ORIGINAL ARTICLE

Short-term effects of particulate matter on mortality during forest fires in Southern Europe: results of the MED-PARTICLES Project

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▸ Additional material is published online only. To view please visit the journal online (http://dx.doi.org/10.1136/oemed-2014-102459).

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Received 17 July 2014
Revised 16 January 2015
Accepted 27 January 2015
Published Online First 17 February 2015

ABSTRACT

Background An association between occurrence of wildfires and mortality in the exposed population has been observed in several studies with controversial results for cause-specific mortality. In the Mediterranean area, forest fires usually occur during spring–summer, they overlap with Saharan outbreaks, are associated with increased temperature and their health effects are probably due to an increase in particulate matter.
Aim and methods We analysed the effects of wildfires and particulate matter (PM_{10}) on mortality in 10 southern European cities in Spain, France, Italy and Greece (2003–2010), using satellite data for exposure assessment and Poisson regression models, simulating a case-crossover approach.
Results We found that smoky days were associated with increased cardiovascular mortality (lag 0–5, 6.29%, 95% CIs 1.00 to 11.85). When the effect of PM_{10} (per 10 $\mu g/m^3$) was evaluated, there was an increase in natural mortality (0.49%), cardiovascular mortality (0.65%) and respiratory mortality (2.13%) on smoke-free days, but PM_{10}-related mortality was higher on smoky days (natural mortality up to 1.10% and respiratory mortality up to 3.90%) with a suggestion of effect modification for cardiovascular mortality (3.42%, p value for effect modification 0.055), controlling for Saharan dust advections.
Conclusions Smoke is associated with increased cardiovascular mortality in urban residents, and PM_{10} on smoky days has a larger effect on cardiovascular and respiratory mortality than on other days.

What is already known

- Increase in natural mortality occur on forest fire days.
- In Europe, forest fires usually occur during the hot season, are associated with increased temperature and dust outbreaks and their health effects are probably due to an increase in particulate matter (PM).

What this paper adds

- Mortality for cardiovascular causes increases in cities during smoky days.
- PM_{10}-related cardiovascular mortality is modified during smoky days.
- PM_{10}-related respiratory mortality increases on smoky days.

INTRODUCTION

Forest fires contribute to the earth's planetary concentrations of organic carbon (OC) and elemental carbon (EC).[1] In Mediterranean countries, carbonaceous compound emissions from wildfires are made up of 71% carbon dioxide (CO_2), 26% carbon monoxide (CO) and 0.3% total particulate carbon.[2] Secondary aerosols may contribute greatly to increases in carbonaceous particulate matter (PM), since the large amounts of volatile organic compounds (VOCs) released during forest fires[3] may be converted into carbonaceous PM by anthropogenic agents, such as NO_x and O_3.[4] In addition, a number of polycyclic aromatic hydrocarbons arise from imperfect combustion of biomass.[5]

Exposure to emissions from forest fires is sporadic and short lasting; it entails high levels of combustion-related pollutants and is usually associated with high ambient temperature.[6 7] In the Mediterranean area, wildfires occur mainly during warm seasons, in high ambient temperatures, and are often concurrent with Saharan dust outbreaks.[8] Climatic conditions, including precipitation, winds and boundary layer height, may influence the occurrence of fires and exposure to the resulting air pollutants. All of these issues make it difficult to assess human exposure to forest fire emissions.

The assessment of human exposure to fires also presents operational difficulties since the surveillance of fire events is currently the responsibility of the fire department: they record dates, locations, durations and extent of burnt areas, but not information about proximity and size of the populated areas affected, which could be relevant when assessing exposure. Satellite data and dispersion models provide qualitative information about the spatial extent of wildfires; they also allow a rough estimate of the contribution of the fire to the ambient concentrations of particles, but they do not assess

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To cite: Faustini A, Alessandrini ER, Pey J, *et al*. *Occup Environ Med* 2015;**72**:323–329.

concentrations at ground level. On the other hand, fixed monitors located in large cities monitor pollutants from anthropogenic sources, such as road traffic, domestic heating, shipping, industries and power generation. Therefore, routine air quality surveillance may fail to represent the atmospheric pollution resulting from forest fires,[9] while rural monitors are often sparse or unavailable in regions affected by fires.[10]

A few studies have reported increases in commonly monitored ambient pollutants, such as fine particles ($PM_{2.5}$), carbon monoxide (CO), sulfur dioxide (SO_2), ozone (O_3) and black carbon (BC), as possible indirect indicators of exposure to fires in urban areas.[10–12] Levoglucosan is the typical indicator of biomass-burning emissions[13] and is a well-known biomarker of fire exposure.[14] Soluble potassium has also been used as a biomass-burning tracer.[15] Currently, however, experience with these indicators to assess wildfires exposure is very limited.

The health effects of wildfires are probably due to PM (fine and ultrafine), but may also owe to other combustion-related factors such as inorganic gases and VOCs, and even the temperature increases generated by nearby fires.[6 7] Mortality is an important potential outcome of this exposure,[9 16–19] in addition to respiratory symptoms,[20] exacerbations of pre-existing diseases[21–24] and cardiovascular effects.[25 26]

As part of the MED-PARTICLES project funded by the European Union under the LIFE+ framework, we studied the short-term effects of forest fire smoke and PM on the mortality of the population living in large cities in southern Mediterranean Europe. Exposure to fires was defined using satellite observations, and it was confirmed against daily changes in temperature and concentrations of fire-related pollutants.

MATERIALS AND METHODS

The study included the cities that took part in the MED-PARTICLES LIFE+ project, namely Madrid and Barcelona in Spain; Marseille in France; Turin, Milan, Bologna, Parma, Modena, Reggio Emilia, Rome and Palermo in Italy; and Thessaloniki and Athens in Greece. Exposure assessment was performed for 9 years (2003–2011) whereas mortality data were collected in each city, for a variable period of 3–8 years, from 2001 to 2010. Data analyses were carried out for the period 2003–2010.

Exposure assessment

Forest fire events were identified on smoke surface concentration maps supplied by the NAAPS model (Navy Aerosol Analysis and Prediction System—US Naval Research Laboratory Marine Meteorology Division, http://www.nrlmry.navy.mil/aerosol/), which takes into account both the aerosol optical depth (AOD) from satellite measurements and the fire-related smoke plumes. Such aerosol maps are initially generated as forecast products, and are thereafter corrected from satellite AOD measurements. The smoke concentration at surface ranges from 1 to over 64 $\mu g/m^3$; however, the influence of low-magnitude wildfires cannot be assessed though they may greatly affect an urban area when they occur nearby. The use of satellite images helped us to distinguish between smoky days and smoke-free days, especially when NAAPS outputs diverged in consecutive days. The fire-related smoke plumes allowed us to assess the involvement of surrounding cities.

In order to be as conservative as possible, we defined a day as being ‘fire smoke-affected, or smoky’ when smoke concentrations were higher than 8 $\mu g/m^3$; additionally, fire smoke intensity was classified for each day as low (smoke concentration between 8 and 16 $\mu g/m^3$), medium (smoke concentration between 16 and 32 $\mu g/m^3$) or severe (smoke concentration above 32 $\mu g/m^3$). An additional assessment of smoke episodes was made on the basis of their duration, classifying them as isolated episodes (1-day duration), short episodes (2–4 consecutive days) and long episodes (5 or more days, where 1 day without smoke in a sequence of at least five days did not interrupt the sequence).

Finally, to confirm the fire smoke assessment, smoky days were classified according to the absolute changes of daily mean temperature,[27] PM_{10}, CO and O_3 levels measured at fixed monitors in each city. The absolute changes in these factors during smoke events of different duration and intensity (defined as a multilevel variable with smoke-free days as reference) were estimated using linear regression analysis adjusting for time trend (year) and seasonality (month).

The daily mean levels of PM_{10} and the other pollutants were provided for each of the 13 cities included in the study by their local monitoring networks.

We also identified the presence of Saharan dust advection and computed the Saharan dust load on daily PM_{10} concentrations.[28] Briefly, the estimate of Saharan dust load was performed by using a method adopted by the European Commission, employing data from rural monitors near each city (http://ec.europa.eu/environment/air/quality/legislation/pdf/sec_2011_0208).

Saharan days were classified as advection days without any Saharan-related PM increase at ground level, days with a PM_{10} load of 1–10 $\mu g/m^3$ and days with a PM_{10} load of more than 10 $\mu g/m^3$.

Health data

Daily death counts due to natural (International Classification of Diseases Ninth Edition (ICD-9) codes 001–799 or ICD-10 codes A00-R99, excluding injuries, poisoning and external causes) and cause-specific mortality (cardiovascular ICD-9 390–459 or ICD-10 codes I00—I99 and respiratory ICD-9 460–519 or ICD-10 codes J00-J99) were collected from each city, for all-age residents, from mortality registers. Deceased participants were considered only if they died in the same city.

Data analysis

We studied the associations of smoky days as assessed by satellite, and PM_{10} as measured from fixed monitors at ground level, with natural, cardiovascular and respiratory mortality, in the period 2003 and 2010. The effect estimates were obtained for each city using Poisson regression models, simulating a stratified case-crossover approach.[29] More specifically, time trends and seasonality were controlled for by including in the regression models a triple interaction of year, month and day of the week. All effect estimates were further adjusted for population decreases in the summer and during holidays, and influenza epidemics.[30]

Figure 1 illustrates the relationships we assumed between fires, PM, Saharan dust, temperature and mortality. In evaluating the association of fire smoke with mortality, we did not adjust for daily PM_{10}, as it is an intermediate factor between fires and mortality. While when evaluating the association of PM_{10} with mortality, we adjusted for the presence of fires. In a separate model we also assessed whether PM_{10} effects were modified by wildfires, adding an interaction term between smoky days and PM levels. The p value for relative effect modification (REM)[31] was used to test the interaction hypothesis. We further adjusted the estimates of fire smoke and PM_{10} effects for temperature and Saharan dust, since they are risk factors for mortality, and are associated with the occurrence of forest fires and with PM_{10} concentrations. Low temperatures were controlled for with a penalised cubic spline for 1–6 lagged values of air temperature

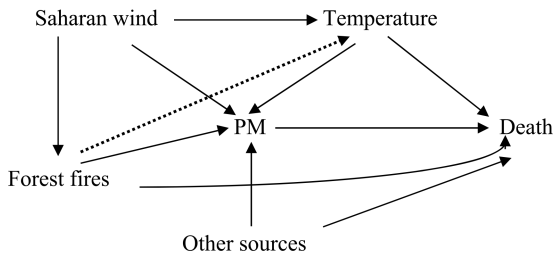

Figure 1 Direct acyclic graph exploring the effects of forest fires on Death. The contribution of forest fires on PM concentrations could not be assessed. The impact of forest fires on temperature could not be assessed.

below the median value in each city; similarly, high temperatures were controlled for with a penalised cubic spline for values of 0–1 lagged temperature above the median value at each city. Saharan dust was controlled for by adding the categorical, three-level variable specified above in the models.

We explored 6-day lags from 0 to 5 days preceding death for the association between PM_{10} and mortality. We also analysed cumulative exposure using unconstrained distributed lags.[32 33] For PM_{10} we adopted the best lags (0–1 for natural mortality and 0–5 for cause-specific mortality) previously reported from MED-PARTICLES.[34] The results were expressed as the percentage increase in risk (%IR) of natural or cause-specific mortality with 95%CIs. For PM_{10}, the effects are per 10 μg/m^3.

After city-specific analysis, pooled estimates were obtained from a random-effects meta-analysis for 10 cities (excluding Parma, Modena and Reggio-Emilia, located in the same region, where only three fire episodes occurred in 3 years). Heterogeneity across cities was assessed by χ^2 (Cochran's Q) and I^2 tests.[35] Pooled results have been reported for the best cumulative lag, as identified by the strength of the association and the lowest heterogeneity.

Finally, we carried out a sensitivity analysis by excluding the cities where temperature and PM_{10} did not increase consistently with fire smoke concentrations, suggesting a possible misclassification of exposure.

RESULTS

The number of smoky days in each city varied, with a total of 391 days affected (2.0% of the studied days). The cities with the highest number of smoky days were Thessaloniki (6% of days), Athens (4%), Madrid and Rome (3%) (table 1, figure 2). The cities most affected by severe smoke were, again, Thessaloniki, Athens and Rome (table 1). Wildfires were more likely to occur from April to September (83%) in all cities except Barcelona (38%; table 1). Thirty-two per cent of smoky days were concurrent with Saharan dust outbreaks contributing more than 1 μg/m^{3}of PM_{10} at ground level. The largest overlap between smoke and Saharan dust was observed in Palermo (59% of smoky days), followed, far away by Rome (39%) and Madrid (37%), in hot as well as in cold seasons (see online supplementary figure SA).

The daily mean number of natural deaths was 36, across all cities studied. The daily mean number of cardiovascular deaths was 13 and the mean number of respiratory deaths was 4 (table 2).

Smoky days were associated with an increase of 1.78% (95% CI −0.91 to 4.53) in natural mortality (lag 0–1) and of 6.29% (95% CI 1.00 to 11.85) in cardiovascular mortality (lag 0–5). No association was observed for respiratory mortality (table 3).

Daily levels of PM_{10} (10 μg/m^3) were associated with natural mortality (lag 0–1) by 0.53% (95% CI 0.30 to 0.76), cardiovascular mortality by 0.74% (95% CIs to 0.30 to 1.18) and respiratory mortality by 1.99% (95% CI 0.80 to 3.20). The results did not change after adjusting for smoke-affected days (and Saharan dust). There was an indication that PM_{10}-related mortality was modified by smoke episodes (after controlling for Saharan dust); the effects of PM_{10} on smoky days were higher than on smoke-free days, amounting to 1.10% for natural mortality, 3.42% for cardiovascular mortality (with a borderline statistically significant effect modification; p-REM=0.055) and 3.90% for respiratory mortality (table 3).

Fire smoke intensity and duration were well correlated on the less affected days (smoke concentration between 8 and 16 μg/m^3) but not on the most affected days (smoke concentration above 32 μg/m^3); 84% of one-day events were mildly affected, whereas only 23% of 2–4-day events and 45% of 5-or-more-day events were medium/severely affected. Only 22 days were severely

Table 1 Smoke-free days and smoke-affected days by season, intensity and length of episodes in 13 cities of the MED-PARTICLES study area in 2003–2010

City	Study period	Study days (N)	No-smoky days (N)	Smoky days (N)	Smoky days (N) by season		Smoky days (N) by intensity*			Smoky days (N) by length of episodes		
					Warm†	Cold†	Mild	Med	Severe	1 day	2–4 days	5+ days
Madrid	2003–2009	2557	2490	67	59	8	45	17	5	20	42	5
Barcelona	2003–2010	2922	2875	47	18	29	45	2	0	18	22	7
Marseille	2003–2008	2190	2154	36	28	8	26	9	1	16	12	8
Turin	2006–2010	1826	1812	14	14	0	8	5	1	4	10	0
Milan	2006–2010	1826	1812	14	14	0	8	5	1	4	10	0
Bologna	2006–2010	1826	1812	14	14	0	8	5	1	4	10	0
Emilia-Romagna‡	2008–2010	1096	1093	3	3	0	3	0	0			
Rome	2005–2010	2191	2137	54	53	1	40	13	1	11	14	29
Thessaloniki	2007–2009	1096	1032	64	53	11	43	16	5	14	13	37
Palermo	2006–2009	1461	1427	34	28	6	28	5	1	8	7	19
Athens	2007–2009	1096	1052	44	42	2	30	8	6	2	16	26
TOTAL		20 087	19 696	391	326	65	284	85	22	101	156	131

*Model estimates according to Navy Aerosol Analysis and Prediction System (NAAPs).
†Warm season=April–September, cold season=October–March.
‡includes three cities (Modena, Parma and Reggio Emilia) in the Emilia Romagna region.

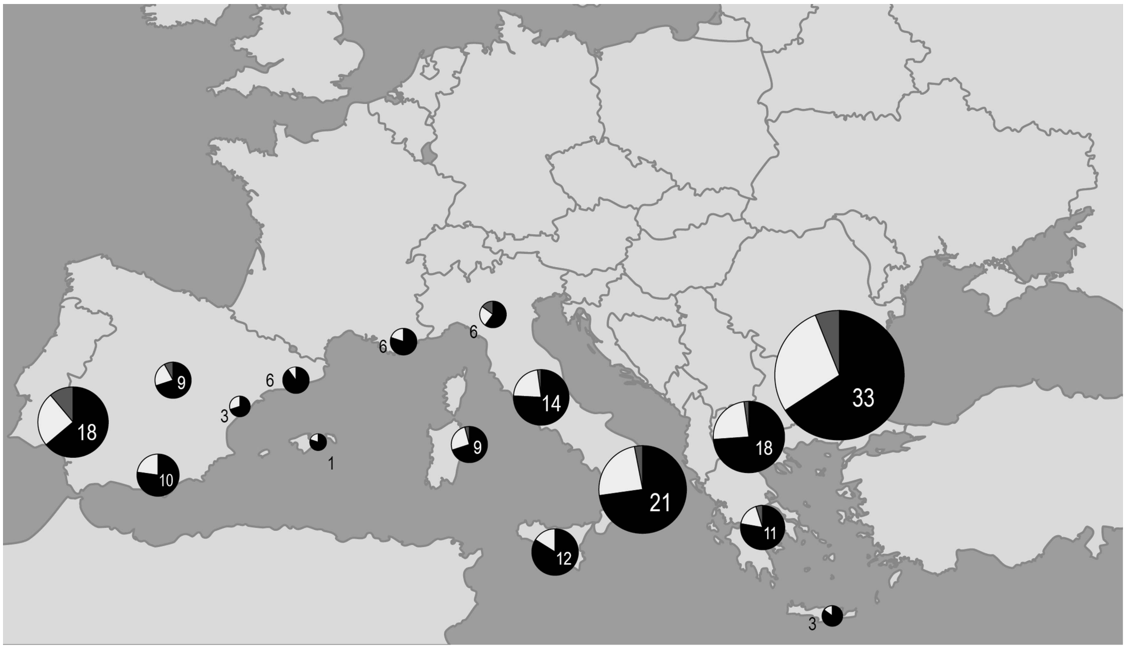

Figure 2 Location, intensity and number of forest fire episodes in the northern Mediterranean area, in the period 2003–2011.
The locations of forest fires are reported in the figure. The cities with fire areas are, from Western to East Europe: Huelva, Madrid, Malaga, Valencia, Barcelona, Palma de Mallorca, Marseille, northern Italy (Turin, Milan, Bologna), Rome, Cagliari, Napoli/Bari, Palermo, Thessaloniki, Athens, Crete, Sofia.
Intensity was classified as low (black, for smoke concentration between 8 and 16 μg/m3, medium (light grey) for smoke concentration between 16 and 32 μg/m3 or severe (dark grey) for smoke concentration above 32 μg/m^3.
The annual mean number of episodes in the location is reported in each circle.

smoke affected, but there were 131 days included in events that lasted 5 or more days (table 1).

When we estimated the changes of temperature and combustion-related pollutants according to episode length (see online supplementary figure SB), we found that mean daily temperature increased by 1.7 C° on smoky days compared to smoke-free days; it increased by 0.9 C° up to 2.3 C° in the long-lasting episodes. The average daily concentrations of PM_{10} increased by around 7 μg/m^{3}on smoky days compared to smoke-free days, and from 5 to 14 μg/m^3 in summer (data not shown). CO on smoky days increased by 0.2 mg/m^3 only during the long-lasting episodes. Similarly, a clear increase in O_3 concentrations (up to 9 μg/m^3) was observed during long-lasting smoke episodes (see online supplementary figure SB). When we estimated the changes in fire-related pollutants by fire smoke intensity, we found a stronger relationship with PM_{10}, and a weaker relationship with CO and ozone (see online supplementary figure SB).

After excluding Turin and Milan (where neither temperature nor PM_{10} increased during fire events) from the analysis, the pooled mortality estimates of PM_{10} showed a stronger increase of respiratory mortality on smoke-affected days than on smoke-free days, in comparison with the base estimates, which included the two cities (see online supplementary table SA).

Table 2 Mean number of deaths that occurred on smoke-free days and smoke-affected days by intensity in 13 cities of the MED-PARTICLES study area in 2003–2010

City	Study period	Study days (N)	Natural deaths (daily mean N)				Cardiovascular deaths (daily mean N)				Respiratory deaths (daily mean N)			
			All days	All smoky days	By smoke intensity* Mild	By smoke intensity* Med-severe	All days	All smoky days	By smoke intensity* Mild	By smoke intensity* Med-severe	All days	All smoky days	By smoke intensity* Mild	By smoke intensity* Med-severe
Madrid	2003–2009	2557	60.1	55.8	55.0	57.4	18.0	16.2	16.0	16.8	9.6	7.8	8.0	7.4
Barcelona	2003–2010	2922	41.7	44.6	44.3	47.0	13.3	13.9	13.8	14.2	4.6	5.2	5.1	5.6
Marseille	2003–2008	2190	21.8	24.7	23.3	28.4	6.7	7.5	7.1	8.5	1.5	1.9	1.7	2.2
Turin	2006–2010	1826	20.5	20.9	20.5	21.3	7.9	8.6	8.6	8.7	1.6	1.6	1.5	1.8
Milan	2006–2010	1826	34.9	33.3	31.5	35.7	12.4	12.1	11.5	12.8	3.0	2.4	2.1	2.7
Bologna	2006–2010	1826	10.6	12.2	11.4	13.3	4.1	5.2	4.4	6.3	1.0	1.1	1.0	1.3
Emilia-Romagna†	2008–2010	1096	13.1	12.0	12.0	–	5.2	4.0	4.0	–	1.0	1.0	1.0	–
Rome	2005–2010	2191	57.9	54.5	53.2	58.1	23.6	21.6	21.9	20.8	3.6	2.9	2.8	3.1
Thessaloniki	2007–2009	1096	17.9	18.7	18.1	20.0	8.3	8.8	8.6	9.2	1.7	1.6	1.5	1.8
Palermo	2006–2009	1461	15.3	14.7	14.9	13.7	6.2	6.3	6.4	5.8	0.9	0.9	0.9	1.0
Athens	2007–2009	1096	80.6	84.1	81.6	89.4	36.3	38.1	36.8	41.0	9.2	8.4	8.7	7.9

*Model estimates according to Navy Aerosol Analysis and Prediction System (NAAPs).
†Includes three cities (Modena, Parma and Reggio Emilia) in the Emilia Romagna region.

Table 3 Pooled* estimates of the effects of smoke and PM_{10} (10 $\mu g/m^3$) on natural and cause-specific mortality (all ages) in 10 MED-PARTICLES cities in 2003–2010

	Natural mortality, lag 0–1					Cardiovascular mortality, lag 0–5					Respiratory mortality, lag 0–5				
	Per cent	95% CI	I^2 (%)	p-het	p REM	Per cent	95% CI	I^2 (%)	p-het	p REM	Per cent	95% CI	I^2 (%)	p-het	p REM
Smoke-affected days	1.78	−0.91 4.53	19	0.260		6.29	1.00 11.85	34	0.140		−3.49	−9.60 3.03	0	0.440	
PM_{10}	0.53	0.30 0.76	22	0.240		0.74	0.30 1.18	1	0.427		1.99	0.80 3.20	39	0.097	
PM_{10}†	0.51	0.16 0.86	50	0.035		0.70	0.14 1.27	25	0.213		2.17	0.89 3.46	43	0.068	
PM_{10}‡															
On smoke-free days	0.49	0.14 0.85	49	0.040		0.65	0.10 1.19	21	0.252		2.13	0.85 3.42	43	0.072	
On smoke-affected days	1.10	−1.51 3.77	51	0.033	0.655	3.42	0.64 6.28	0	0.491	0.055	3.90	−1.63 9.74	0	0.888	0.549

*From random meta-analysis.
†Adjusted for smoky days and Saharan dust in three levels.
‡Adjusted for Saharan dust in three levels and stratified in smoke-free days and smoke-affected days.
p-het, p value of the heterogeneity test; PM, particulate matter; p REM means p value of the difference between the effects on the smoke free days and on smoke affected days; REM, relative effect modification.

DISCUSSION

We found that cardiovascular mortality was significantly higher in the Mediterranean cities on smoky days. There was a weaker association with natural mortality and no association was observed with respiratory mortality. We also found that PM_{10} effects on natural, cardiovascular and respiratory mortality were greater on smoky days than on other days, while an effect modification was clear only for cardiovascular mortality.

While high toxicity of particles from wood fires (higher than from particles originating from other sources) has been reported in experimental and toxicological research,[6 36] epidemiological studies have reported conflicting effects of particles on cause-specific mortality on smoky days,[9 17–19 22] or very similar effects of PM_{10} on smoke-affected and smoke-free days.[21 22] Our results indicate that PM_{10} from forest fires increases mortality more than PM_{10} from other sources does. It is possible that the stronger effects of particles during smoke-affected days are due to differences in their composition, but other factors also play a role in increasing mortality on those days, such as temperature increase. Cardiac patients are more susceptible than other participants to high temperatures that, in turn, are known to enhance the effects of ambient particles.[37]

The mortality increase associated with PM_{10} is consistent with the estimates reported in multicity European studies: APHEA2,[38] APHENA[39] and EpiAir.[40] All these studies also showed higher PM_{10} effects on respiratory mortality. Then, the effects we found on cardiovascular mortality during fires may be due to a different PM composition or increasing temperature.

In contrast, results from studies on the effects of wildfire emissions on cause-specific mortality have been inconsistent. Johnston[17] reported the highest effects on cardiovascular mortality, but Morgan[22] did not find any consistent effect with cardiovascular deaths in Australia, and Analitis[9] found the highest effects on respiratory mortality in Greece; this last study, however, used an exposure definition that differs from nearly every other fire smoke study. The toxicological studies on effects of fire smoke usually focus on lung damage and have consistently reported trachea-bronchial cell injuries, changes in the immune cell morphology in the lungs and diminishing ventilator responses.[6] On the other hand, it may be that different degrees of toxicity on cardiovascular and respiratory systems are due to different PM_{10} components or to varying gaseous emissions (CO, VOCs, NOx or SO_2) from wildfires. Natural mortality has been already reported as less affected by fires[9 17] when compared to cause-specific mortality. We did not attempt to explain the high heterogeneity of PM_{10} effects on natural mortality during fires, however, it is worth noting that natural mortality is likely to be penalised by a misclassification of accidental deaths (injuries, poisoning and external causes); these causes of death are usually not included as plausible effects of air pollution, but are likely to occur during fire episodes or result from them at longer distance, in the case of poisoning.

An underestimation of PM levels from wildfires at ground level is usually due to satellite observations, which incorrectly identify some aerosol plumes as clouds, and fires produce smoke as thick as some clouds.[10] On the other hand, an overestimate of PM from wildfires would occur because of their high prevalence of carbonaceous particles, increasing the absorption of the satellite signal. Therefore, a misclassification was the most likely bias affecting our assessment of exposure. The sensitivity analysis we performed excluding cities with no PM and temperature increases on smoky days, supports the hypothesis of a misclassification of smoky days in the two cities.

We did not have chemical transport models available to estimate PM aerosol vertical profiles, though they have been shown to improve the accuracy of satellite estimates of $PM_{2.5}$,[41] nor were we able to directly estimate the contribution to PM_{10} from forest fires. Therefore, to validate fire exposure, we used indirect indicators, such as fire-related pollutant levels from fixed monitors despite the important assumptions this required. We observed a clear PM increase on smoky days and this is consistent with previous studies, which used PM increases as a fire exposure indicator,[21 22] or validated the satellite data on fires using background $PM_{2.5}$.[41]

Assessment of fire smoke intensity is even more likely to be affected by misclassification; it relies on fire characteristics not directly related to human exposure, such as the extension of the burnt area,[9] AOD from satellites[42] or plume detection.[26 43] The weak consistency we observed between smoke intensity and duration with fire-related indicators, induces caution in relying on intensity estimates based on satellite data. Moreover, the high correlation we observed between the shortest episodes and the mild smoke intensity fell very much between the longest events and days of intense smoke. A recent study aids in understanding this issue; Yao and Henderson[44] validated an empirical model to estimate forest fire-related $PM_{2.5}$ using background PM, remotely sensed aerosols and remotely sensed fires, smoke plumes from satellite images, fire danger ratings and the venting index (the probability of the atmosphere to disperse smoke from a fire). In contrast to our results, the correlation between estimated and observed values was 84%, and decreased on days with moderate to low levels of smoke up to 59%–58%. Thus the model more reliably assessed exposure to high-intensity smoke, than to smoke of low intensity.

CONCLUSIONS

We observed increases in natural and cause-specific mortality on smoky days; mortality from cardiovascular causes had the largest increase. PM_{10} had larger effects on cardiovascular and respiratory mortality on smoky days than on other days, suggesting a priority role of particulate as an effective component of fire smoke. Our study highlighted the need to make improvements in exposure assessments and estimations of fire-related health outcomes. Wildfire exposure assessment would benefit from remote sensors, source apportionment of particles during fires and from a detailed definition of their components, as well as assessing fire-related increases in temperature. A better understanding of the role that meteorology plays in influencing the direction and the spatiotemporal extension of wild fires is also important. Health assessments could benefit from the analysis of other health outcomes such as accidental causes of death during fires, and specific syndromes related to fire resulting at longer distance.

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Acknowledgements The authors thank Margaret Becker for revising the English and Simona Ricci for her help with the figures. The authors express their gratitude to the Naval Research Laboratory for the provision of NAAPS aerosol maps (http://www.nrlmry.navy.mil/aerosol/), without which this study would not have been possible.

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Funding This research was supported by the European Union under the grant agreement LIFE+ ENV/IT/327.

Competing interests None.

Provenance and peer review Not commissioned; externally peer reviewed.

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