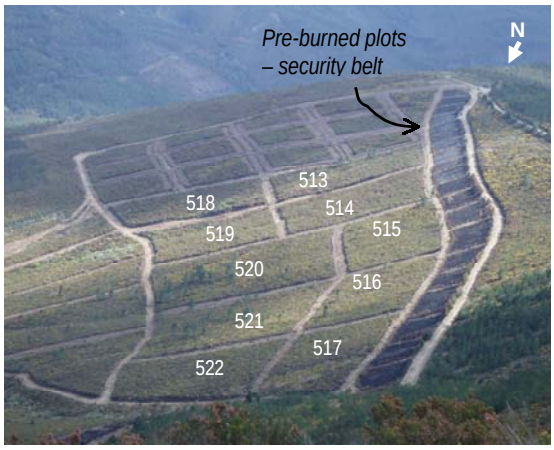

Figure 1 – Gestosa-2002 study area, with location of experimental plots.

Systematic vegetation sampling was started along the plots. Non-destructive sampling along linear transects was made to determine vegetation cover, species composition and vegetation height. Using the results of previous destructive sampling the biomass for each species was evaluated for each plot.

Table I presents some data characterising the experimental plots.

Table I – Characteristics of the experimental plots.

Plot	Dimension m		Slope	Med height	Total cover	Fuel load
	Width	Length	º	m	%	kg.m^{-2}
513	58	97	21	1.2	89	6.3
514	85	90	21	1.1	97	9.9
515	87	53	27	0.8	98	5.4
516	101	51	22	1.1	88	8.7
517	86	52	24	1.3	100	11.1
518	58	108	17	1.6	97	11.0
519	89	91	21	1.2	98	7.8
520	89	109	18	1.2	95	5.7
521	87	99	19	1.3	100	6.6
522	68	90	18	1.2	100	7.2

The area of the plots ranges from 0.4 (plot 517) to 1 ha (plot 520). Smaller plots present higher slopes. The plots are SW and SSW oriented with a terrain slope varying between 17 and 27°. These experimental plots are located side to side inside the same vegetation mosaic, which consists in continuous shrub land with some isolated *Pinus pinaster* trees. Three species are dominant: *Erica umbellata*, *Erica australis* and *Chamaespartium tridentatum* and fuel properties were assumed as similar for each plot (see Table I).

2.2. Equipment used

During the experimental fires, which occurred in warm and dry days, temperature, humidity, and wind speed and direction were measured at several locations, namely near the fire plots. Different types of techniques and equipment were used to measure different pollutant concentration values. Table II summarises the used measuring techniques.

Table II – Summary of air pollutant measurement techniques during Gestosa experiments.

Pollutant	Technique
NO_x (NO, NO_2)	Automatic equipment Van 2
CO	Automatic equipment Van 2
Particulate matter: PM_{10} $PM_{2.5}$	Automatic equipment Van 2 Van 1
NO_2, SO_2	Passive samplers
VOC	Sampling in Tedlar bags and laboratorial analysis with a FID

Two luggage-vans, equipped with meteorological measuring equipment and air quality analysers in continuum to get concentrations of particles with an aerodynamic diameter lesser than 2.5 µm ($PM_{2.5}$), in van nr. 1, and lesser than 10 µm (PM_{10}), nitrogen dioxide (NO_2) and nitric oxide (NO), and carbon monoxide (CO) in van nr. 2, were acquiring data in the proximity of the burning plots. Table III presents the distance between the vans and the centre of the nearest plots. In Figure 2 a photo of van nr. 2 and its air quality equipment is shown and the location of both vans is indicated in Figure 3.

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Table III – Average distance between the vans and nearest plots.

Van - Plot	Distance (m)
2 – 513	130
2 – 514	75
2 – 515	90
2 – 516	150
2 – 518	200
2 – 519	170
2 – 520	180
1 – 515	200
1 – 516	110
1 – 517	65
1 – 521	150
1 – 522	125

Figure 2 – Photo of van nr. 2 and its air quality equipment.

The continuous acquisition of NO and NO_2 concentrations in the air was performed using automatic equipment (Dual Chamber Chemiluminescent Nitrogen Oxides, Model AC31M^{TM} from *Environnement*).

CO was measured in continuum with the analyser *Environnement* CO11M. Its principle is based in the selective absorption of infrared radiation by the CO molecules.

To monitor particulate matter, namely PM_{10} and $PM_{2.5}$ concentrations, two analysers *Environnement* MP101M were used with adequate sampling inlets for each diameter. The particle's mass is determined by a beta gauge mass monitor. The obtained concentration values are 15 minutes averaged.

Taking into account the potentialities of the passive sampler technique, namely a larger spatial cover, passive samplers (Radiello equipment) were used to measure NO_2 and sulphur dioxide (SO_2) close to the burning plots. The sampling was performed with trietanolamine diffusivity passive samplers and the analyses were made by ionic chromatography. Some of them were changed various times a day aiming to evaluate the influence of the burned plots characteristics on the air pollutants concentration values. Replicates of each passive sampler were used. In Figure 3 the location of the two lines of passive samplers, one line with the samplers that were sampling during all the day (fixed samplers - FS) and the other one, closer to the burning area, where the samplers were replaced one or two times a day ("mobile" samplers - MS), is presented.

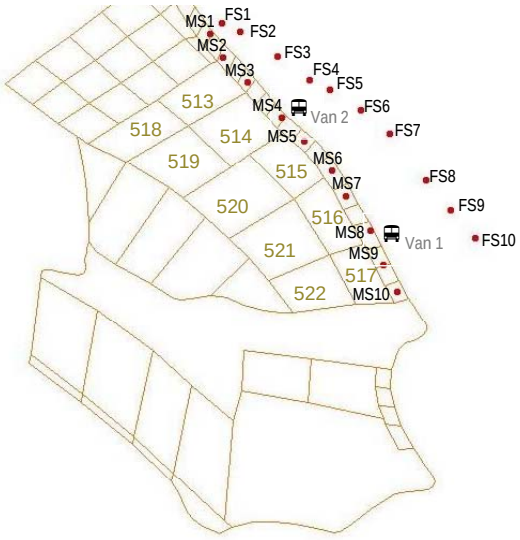


Figure 3 – Gestosa-2002 study area, with location of measuring equipment.

Firemen and members of the research team carried a passive sampler during the two days of the experiments in order to estimate the human exposure to NO_2 and SO_2. Figure 4 shows passive samplers used during the experiments, namely the fixed sampler on location 6 and a member of our team using one diffusive tube.

Figure 4 – Photo of passive samplers.

Measurements of volatile organic compounds (VOC) emissions were carried out during the flaming and the smoldering phases of each burnt plot, by sampling the smoke pumping it into *Tedlar* bags and analysing it afterwards in the laboratory through a flame ionisation detector.

2.3. Experimental procedure

The main experiments of Gestosa-2002 were carried out on May, 30th and 31st. Table IV presents some important information concerning the development of the experiments, namely the beginning and the end time of each plot burning. Information concerning some particular techniques to ignite and extinguish the fire, which were tested during Gestosa-2002, is also given in Table IV.

Table IV – Plots burning information and time schedule.

Plot	Day	Local Time Begin	Local Time End	Burn time	Observ
513	30 May	10:19	10:44	25'	line ignition at top and bottom
517	30 May	11:26	11:44	18'	linear ignition at top, upper third pyrotechnic
516	30 May	12:21	12:28	7'	single line at the bottom
514	30 May	13:11	13:30	19'	hoses of explosives filled with water
515	30 May	16:20	16:39	19'	
518	30 May	17:04	18:05	61'	stronger wind blowing downslope
522	31 May	11:00	11:30	30'	safety burn
521	31 May	12:00	12:30	30'	point ignition
520	31 May	13:45	14:03	48'	hoses of explosives
519	31 May	14:32	14:51	19'	oblique ignition

In the morning of the first day, plots 513 and 517 were burned. In the first one, line ignition was done at its top and then bottom. Plot 517 was burned by linear ignition on the top and then linear ignition on its upper third with pyrotechnic devices.

One of the most striking events of Gestosa-2002 were the tests with the German hoses filled with water and with a detonating cord that exploded just before the fire reached them (Viegas, 2002). This technique was applied to plots 514 and 515 as it can be seen in Figure 5.

The fire front was extinguished after a short time in these plots where the blasting hoses were used. Aiming to identify the influence of using hoses of explosives, some of the passive diffusers closer to the burning area were replaced before the burn of plot 514 (MS4, MS5, MS6 and MS7) and the others were changed between plot 514 and 515 burn.

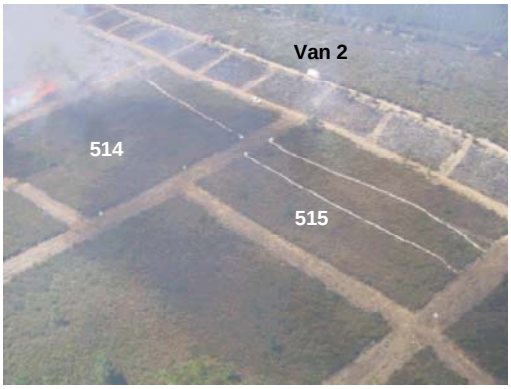
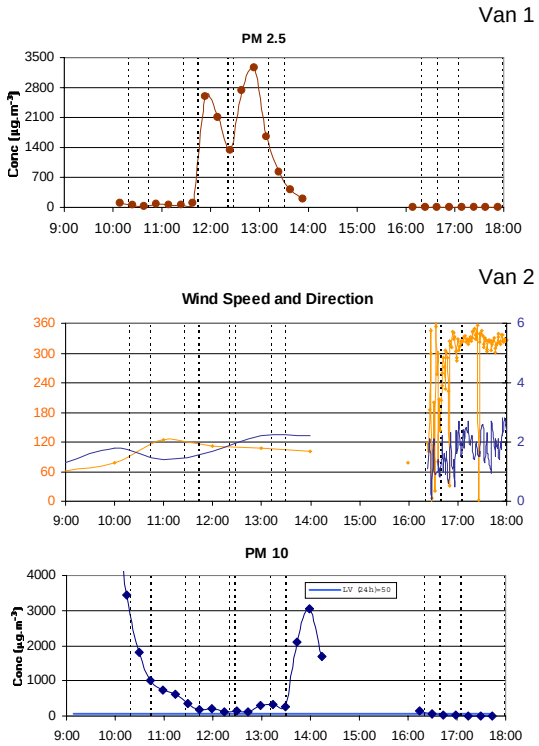


Figure 5 - Aerial view of hoses in plots 514 and 515.

3. PRESENTATION AND ANALYSIS OF RESULTS

Figure 6 presents the meteorological and air quality data acquired in the luggage-vans using automatic equipment during the 1st day of the experiments. Dotted lines represent the beginning and the end time of each burning plot. Limit air quality concentration values settled in the European Legislation are also represented in the graphs, namely the daily average for PM10 (50 $\mu g.m^{-3}$), established in the Council Directive 1999/30/EC, the 8 hours average for CO (10 $mg.m^{-3}$) defined by 2000/69/EC, the hourly average for NO_2 (200 $\mu g.m^{-3}$) implemented by 1999/30/EC.



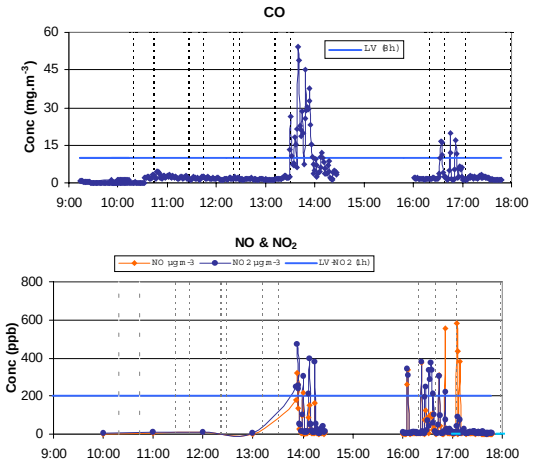


Figure 6 - $PM_{2.5}$, PM_{10}, CO, NO and NO_2 concentration values measured during the 1st day of experimental fires.

It is possible to verify that the burns occurred with weak winds (rounding 2 $m.s^{-1}$) blowing from NE-SE in the morning hours and changing towards NW during the afternoon. In the afternoon, the 1st burning plot was influenced by a variable wind direction. This wind behaviour is closely related to the air pollutants concentration measured values in each van.

Notwithstanding the closest location of the two vans, separated by 250 m distance, they were affected by the burning emissions of different plots, accordingly to the wind direction. Van nr. 1 registered the influence of emissions from plots 517 (see Figures 6 and 7) and 516, and van nr. 2 the effects of plots 514 and 515 (see Figures 6, 8 and 9).

Figures 7, 8 and 9 are photos of the smoke plume during plots 517, 514 and 515 burning, respectively.

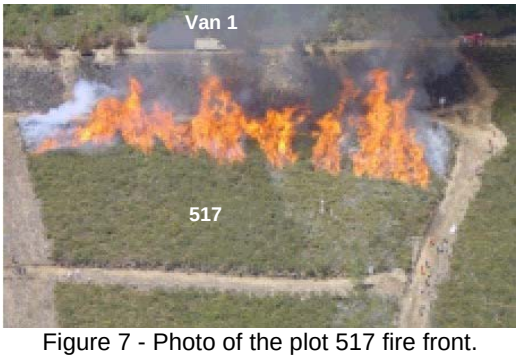


Figure 7 - Photo of the plot 517 fire front.

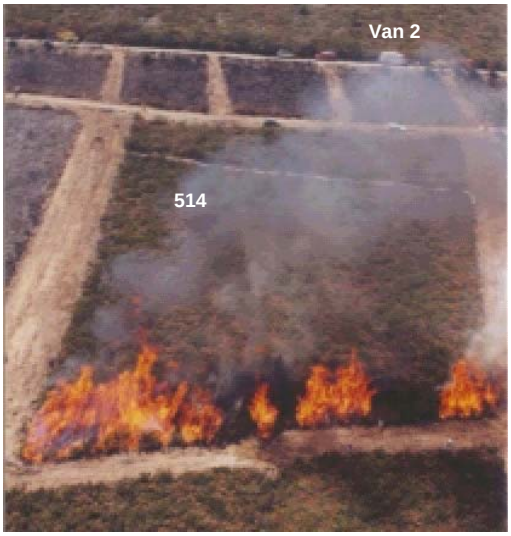


Figure 8 – Photo of the plot 514 burning.

Figure 9 – Photo of plot 515 burning (effect of explosive hoses).

In general, air quality equipment registered the effect of fire emissions after the end of each burn. Possibly during the flaming stage, the smoke rose in a convection column due to the higher temperatures, not reaching the vans. After this stage the smoke plumes were transported by the wind towards the vans.

The 1st burning of the experiments, plot 513, did not affect the air quality measured values in both vans because the wind blew from east and the smoke plume did not reach the vans.

As seen in Figure 7, van nr. 1 was affected by plot 517 emissions. The van was located just above the plot (65 m distance) and the wind blew from SE transporting the smoke towards the van. $PM_{2.5}$ concentration values, 15 minutes average, reached 2500 $\mu g.m^{-3}$. The following burning plot also contributed to $PM_{2.5}$ concentration values measured in van nr. 1, even reaching higher values (3000 $\mu g.m^{-3}$).

Regarding the measured concentrations in van nr. 2, it should be stressed that the high PM_{10} values acquired at the beginning of the experiments are related to some problems with the warming up of the equipment. Van nr. 2 was affected by emissions from the plots with explosive hoses (514 and 515).

PM_{10} concentration values acquired in van nr. 2 during plot 514 burning were considerably high reaching 3000 $\mu g.m^{-3}$. After this experiment, the filters had to be replaced and no data is available for the afternoon experiments (namely, the plot 515).

Still related to plot 514 are CO, NO and NO_2 measured values just after the end of the burning. CO measured values are quite high, even exceeding the WHO hourly limit values for this pollutant (40000 $\mu g.m^{-3}$) during approximately half an hour, which should raise some concern. Wildland fire fighters would probably be in contact with these high, and even higher, values of CO. Measured NO_2 and NO concentration values attained 400 $\mu g.m^{-3}$ exceeding the hourly European limit for NO_2. These levels could be dangerous, mostly for fire fighters working close to the fire front.

The explosive hoses placed in plot 515 actuated sooner than those of plot 514 and then CO and NO_x concentration values are not so high.

Because of the wind direction change during the afternoon, smoke from plot 518 was transported in the opposite direction of the measuring equipment.

Concerning NO_2 and SO_2 measurements, with the passive sampling technique, Tables V, VI and VII present the acquired values for the FS and the MS locations, and for the humans, respectively. These concentration values are hourly averaged.

Table V – Hourly concentration values for FS.

Fixed Samplers locations	30 May 2002 Exposure Period	NO_2 ($\mu g.m^{-3}$)	SO_2 ($\mu g.m^{-3}$)
FS 1	9h30 – 17h47	40	10
FS 2	9h29 – 17h47	35	11
FS 3	9h20 – 17h45	38	15
FS 4	9h10 – 17h44	47	19
FS 5	9h12 – 17h42	50	26
FS 6	9h10 – 17h41	47	13
FS 7	9h07 – 17h39	53	18
FS 8	9h04 – 17h37	48	17
FS 9	8h59 – 17h34	46	15
FS 10	8h55 – 17h32	45	14
	31 May 2002		
FS 1	8h40 – 16h03	30	7
FS 2	8h38 – 16h00	43	9
FS 3	8h35 – 15h59	31	9
FS 4	8h33 – 15h52	32	8
FS 5	8h30 – 15h50	31	7
FS 6	8h28 – 15h50	30	8
FS 7	8h25 – 15h51	30	10
FS 8	8h21 – 15h48	48	6
FS 9	8h19 – 15h40	22	?
FS 10	8h16 – 15h37	32	9

In what regards NO_2 all the passive samplers measured values higher than the rural background concentration value (12 $\mu g.m^{-3}$) indicating the influence of the smoke plume. The SO_2 concentration values are not significant and are considerably smaller than the European Legislated value of 125 $\mu g.m^{-3}$ (daily average).

Table VI – Hourly concentration values for MS.

Mobile Samplers locations	30 May 2002 Exposure Period	NO_2 ($\mu g.m^{-3}$)	SO_2 ($\mu g.m^{-3}$)
MS 1	9h19 – 14h42	61	29
MS 2	9h14 – 14h40	58	26
MS 3	9h11 – 14h35	64	?
MS 4	9h09 – 12h40	85	?
MS 5	9h06 – 12h41	92	33
MS 6	9h03 – 12h44	105	36
MS 7	9h00 – 12h47	79	60
MS 8	8h56 – 14h40	69	56
MS 9	8h53 – 14h42	181	35
MS 10	8h50 – 14h38	124	17
MS 1	14h42 – 17h47	85	57
MS 2	14h42 – 17h50	94	33
MS 3	14h36 – 17h53	90	27
MS 4	12h40 – 17h40	94	19
MS 5	12h42 – 17h58	72	15
MS 6	12h45 – 18h07	33	14
MS 7	12h47 – 18h05	55	16
MS 8	14h46 – 18h04	80	48
MS 9	14h42 – 17h53	66	28
MS 10	14h38 – 17h59	61	26
	31 May 2002		
MS 1	8h22 – 15h48	24	24
MS 2	8h25 – 15h47	24	14
MS 3	8h27 – 15h46	21	12
MS 4	8h30 – 15h43	24	13
MS 5	8h15 – 15h45	23	10
MS 6	8h19 – 15h40	0	10
MS 7	8h23 – 15h37	27	12
MS 8	8h21 – 15h38	29	22
MS 9	8h25 – 15h30	31	13
MS 10	8h36 – 15h35	35	13

Figure 10 presents the spatial distribution of the measured NO_2 concentration values for the 1st day of the experiments.

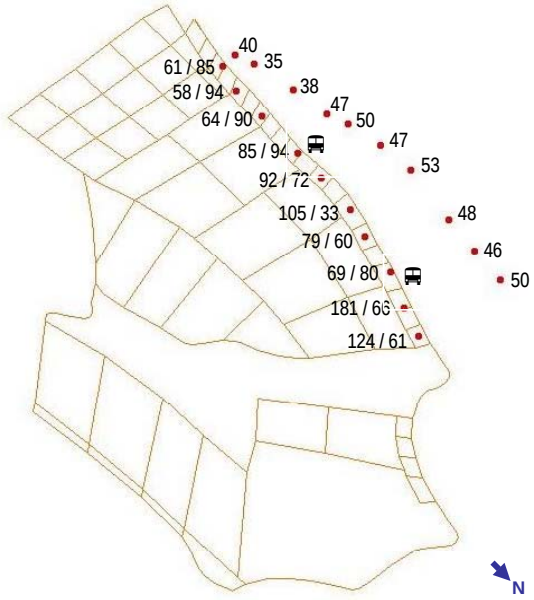


Figure 10 – Spatial distribution of NO_2 concentration values for the 30th of May.

The comparison of hourly concentration values measured by fixed and mobile passive samplers allows verifying the effect of the sampling period. For the 1st case, the diffusive tubes were acquiring during a larger period, which included non-burning hours, and were located faraway from the burning area. Therefore, this effect was reflected in the obtained values, which are smaller. In addition, the location of the MS, closer to the plots, can also be an explanation of these higher values.

The changing of diffusive tubes aiming to understand the effect of explosive hoses on SO_2 and NO_2 values allowed verifying that plots testing this technique emitted lesser NO_2 and SO_2, probably because the fire was extinguished sooner.

During the 1st day of the experiments some higher concentration values of SO_2 were acquired in some tubes (MS7 and MS8). This can be related to another test that occurred during burning of plot 516, where two cars were carried out on it. The intensity of the fire line was extremely high and SO_2 emissions can result from the cars.

In the 2nd day of experiments, for both FS and MS, NO_2 and SO_2 concentration values were smaller than those acquired at the 1st one. The area consumed by fires affecting the samplers was smaller at the 2nd day and than probably lesser emissions occurred.

Table VII – Hourly concentration values.

	Exposure Period	NO_2 ($\mu g.m^{-3}$)	SO_2 ($\mu g.m^{-3}$)
Fireman 1	30May 9h51 – 31May 17h30	38	5
Fireman 2	30May 9h46 – 31May 15h10	52	6
Fireman 3	30May 9h46 – 31May 15h10	50	7
Fireman 4	30May 9h44 – 31May 15h10	48	9
Fireman 5	30May 9h40 – 31May 17h30	30	4
Team Member 1	31May 10h17 – 15h10	67	12
Team Member 2	31May 10h17 – 15h10	57	21

The night period (from 6pm, 30/05 to 9am, 31/05) was not considered to estimate firemen exposure. Concerning the results of passive samplers taken by firemen and research team members, hourly concentrations of NO_2 and SO_2 are higher in the team members' samplers. One can say that team members were more exposed to these pollutants than the chosen firemen, even taking into account that the exposure period was smaller in the first case (Table VII).

VOC emissions were carried out using Tedlar bags. Samples were taken just close to the burning plots and the obtained values should be considered as emissions and not air quality values. Table VIII summarises the measured values.

Table VIII – VOC concentration emissions.

Day	Plot burned	Local Time	VOC ($mgC.Nm^{-3}$)
30 May 2002	513	10:30	**7,0**
	513	10:35	**17,7**
	517	11:35	**14,3**
	517	11:45	**27.3**
	516	12:29	**8,5**
	516	12:30	**19,3**
	514	13:28	7,5
	514	13:34	5,4
	515	16:34	15,4
	515	16:36	13,3
	518	17:13	8,3
	518	17:15	6,5
31 May 2002	522	11:32	**17,7**
	522	11:40	**49,8**
	521	12:33	**9,5**
	521	12:38	**32,1**
	520	14:04	22,5
	519	?	5,3

The members of the team tried to sample VOC during the flaming (1st sample) and the smoldering (2nd sampling) phases, separately. With the exception

of plots 514, 515 and 518, the acquired values indicate these different phases emissions, with smaller values for the 1st sampling (flaming phase) and higher for the other one (smoldering phase) (Table VIII).

Concentration values acquired for plots 514, 515 and 518 are very similar for both samplings. In addition, for plots 520 and 519 only one sampling was possible. With the exception of plots 515 and 520 the others plots emissions point to flaming phase sampling.

The Portuguese emission limit value for anthropogenic VOC is 50 $mg.Nm^{-3}$. The measured values during the experiments did not exceed this limit, even for the smoldering emissions, but they are quite significant.

4. CONCLUSIONS

Gestosa-2002 experimental burns affected the ambient air quality, giving rise to considerable concentration levels of NOx, CO, PM2.5 and PM10. Regarding the automatic acquisition, the highest PM (2.5 and 10), CO and NO_2 concentration values recorded, were 3000, 50000 and 450 $\mu g.m^{-3}$, respectively. Personal breathing samples for NO_2 and SO_2 were between 30 and 67 $\mu g.m^{-3}$ and 4 and 21 $\mu g.m^{-3}$, respectively. From all the measured pollutants, SO_2 was the only one not clearly affected by the experimental fires.

It was possible to distinguish flaming and smoldering VOC emissions. The last ones are higher than the double of the flaming emissions.

Although the small size of the burning plots, the measured levels of pollutants are considerable, indicating the effect of these experiments on the local air quality and stressing the serious levels of air pollution, which can be expected during wildfires.

More information is still needed concerning the exposure and resulting adverse health effects of smoke on wildland fire fighters and personnel involved in prescribed burning operations.

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