Journal of Exposure Science and Environmental Epidemiology (2009) 19, 414–422
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www.nature.com/jes

Population exposure to fine particles and estimated excess mortality in Finland from an East European wildfire episode

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Long-range transported particulate matter (PM) air pollution episodes associated with wildfires in the Eastern Europe are relatively common in Southern and Southeastern Finland. In severe cases such as in August–September 2002, the reduced visibility and smell of the smoke, and symptoms such as irritation of eyes and airways experienced by the population raise the issue into the headlines. Because PM air pollution, in general, has been identified as a major health risk, and the exposures are of repeating nature, the issue warrants a risk assessment to estimate the magnitude of the problem. The current work uses the available air quality data in Finland to estimate population exposures caused by one of the worst episodes experienced in this decade. This episode originated from wildfires in Russia, Belarus, Ukraine, and the Baltic countries. The populations of 11 Southern Finnish provinces were exposed between 26 August and 8 September 2002, for 2 weeks to an additional population-weighted average $PM_{2.5}$ level of 15.7 $\mu g/m^3$. Assuming similar effect on mortality for these particles as observed in epidemiological time series studies on urban particles (0.5%–2% increase in mortality per 10 $\mu g/m^3$, central estimate 1%), this exposure level would be associated with 9–34 cases (17 cases central estimate) of additional mortality. Epidemiological evidence specific to particles from biomass combustion is scarce, affecting also the reliability of the current risk assessment. Do the wildfire aerosols exhibit the same level of toxicity as the urban particles? To shed light on this question, it is interesting to look at the exposure data in relationship to the observed daily mortality in Finland, even though the limited duration of the episode allows only for a weak statistical power. The percentage increases observed (0.8%–2.1% per 10 $\mu g/m^3$ of fine PM) are in line with the more general estimates for urban PM and those used in the current risk assessment.
Journal of Exposure Science and Environmental Epidemiology (2009) **19,** 414–422; doi:10.1038/jes.2008.31; published online 4 June 2008

Keywords: *$PM_{2.5}$, mortality, uncontrolled biomass combustion, long-range transport, forest fire.*

Introduction

Besides the main combustion products, carbon dioxide and water, the uncontrolled conditions in wildfires produce large amounts of other combustion products such as polycyclic aromatic hydrocarbons (PAHs), carbon monoxide (CO), nitrogen oxides (NO_x), volatile organic compounds (VOCs), sulphur dioxide (SO_2), and fine particulate matter ($PM_{2.5}$, particles with aerodynamic diameter $\leq 2.5\,\mu m$) consisting of soot, organic carbon compounds, and inorganic ash. These air pollutants have half-lives of days in the atmosphere and they can be transported to hundreds of kilometres. Depending on the affected area determined by the prevailing winds and air mass movements, millions of people can be exposed to the harmful combustion products.

Ambient fine particles have been identified as the most harmful pollutant affecting public health in Europe. In the Clean Air for Europe (CAFE) Study, the central estimate presented for yearly excess mortality associated with $PM_{2.5}$ air pollution was 348,000 (EC, 2005). Source apportionment studies have shown that long-range transported air pollution forms a significant fraction of levels of fine particles. Koistinen et al. (2004) estimated that 46% of fine particle mass ($PM_{2.5}$) in the ambient air and 31% of personal exposures of the working age population in Helsinki consisted of secondary inorganic long-range transported particles. The corresponding observed mass concentrations were 4.7 and 3.3 $\mu g/m^3$, respectively. Vallius et al. (2003) reported slightly higher contribution (51%) of long-range transport to $PM_{2.5}$.

Besides the substantial contribution to the long-term average levels, episodes of elevated PM caused by long-range transported particles occur regularly. Niemi et al. (2006) found 30 episodes during which the $PM_{2.5}$ levels were above 25 $\mu g/m^3$ (i.e., approximately three times higher than the long-term average) in 1999–2005 in Helsinki. Elemental

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Received 5 October 2007; accepted 24 April 2008; published online 4 June 2008

data allowed more careful source analysis of 20 of the episodes between 2001 and 2005. Practically, all these episodes originated from Eastern Europe, including Baltic countries, Russia, Belarus, Ukraine, and Poland and 10 episodes were either directly caused or significantly affected by biomass burning products from wild and agricultural fires. Episodes occurred typically in March–April, less frequently in January–February and in August–October. Both the highest hourly and daily $PM_{2.5}$ concentrations during episodes in Helsinki (46 and 81 $\mu g/m^3$, respectively) were observed in 2002 and were associated with wildfires (Niemi et al., 2006).

Boman et al. (2003) reviewed epidemiological studies specific to biomass combustion smoke. Their PubMed search produced nine relevant studies, including five general population studies and four panel studies. Only one of the studies (Hales et al., 2000) looked at the effects on daily mortality, reporting 1% increase in risk of all-cause mortality and 4% increase for respiratory mortality per 10 $\mu g/m^3$ increase in the ambient PM_{10} level during the day before. The exposure–response relationships reported for wood smoke in studies reviewed by Boman et al. (2003) were in most cases equal or higher than those reported for the same pollutants in urban settings without influence from wood combustion. In a recent experimental study of wood smoke exposure in healthy humans (Barregard et al., 2006), this exposure appeared to elicit effects on systemic and pulmonary inflammation; the effects were probably stronger than those shown after experimental diesel exposure at similar particle mass concentrations.

The statistical power of the epidemiological studies on the public health impacts of wildfires tends to be substantially weaker than that of the studies on urban air pollution, in general, mainly due to the limited duration of the exposure periods. For example, Vedal and Dutton (2006) analysed a wildfire episode case in Denver (CO, USA), where a population of 2 million was exposed to 40–50 $\mu g/m^3$ levels of wildfire smoke for 2 days in June 2002. They were not able to detect mortality effects from the observed data. However, assuming an increase of 1% in daily mortality per 10 $\mu g/m^3$ for the exposures in the Denver case, with the average daily background mortality of 35 cases, the expected value of additional mortality would be less than $5 \times 1\% \times 35 = 1.75$ cases, which is impossible to observe from 2 days of episode data when the normal daily standard deviation (SD) of mortality is 6.7 cases. For the excess mortality to be clearly visible in such data $2 \times SD$, or more than 13 daily cases would be needed. This would require approximately 10 times higher toxicity for the smoke $PM_{2.5}$ particles than observed in the urban PM epidemiology studies. Studies covering several seasons may be necessary, as illustrated by a recent study in Australia showing an association between bushfires and hospital admissions, when data from three seasons in the 2000s were combined (Johnston et al., 2007).

During some extreme episodes, such as the one in Indonesia in 1997, huge numbers of people have been exposed, but there has been limited information available for exposure assessment as well as scarce data on health outcomes (Brauer and Hisham-Hashim, 1998). Sastry (2002) used PM_{10} measurements ($\geq 210\,\mu g/m^3$) and visibility data to identify high air pollution days and observed 19%–22% increase in the next day all-cause mortality. Translated to the traditional risk ratio per 10 $\mu g/m^3$ increase in PM_{10} this corresponds approximately 1%. During the same episode, Mott et al. (2005) and Emmanuel (2000) reported significant increases in outpatient attendance for haze-related conditions. Nevertheless, in their recent review, Naeher et al. (2007) concluded that there is insufficient evidence at present to conclude that wood smoke particles are significantly less or more damaging to health than general ambient fine particles of similar size.

Similar position is taken by the World Health Organization. The recently updated Guidelines for Air Quality (WHO, 2006) are given for mass concentrations ($\mu g/m^3$) based on the implicit assumption that all fine particles are equally harmful and that the guideline value depends only on the particle size distribution (defined in the Guidelines as $PM_{2.5}$ or PM_{10}). The exact value of relative risks associated with even the more general urban fine particles contains nevertheless some uncertainty. WHO (2004) reviewed time series and panel studies on fine particles ($PM_{2.5}$) for a meta-analysis of dose–response functions and found very few European studies on all-cause or cause-specific mortality. In the West Midlands Study, the relative risk for all-cause mortality was 1.0034 (0.9915, 1.0154) (Anderson et al., 2001). This compares with 1.0057 (0.9980, 1.0136) and 0.9837 (0.9677, 0.9999) from studies in the Czech Republic (Peters et al., 2000) and Erfurt (Wichmann et al., 2000), respectively.

The objectives of the current work are (i) to estimate the population exposure to fine particles from a serious transboundary wildfire episode in Finland; (ii) to estimate additional mortality associated with the episode using published exposure–response relationships of urban fine particles; and (iii) to use observed mortality data to investigate the relative risk specific to the episode particles and compare it with the relative risk estimate chosen for the risk assessment. In the current work, independent results from parallel studies on the atmospheric conditions leading to the episode, source apportionment and chemical characterization of PM, and evaluation of PM toxicity *in vitro* are used. These are shortly summarized before the Materials and methods section.

Atmospheric conditions of the episode

In August–September 2002, North European weather was dominated by a long period of stagnant anticyclones above the Eastern Europe and a cyclone in the Northern Atlantic. These conditions typically lead to sunny and warm weather in the Eastern Europe: average temperatures were higher and precipitation values much lower than the average values for the summer season (Chubarova et al., 2003). As a consequence of the hot and dry conditions, the summer was an extreme with fires on drained peat soils in Russia (Bannikov et al., 2003; Goldammer, 2003). Between April and October, 35,800 fires were recorded by the Russian Aerial Forest Protection Service Avialesookhrana, and almost 2 million hectares was affected by fires in Russia alone (Davidenko and Eritsov, 2003). A continuous patchwork of fires 2500 km long and for the most part 1000 km wide extends from Ural in the East to the borders of Ukraine and Poland, and Russia and the Baltic countries in the West (Figure 1).

The significantly degraded visibility and irritating smell of the smoke together with associated symptoms of eyes and airways experienced by the population lead to alarmed calls to the authorities, including the National Public Health Institute and raised the issue into the TV news, radio, and, during the consequent days, the headlines. The current analysis was started in response to these events. Different aspects of the episode have been analysed and published elsewhere, and are shortly summarized to the extent where the results are relevant for the current risk analysis.

Backward Trajectory Analysis for the Origin of the Aerosol

The trajectories shown in Figure 2 as well as the more detailed backward trajectory analyses conducted by Niemi et al. (2005) and Sillanpää et al. (2005) show that the aerosols observed in Finland during 26 August–6 September originated from the wildfire areas in Eastern Europe. In comparison to the fire maps (Figure 1), the trajectories emphasize especially the role of fires in the Baltic countries. The spread of the smoke was also clearly visible in the Terra-satellite images affecting large areas in Poland, Germany, and Denmark (http://www.sat.dundee.ac.uk; data not shown).

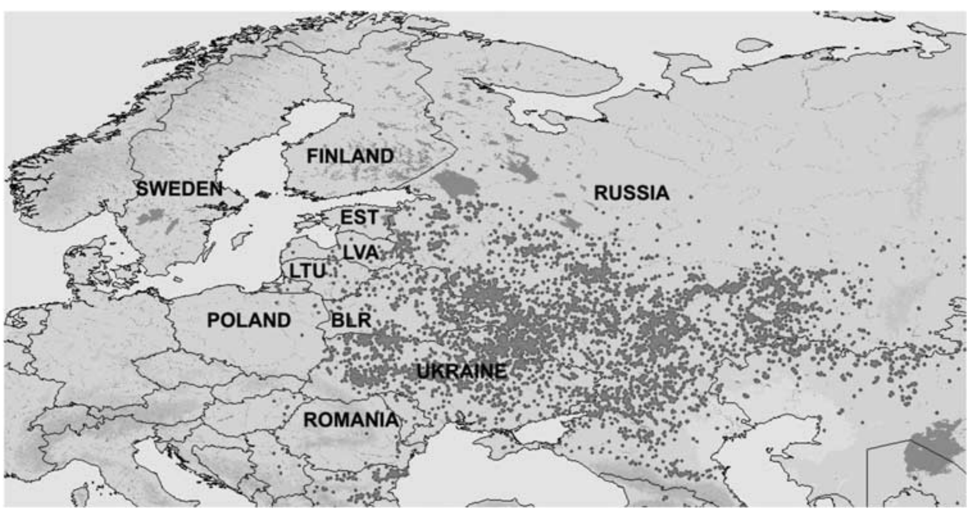

Figure 1. A map adjusted from the Web Fire Mapper (http://maps.geog.umd.edu) output, showing active fires (grey dots) detected from the MODIS satellite data for the period 26 August–8 September 2002. Each detection represents a 1-km^2 pixels identified as containing an active fire. NOTE: Figure 1 caption: "grey dots" on black and white print, red in colour.

Figure 2. Four-day backward trajectories (HYSPLIT model, NOAA Air Resource Laboratory) for the highest episode peaks observed in (1) Southern Sweden (4.9 at 18 O'clock), (2) Helsinki (5.9. at 20 O'clock) and (3) Kuopio (6.9. and 10 O'clock), highlighting the role emissions in the Baltic countries. Trajectory height indicated in the figure.

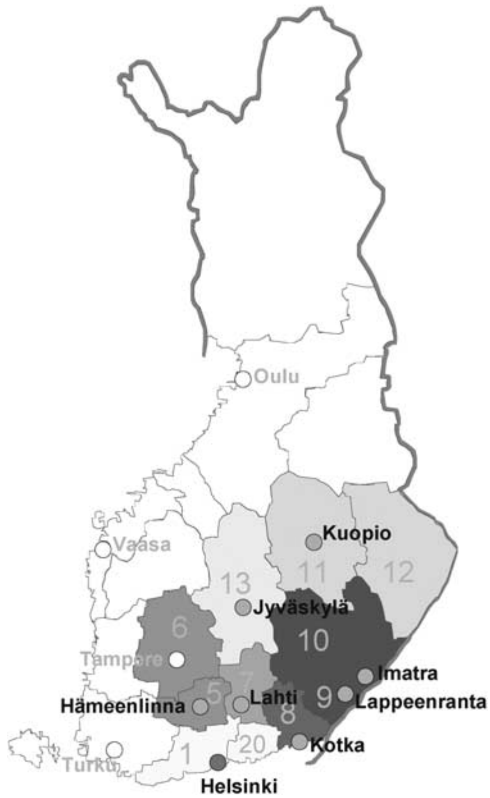

Figure 3. Locations of continuous air quality monitoring stations (o), provinces (numbered), and relative exposure levels in provinces (darkness of colour only indicative; see actual exposure levels in Table 1) during the forest fire episode. PM_{10} data were not available from Tampere, and $PM_{2.5}$ data were available only from Helsinki, Vaasa, and Oulu.

Observed Air Quality

Continuous fixed site-monitoring networks are operated in 13 cities in Finland (locations in Figure 3, concentration data for three of the stations in Figure 4). Daily average $PM_{2.5}$ (Helsinki) and PM_{10} (other cities) concentrations were obtained from eight cities within the affected area. Peak concentrations, raising wide public attention, approached 200 $\mu g/m^3$ in Lappeenranta and in the other cities 100 $\mu g/m^3$ (hourly averages).

When the worst episode day reached Kuopio area on Friday morning, 6 September 2002, emergency measurements of $PM_{2.5}$ particles were started within 2 h time at KTL. Size selective Climet optical particle counter (Climet Inc.) and pDR-1200 (Thermo Electron Inc., MA, USA) and DustTrak (TSI Inc.) optical particle monitors with $PM_{2.5}$ cyclones were placed on the roof of the KTL three-storey building. The Climet monitor classifies particles into five size classes between 0.3 and 25 μm based on their aerodynamic diameter and counts continuously the respective number concentrations. The other two monitors estimate the particle mass concentrations based on the optical aerosol properties and were logged on a 1-min basis. Besides the optical measurements, the US EPA reference method, EPA-Wins sampler with $PM_{2.5}$ impactor, was used to collect four consecutive samples for analysis of mass concentrations and chemical composition.

Source apportionment and PM toxicity

Two independent studies on the source apportionment and chemical characterization of the episode particles in Helsinki, and consequent *in vitro* studies on the cellular toxicity of the size-segregated high-volume PM samples are summarized to support the assumptions of the current work. Two shorter parts of the current 2-week episode period (26–29 August and 5–6 September) were analysed by Niemi et al. (2005). Biomass combustion was identified as the main cause for the elevated $PM_{2.5}$ levels, but elevated SO_2 and NH_4 levels also indicated potential impacts from emissions of industrial and other sources.

Composition of particles in Helsinki was also investigated by Sillanpää et al. (2005) using nine multiday size-segregated high-volume PM samples collected between 23 August and 23 September 2002, overlapping the current episode. Four of the samples were collected during the target period of the current study. A high correlation of $PM_{2.5}$ mass was observed with succinate, malonate, oxalate, K^+, Ca^{2+}, and monosaccharide anhydrides, and a good correlation with NH_4^+, Br^-, Al, Si, and P supporting the origin of the particles from wildfires.

These high-volume samples were further used in *in vitro* toxicological experiments. Mouse macrophage cultures were exposed to particles of four different sizes (<0.2, -1.0, -2.5, and -10 μm) to study their inflammogenic and cytotoxic activities (Jalava et al., 2006). They reported that the episode particles were associated with increased inflammogenic and cytotoxic activities per inhaled cubic metre of air due to the greatly increased particulate mass concentration in the accumulation size range (Jalava et al., 2006).

Materials and methods

Exposure Assessment

$PM_{2.5}$ or PM_{10} data were available from eight stations on an area covering approximately 100,000 km^2 and 3.4 million inhabitants (Table 1). To estimate the exposure levels, the concentrations from various stations were plotted as time series together, displaying convincing similarities in the profiles. Exposures in the 11 provinces affected by the smoke were estimated using the most representative urban background monitoring data (Table 1) after subtraction of the seasonal background. Seasonal background concentrations were visually estimated using the baseline levels of hourly concentration data and subtracted from the observations using the minimum daily average value.

Owing to the lack of $PM_{2.5}$ monitoring stations in all other cities, but Helsinki (Kallio) (and the $PM_{2.5}$ emergency

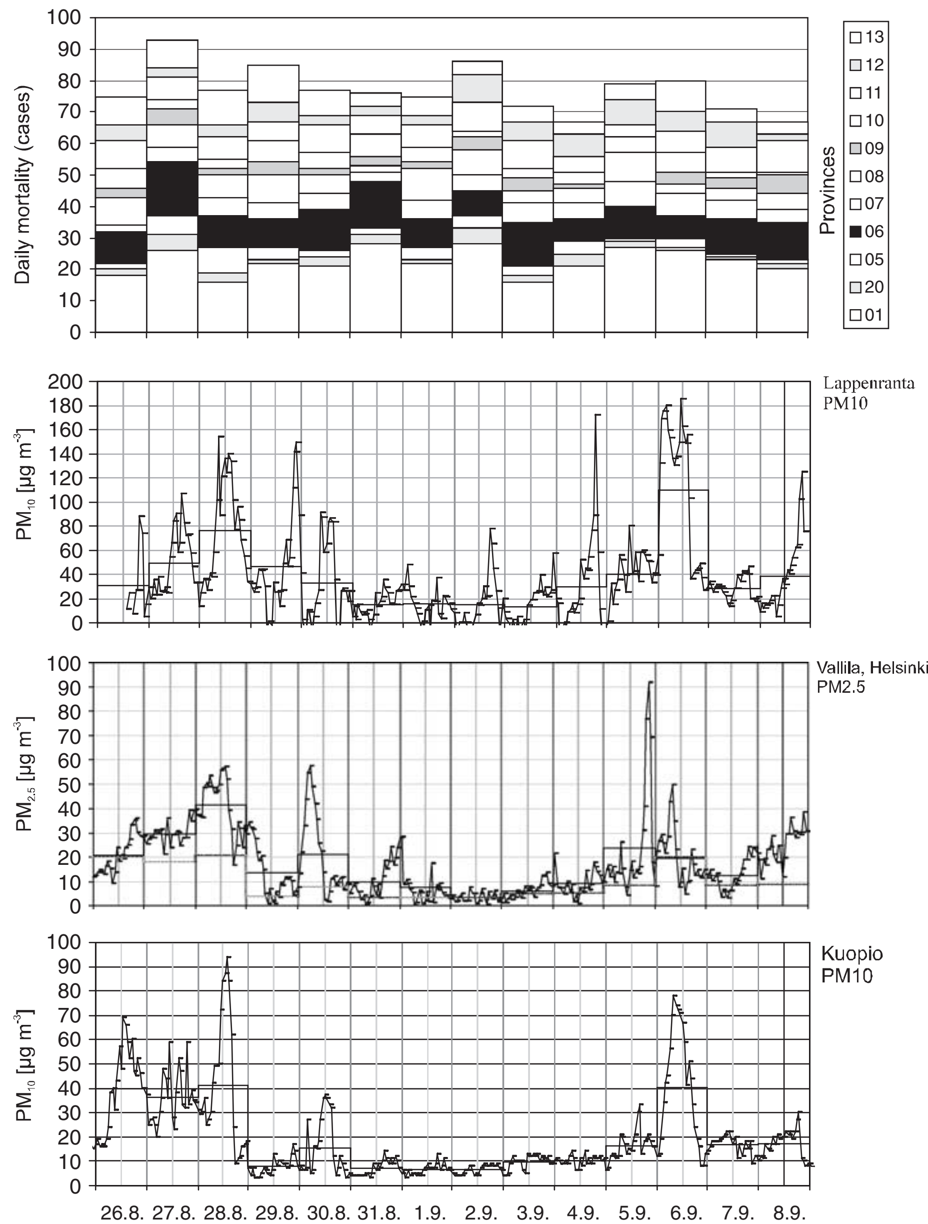

Figure 4. Observed mortality data by provinces and ambient air quality data from three cities ($PM_{2.5}$ for Helsinki, PM_{10} for Kuopio, and Lappeenranta; hourly and daily values).

measurements in Kuopio that covered the last couple of days of the full period), the $PM_{2.5}$ size fraction of the particles originated from the forest fires had to be estimated indirectly. The average $PM_{2.5}$ and PM_{10} concentrations during the 2-week episode in 2002 in Helsinki were compared with the monthly average of those parameters at the same season 1 year after the episode. Assuming that the background levels during the episode would have been at the same level as the monthly average values in September 2003, the particle size fraction originated from the forest fires could be estimated. This analysis showed that 95% of the increase of PM_{10} was due to the increase of $PM_{2.5}$. Comparison of the difference between the minimum and maximum levels of $PM_{2.5}$ and PM_{10} during the episode produced similar results (data not shown). Theoretical considerations as well as measurements conducted by KTL in Kuopio also showed that the part of the episodic haze observed as PM_{10} at the fixed monitoring stations corresponded quite well to gravimetric $PM_{2.5}$ measurements. Thus, the concentrations above the seasonal regional PM_{10} background level were considered as $PM_{2.5}$ particles in the exposure assessment.

Moreover, PM_{10} and $PM_{2.5}$ measurements in Helsinki metropolitan area and PM_{10} levels in Imatra in the South-eastern part of the country followed roughly the same

Table 1. Observed daily mortality by provinces and additional $PM_{2.5}$ population exposure as estimated from the air quality monitoring data during 26 August–8 September 2002 in Finland.

Province[a]	Observed daily mortality (cases)														Total	Average	Population	Relative mortality cases per day per million
	26 August 2002	27 August 2002	28 August 2002	29 August 2002	30 August 2002	31 August 2002	1 Sepetember 2002	2 Sepetember 2002	3 Sepetember 2002	4 Sepetember 2002	5 Sepetember 2002	6 Sepetember 2002	7 Sepetember 2002	8 Sepetember 2002				
1 Uusimaa	18	26	16	22	21	28	22	28	16	21	27	26	23	20	314	22.4	1,318,324	17.0
20 Itä-Uusimaa	2	5	3	1	3	3	1	5	2	4	2	1	1	2	35	2.5	90,201	27.7
5 Kanta-Häme	2	6	8	4	2	2	4	4	3	4	1	3	1	1	45	3.2	165,509	19.4
6 Pirkanmaa	10	17	10	9	13	15	9	8	14	7	10	7	11	12	152	10.9	450,745	24.1
7 Päijät-Häme	2	5	6	5	5	3	6	5	6	5	8	7	6	4	73	5.2	197,656	26.4
8 Kymenlaakso	9	7	7	9	6	2	10	8	4	5	9	3	4	5	88	6.3	186,707	33.7
9 Etelä-Karjala	3	5	2	4	2	3	2	4	4	1	0	4	3	6	43	3.1	137,019	22.4
10 Etelä-Savo	6	3	3	7	5	7	5	2	3	4	5	6	2	1	59	4.2	164,471	25.6
11 Pohjois-Savo	9	7	7	6	9	6	7	9	9	5	4	7	8	10	103	7.4	252,842	29.1
12 Pohjois-Karjala	5	3	4	6	3	3	3	9	6	7	8	6	8	2	73	5.2	170,793	30.5
13 Keski-Suomi	9	9	11	12	8	4	6	4	5	4	5	10	4	4	95	6.8	264,762	25.6
Total	75	93	77	85	77	76	75	86	72	67	79	80	71	67	1080	77.1	3,399,029	22.7
Province	Daily exposure increments ($\mu g/m^3$)														Mean ($\mu g/m^3$)		Monitoring station	
1 Uusimaa	15.2	25.8	39.3	13.1	17.0	6.0	3.8	0.0	9.5	3.9	14.4	20.6	9.1	17.3	13.9		Helsinkiki-Kallio $PM_{2.5}$	
20 Itä-Uusimaa	15.2	25.8	39.3	13.1	17.0	6.0	3.8	0.0	9.5	3.9	14.4	20.6	9.1	17.3	13.9		Helsinkiki-Kallio $PM_{2.5}$	
5 Kanta-Häme	42.2	52.5	41.1	18.2	10.8	7.0	0.0	2.1	4.5	8.6	11.1	23.7	14.1		18.1		Hämeenlinna PM_{10}	
6 Pirkanmaa	42.2	52.5	41.1	18.2	10.8	7.0	0.0	2.1	4.5	8.6	11.1	23.7	14.1		18.1		Hämeenlinna PM_{10}	
7 Päijät-Häme	18.2	29.7	37.3	14.2	13.4	5.4	0.0	0.8	0.6	5.7	16.3	36.4	15.5	21.1	15.3		Lahti-Laune PM_{10}	
8 Kymenlaakso	28.3	34.5	52.7	12.8	24.3	7.2	2.7	0.0	4.0	9.4	33.7	45.5	11.2	13.9	20.0		Kotka-Rauhala PM_{10}	
9 Etelä-Karjala	28.8	33.2	48.1	12.6	20.9	4.2	5.8	0.0	2.6	11.2	39.9	127.2	20.4	12.8	26.3		Imatra-Rautionkylä PM_{10}	
10 Etelä-Savo	14.9	33.8	60.4	35.2	25.3	0.0	2.5	5.9	8.1	26.2	26.5	95.8	12.6	23.1	26.5		Lappeenranta PM_{10}	
11 Pohjois-Savo	32.2	30.4	27.4	4.0	9.1	1.8	0.0	3.9	4.4	6.9	10.4	40.8	12.3	12.4	14.0		Kuopio-Itkonniemi PM_{10}	
12 Pohjois-Karjala	32.2	30.4	27.4	4.0	9.1	1.8	0.0	3.9	4.4	6.9	10.4	40.8	12.3	12.4	14.0		Kuopio-Itkonniemi PM_{10}	
13 Keski-Suomi	23.0	20.9	23.7	0.8	6.4	0.8	0.6	0.0	2.0	5.6	10.1	27.2	9.9	13.5	10.3		Jyväskylä-Palokka PM_{10}	
Weighted mean	24.2	32.2	38.9	13	14.8	4.91	2.14	1.2	6.22	7.03	15.8	34.4	11.6	13.4	15.7			

[a]Province numbers used by Statistics Finland; province name in Finnish.

temporal pattern throughout the whole month (Niemi et al., 2005), indicating a significant, evenly distributed long-range transportation contribution in the $PM_{2.5}$ fraction.

Risk Assessment

The additional daily mortality caused by the episode was estimated by using air quality monitoring data in combination with exposure–response values from epidemiological studies as suggested by WHO (Schwela et al., 1999), but with the exposure–response factor of $PM_{2.5}$ instead of the value for PM_{10}. The calculation was based on the assumption that the daily mortality is increased by 1% per each increment of $10\,\mu g/m^3$ (WHO, 2004, 2006). Population and daily mortality for the provinces affected by the episode were provided by Statistics Finland (Table 1, top part of Figure 4). To assess the uncertainty of our analysis, a range of mortality estimates was tested. A lower estimate of $0.5\%/10\,\mu g/m^3$ $PM_{2.5}$ was selected on the basis of the lowest estimates for total mortality presented in previous original studies selected into the meta-analysis of WHO (2004) and review by Pope and Dockery (2006).

Epidemiology

Short duration (2 weeks), relatively low additional exposure level (ranging from 10.3 to $26.5\,\mu g/m^3$ in the various provinces; population-weighted mean $15.7\,\mu g/m^3$), and limited population affected (3.4 million) made it unreasonable to expect statistically significant associations between PM exposure and mortality in the current work. Similar limitations have haunted previous studies on the effects of wildfire particles. Nevertheless, having access to a reasonably well-built and evaluated population exposure model, it was interesting to test the observations in an epidemiological model.

Poisson's regression was used to evaluate the associations between daily levels of PM and mortality during the 2-week period. The area-specific models included linear term for time trend; smooth term was not considered to avoid overadjusting the short study period. Inclusion of a dummy variable for weekdays did not affect the results. Daily temperature cycle remained in practice unchanged, afternoon temperatures being 19–22°C in the Southern Finland during the study and, consequently, was not included in the model. The pooled effect estimate was calculated as the weighted average of city-specific regression coefficients using the inverse of the squared standard errors of the regression coefficients as weights. The results were calculated for an increase of $10\,\mu g/m^3$ in $PM_{2.5}$ to be comparable to previous studies.

Results

Exposure Assessment

Exposures of the general Finnish population were estimated for the 11 provinces most seriously affected by the wildfire smoke. Increase in the population exposure to $PM_{2.5}$ was estimated to be $15.7\,\mu g/m^3$ for the 2-week period in August–September 2002 (Table 1).

Daily variability in the $PM_{2.5}$ and PM_{10} levels throughout the period at the three selected sites shown in Figure 4 exhibit clear similarities in the levels. In the beginning of the 2-week period, all stations represent approximately 3 days of clearly elevated levels, in Lappeenranta PM_{10} exceeding $100\,\mu g/m^3$, $PM_{2.5}$ in Helsinki reaching $60\,\mu g/m^3$, and PM_{10} similar levels in Kuopio. Towards the end of the period, a shorter and sharper peak with small differences in timing occurs, and the minimum levels in between represent plausible values for seasonal background concentrations.

Risk Assessment

The additional mortality potentially associated with the episode was calculated to be 17 (lower and upper estimates 9 and 34, respectively) cases in 2 weeks (Table 2). Risk in each

Table 2. Estimated excess daily mortality by provinces caused by the wildfire episode during 26 August–8 September 2002 in Finland.

Province[a]	Daily excess mortality (cases) based on RR = 1.0%/10 $\mu g/m^3$														Lower RR = 0.5%	Central RR = 1%	Upper RR = 2%
1 Uusimaa	0.27	0.46	0.71	0.23	0.31	0.11	0.07	0.00	0.17	0.07	0.26	0.37	0.16	0.31	1.8	3.5	7.0
20 Itä-Uusimaa	0.03	0.05	0.08	0.03	0.03	0.01	0.01	0.00	0.02	0.01	0.03	0.04	0.02	0.03	0.2	0.4	0.8
5 Kanta-Häme	0.08	0.10	0.08	0.04	0.02	0.01	0.00	0.00	0.01	0.02	0.02	0.05	0.03	0.00	0.2	0.5	0.9
6 Pirkanmaa	0.42	0.52	0.41	0.18	0.11	0.07	0.00	0.02	0.04	0.09	0.11	0.24	0.14	0.00	1.2	2.4	4.7
7 Päijät-Häme	0.04	0.06	0.07	0.03	0.03	0.01	0.00	0.00	0.00	0.01	0.03	0.07	0.03	0.04	0.2	0.4	0.9
8 Kymenlaakso	0.25	0.31	0.47	0.12	0.22	0.06	0.02	0.00	0.04	0.08	0.30	0.41	0.10	0.12	1.3	2.5	5.0
9 Etelä-Karjala	0.09	0.10	0.14	0.04	0.06	0.01	0.02	0.00	0.01	0.03	0.12	0.38	0.06	0.04	0.6	1.1	2.2
10 Etelä-Savo	0.09	0.20	0.36	0.21	0.15	0.00	0.01	0.04	0.05	0.16	0.16	0.57	0.08	0.14	1.1	2.2	4.4
11 Pohjois-Savo	0.29	0.27	0.25	0.04	0.08	0.02	0.00	0.03	0.04	0.06	0.09	0.37	0.11	0.11	0.9	1.8	3.5
12 Pohjois-Karjala	0.16	0.15	0.14	0.02	0.05	0.01	0.00	0.02	0.02	0.03	0.05	0.20	0.06	0.06	0.5	1.0	2.0
13 Keski-Suomi	0.21	0.19	0.21	0.01	0.06	0.01	0.01	0.00	0.02	0.05	0.09	0.24	0.09	0.12	0.7	1.3	2.6
Total	1.9	2.4	2.9	0.9	1.1	0.3	0.1	0.1	0.4	0.6	1.3	3.0	0.9	1.0	8.5	17.0	34.1

[a]Province numbers used by Statistics Finland; province name in Finnish.
Three risk estimates (lower, central, and upper) were calculated using corresponding relative risk (RR) values from the PM epidemiology.

Table 3. Poisson's estimates for relative daily mortality presented as % change per 10 μg/m^3 of PM.

Lag	Avg	RR	95% confidence interval	
		(%/10 μg/m^3)	%/10 μg/m^3	%/10 μg/m^3
0 day	24 h	0.8	−3.5	5.3
1 day	24 h	1.0	−3.3	5.5
2 day	24 h	1.9	−2.4	6.4
3 day	24 h	1.9	−3.5	7.6
0–4 days	5 days	2.1	−6.9	12

Avg, averaging time.

province is a combination of the size of population and the exposure level listed in Table 1. Highest contribution (3.5 cases) was associated with Uusimaa (no. 1) containing the Metropolitan area of Helsinki, due to the largest population and relatively high exposure, followed by provinces Kymenlaakso (no. 8; 2.5 cases), Pirkanmaa (no. 6, 2.4 cases), and Etelä-Savo (no. 10, 2.2 cases). The result for Pirkanmaa is related to high population, whereas the two others represent high exposures.

Epidemiology

Relative risk for daily mortality (RR) varied between 0.8% and 2.1% per additional 10 μg/m^3 of $PM_{2.5}$ exposure in the various regression model calculated (Table 3). Lowest values were observed for same day concentration (lag 0) and highest values for lags 2–3 and for 5-day average concentration. All regression coefficients were statistically nonsignificant as could be expected already from the theoretical considerations. Nevertheless, the consistency of the results over the various lags and averaging times investigated suggests an association.

Discussion

Statistical Power

The epidemiological attempt to estimate the relative mortality risk produced results that were in line with the other studies, but far from statistical significance due to the limited duration of the episode. A much longer single episode or a pooled data from multiple episodes would be needed to detect effects of PM from wildfires more clearly. Standard deviation of the daily mortality in the current study population (3.4 million) was 7.25 for the 2-week period and the estimated daily mortality (central estimate) was 1.2 cases per day (17 cases/14 days). Crude calculation for the needed data to reduce the standard error of the additional daily mean mortality to below 1 cases (i.e., to smaller than the estimated potential mortality of 1.2 cases per day) would require 7.25^2 or 52 days of similar episodic conditions. Therefore, it seems reasonable to assume that by pooling the episodes from 5 to 10 years should yield sufficient data to obtain statistically significant results on daily mortality.

Intermediate Time Scale Effects for Multiday Episodes

Recent scientific literature has suggested that the traditional split used in epidemiology to chronic (one to several years) and daily effects may not fully characterize the temporal variability in toxic effects of PM. The exposure–response values presented for chronic exposures are one order of magnitude higher than those presented for daily exposures, and it is quite reasonable to assume, that there is a more continuous transition between short- and long-term effects than depicted by these two points (Pope and Dockery, 2006).

If this is the case, a substantially increased $PM_{2.5}$ concentration for consecutive days during a period of 2 weeks would be likely to lead to some cumulative effects. According to previous comparisons of daily and intermediate time scale (5–20 days) mortality estimates for PM (Pope and Dockery, 2006), it can be estimated that these cumulative effects could double the daily mortality estimate.

Extent of the Wildfire Problem

The current analysis covers only 2 weeks, but the data shown by Niemi et al. (2005) indicated that substantially longer period was affected by the wildfires. Although the levels were not quite as high throughout the 6 weeks, the estimated mortality would probably more than double if the whole period was accounted for. Niemi et al. (2006) found that in 2001–2005, there have been on the average two wildfire episodes per year affecting Helsinki. In contrast, in August 2002, the devastating air quality and population health problems in Moscow got wide attention and, for example, air traffic was stopped because of the degraded visibility caused by the fires. Poland, Germany, Denmark, and Sweden were affected for variable periods of time as indicated by satellite images (data not shown). The global health risks of the fires are by no means captured by the current analysis. Moreover, it has also been suggested that the climate change may increase the occurrence and extent of forest fires in the future (Westerling et al., 2006).

Conclusion

The current work investigated the population exposures to smoke originating from East European wildfires that affected the air quality in Finland in 2002. During the studied episode, 3.4 million people in Finland (total population 5.3 million) were exposed to elevated $PM_{2.5}$ levels. The mean exposure level for 2 weeks was 15.4 μg/m^3 above the seasonal background.

Population mortality risk was estimated based on the exposures, background mortality, and the relative risks estimated for general urban fine particles. Central estimate for the associated additional mortality was 17 cases (9–34 cases as lower and upper estimates, respectively).

Observed increase in daily all-cause mortality in the time series analysis was not statistically significant due to the short duration of the episode, but was in line with the effect estimates reported elsewhere for urban PM air pollution in general.

Acknowledgements

We thank the Helsinki Metropolitan Area Council (YTV) and the environmental offices of the cities of Kuopio and Lappeenranta for providing us with the air quality monitoring data, the Finnish Meteorological Institute for air quality data from the other cities and IC analysis of the $PM_{2.5}$ filters, and Juhani Tarhanen from the University of Kuopio for data on VOC concentrations. Diane Davies and Minnie Wong from the Department of Geography, University of Maryland provided numerical MODIS fire mapping data combining the West and East European Regions. We are thankful also for Peter Wåhlin from the Danish National Environmental Research Institute (NERI) for providing information on the assessment of the episode in Denmark. This work has been supported by intramural funding in KTL.

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