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RESPIRATORY HEALTH ISSUES IN THE ASIA–PACIFIC REGION

The effects of bushfire smoke on respiratory health

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ABSTRACT

Bushfire smoke has the potential to affect millions of people and is therefore a major public health problem. The air pollutant that increases most significantly as a result of bushfire smoke is particulate matter (PM). During bushfire smoke episodes, PM concentrations are usually much higher than urban background concentrations, at which effects on respiratory health have been observed. The smoke can cover large areas including major cities and even small increases in the risk of respiratory health effects can cause large public health problems.The association between respiratory morbidity and exposure to bushfire smoke is consistent with the associations found with urban air pollution. Although using different methods, all studies looking at Emergency Department presentations in relation to a bushfire smoke event have found associations and most studies have also found an association with hospital admissions. However, only a few studies have distinguished between the effects of bushfire PM_{10} (particles with a median aerodynamic diameter less than 10 μm) and background PM_{10}. These studies suggest that PM_{10} from bushfire smoke is at least as toxic as urban PM_{10}, but more research is needed.

Key words: bushfire, forest fire, respiratory health, wildfire.

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INTRODUCTION

There are different terms around the world for bushfires, which are also called wildfires, forest fires, vegetation fires or brushfires. In this paper, we will use the term bushfire (mainly used in Australia), by which we mean fire that occurs in forest, scrub or grassland anywhere in the world.

Bushfires occur on every continent except Antarctica. Bushfire smoke has always been a part of Australia and Asia since human settlement. Fires mainly occur in climates where there are long dry spells. The Asia–Pacific region has experienced some of the worst bushfire events on record. For example, the 1997 Indonesian fires burnt over 5 million hectares, and 173 people lost their lives in the 'Black Saturday' 2009 fires in Australia. Health effects of bushfires go beyond the immediate severe health effects, such as loss of life or burns. During bushfires, large areas of land can be covered in layers of smoke, hundreds of kilometres away from the actual fires (Fig. 1), potentially involving major cities and exposing millions of people to bushfire smoke. Even small increases in risk could cause large public health problems.

Bushfire smoke, like background urban air pollution, consists of pollutants which can affect health. It contains large amounts of particulate matter (PM), but also polycyclic aromatic hydrocarbons, carbon monoxide, aldehydes, organic acids, volatile organic compounds and ozone following reactions in sunlight.[1] The pollutant most consistently elevated due to bushfire smoke is PM,[2,3] most commonly measured as PM_{10} (particles with a median aerodynamic diameter less than 10 μm).

In the past decade, interest has shifted towards the smaller fraction of PM_{10}, that is, $PM_{2.5}$ (particles with a median aerodynamic diameter less than 2.5 μm) which are able to penetrate deeper into the alveolar region of the lung and can potentially be more harmful.[4] Currently, there is only an Advisory Reporting Standard for $PM_{2.5}$ in Australia. However, very few studies on bushfire smoke and health have been able to directly assess effects of $PM_{2.5}$, simply because this fraction is not as easily measured as PM_{10}. Although 24-h gravimetric measurements of $PM_{2.5}$ are feasible,

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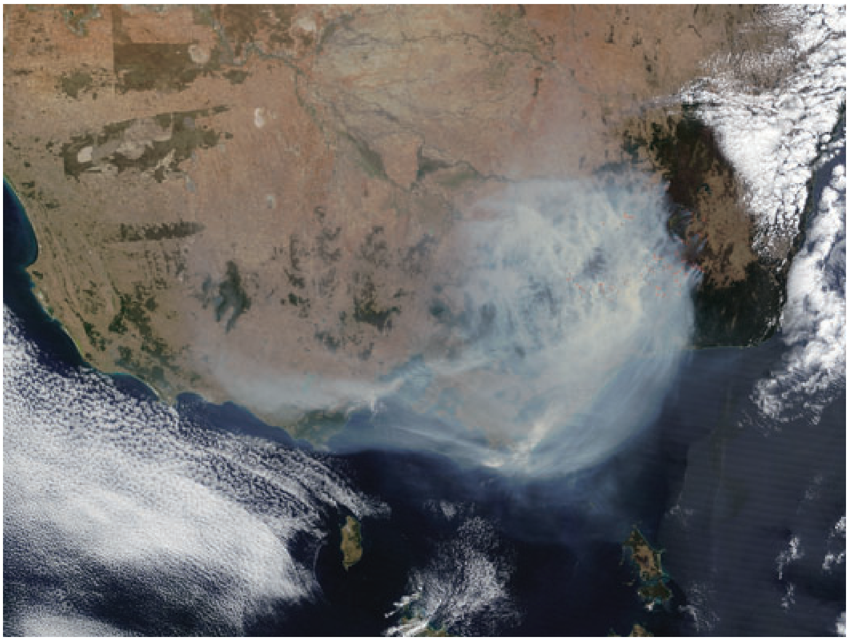

Figure 1 Satellite image made on 10/01/2003 showing south-east of Australia during a bushfire event. The locations of the fires are marked red (courtesy of Jeff Schmaltz, MODIS Rapid Response Team, National Aeronautics and Space Administration/Goddard Space Flight Center).

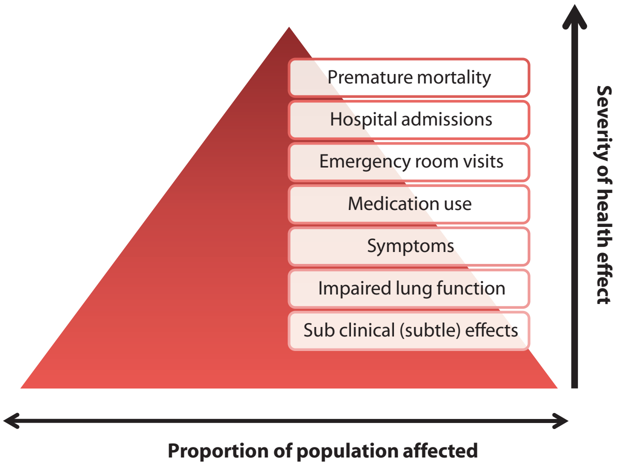

Figure 2 The air pollution health effects pyramid (adapted from American Thoracic Society 2000).[43]

real time measurement requires more complex equipment such as Tapered Element Oscillating Microbalances.

Urban air pollution, and especially PM, has been associated with a wide range of health effects, including exacerbations of respiratory symptoms, declines in lung function, asthma attacks, emergency department (ED) presentations, hospital admissions and premature mortality.[5,6] In fact, ambient PM air pollution has been estimated to be responsible for at least 0.8 million premature deaths and 6.4 million years of life lost worldwide.[7] The health effects associated with particulate air pollution have been observed at levels well below current air quality standards. Table 1 presents the air quality standards for the countries covered in this review. During bushfire smoke episodes, PM concentrations several times above background urban concentrations can occur, with air quality standards commonly being exceeded. This then raises the question: If respiratory effects are observed well below current air quality standards, what health effects can be expected when air pollutant concentrations are significantly elevated due to bushfire smoke?

In this review, we will summarize the literature on the respiratory health effects of bushfire smoke. We will first summarize the literature available in the Asia–Pacific region, followed by studies from North America and Europe. Those studies with stronger study designs and rigorous analysis will be discussed in more detail.

We have only included peer-reviewed published studies which have investigated the association between bushfire events and respiratory morbidity. Some of these studies looked at other health outcomes such as cardiovascular effects, but for the purpose of this review we have only focused on respiratory outcomes. In Table 2, 3 and 4, we have included risk estimates for those studies which measured PM concentrations and related this to the health risks. The studies have used different methods to analyse their data ranging from simply comparing health events before and during a bushfire smoke episode, to more sophisticated statistical models. Case-crossover studies and time series represent different approaches to define associations between exposure to ambient air pollution and health events over time.[20]

AUSTRALIA

Around Australia, studies of the effect of bushfire smoke on respiratory health have been done in

Table 1 Air quality standard for PM for countries where studies have been conducted and the WHO AQG

	PM_{10}	Allowable exceptions	$PM_{2.5}$	Allowable exceptions
WHO AQG[†]	50 μg/μm³ avg per day 20 μg/m³ avg per year	—	25 μg/μm³ avg per day 10 μg/m³ avg per year	—
Australia	50 μg/m³ avg per day	5 days per year	25 μg/m³ avg per day[‡] 8 μg/m³ avg per year[‡]	—
Indonesia	150 μg/m³ avg per day	—	—	—
Malaysia	150 μg/m³ avg per day 50 μg/m³ avg per year	—	—	—
Singapore	150 μg/m³ avg per day	—	35 μg/m³ avg per day 15 μg/m³ avg per year	—
European Union[§]	50 μg/m³ avg per day 40 μg/m³ avg per year	35 days per year	—	—
USA	150 μg/m³ avg per day	1 day per year (on average over 3 years)	35 μg/m³ avg per day 15 μg/m³ avg per year	The 3 year average of the 98th percentile of 24-h PM is not allowed to exceed 35 μg/m³

[†] The World Health Organisation assists countries in reducing the health effects of air pollution by providing guidance to countries in setting their standards.
[‡] $PM_{2.5}$ is only an advisory reporting standard in Australia.
[§] Lithuania has adopted the European Union limit value.
Avg, average; PM, particulate matter; $PM_{2.5}$, particles with a median aerodynamic diameter less than 2.5 μm; PM_{10}, particles with a median aerodynamic diameter less than 10 μm; WHO AQG, World Health Organisation Air Quality Guidelines.[8]

Melbourne,[9] Sydney,[10–14] Brisbane[21] and Darwin (Table 2).[16–19]

Victoria

As for most of the Australian studies, Tham *et al.*[9] used a time series approach to investigate the effects of PM_{10}, Airborne Particle Index (API representing fine particulate pollution 0.1–1 μm in diameter) and ozone on respiratory-related ED visits and hospital admissions during a 6-month bushfire season(2002–2003). Figure 1 shows a satellite image of the extensive smoke plume covering part of south-east Australia during this bushfire season. No associations were found in the Gippsland region of Victoria. However, the lack of association might be due to lack of statistical power as a result of a small population size or because those in rural areas lived further away from hospitals and were therefore more likely to go to primary health-care providers.

Nonetheless, this study found an association between PM_{10} and ED visits after adjusting for day-of the week, temperature and humidity. An increase of 9.1 μg/m³ in PM_{10} was associated with an increase in respiratory ED attendances of 1.8%. The associations with API and ozone were not significant. This study was done in a bushfire season period with fires burning for 2 of the 6-month study period. Although it is likely that a large amount of PM_{10} was due to bushfire smoke, a limitation of this study was that the association found could not be attributed solely to bushfire PM_{10}. Two other longitudinal Australian studies from Sydney[14] and Brisbane[21] covered several years and did try to attempt to separate bushfire PM_{10} from background PM_{10}.

New South Wales

Several studies investigating the respiratory effects of bushfire smoke have been conducted in Sydney, with conflicting results. Two early studies investigated exposure to bushfire smoke in Sydney for the 1994 fires. They did not find an increase in emergency visits for asthma.[10,11] The average daily air particulate concentration was not given, but daily PM_{10} levels exceeded 150 μg/m³. The maximum hourly PM_{10} reading in Sydney was 250 μg/m³.[11] Cooper and colleagues[10] compared numbers of asthma ED visits in three inner-city hospitals for the month of January and divided this into three time periods. They did not find any significant difference between before, during or after the bushfires. Statistical power was an issue as the total number of ED presentations for the study period was less than 100. Complex statistical modelling was not used for this comparison and no confounding factors were considered.

The same bushfire period was investigated by Smith *et al.*[11] using ED presentations in western Sydney. The authors used two different analytical methods which would have been able to detect an increase in asthma presentations of 50% for the bushfire period. However, they also did not find any increase in ED presentations for the bushfire period for the week of the bushfires compared to the same

Table 2 Peer-reviewed studies investigating the association between bushfire smoke events and respiratory health effects in Australia

Location	Study	Study period	Study area	Exposure variable	Health outcome and study population	Analytical methodology	Study result
Australia							
Victorian fires, 2002–2003	Tham *et al.*, 2009[9]	October 2002–April 2003	Melbourne and Gippsland region	PM_{10}, API	ED presentations and hospital admissions for respiratory disease	Time series analysis adjusting for temperature, humidity and day of the week	A 9.1 $\mu g/m^3$ increase in PM_{10} was associated with a 1.8% (95% CI: 0.4–3.3%) increase in respiratory-related ED presentations in Melbourne. No association with hospital admission was found after adjustment for confounders.
New South Wales fire, 1994	Cooper *et al.*, 1994[10]	January 1994	Sydney	—	ED presentations for asthma at three inner-city hospitals	No details given	No increase in asthma presentations compared with before the event.
	Smith *et al.*, 1996[11]	January 1994	Western Sydney	PM_{10}	ED presentations for asthma at seven hospitals	Comparisons between case and control periods and time series analysis[†]	No association between asthma presentations and PM_{10} from bushfire smoke.
	Jalaludin *et al.*, 2000[12]	January 1994	Sydney	PM_{10}	PEFR in 32 children with wheeze	Time series analysis adjusted for temperature, humidity, time spent outdoors and pollen count	No association between the bushfire period or daily PM_{10} and evening PEFR was found.
	Jalaludin *et al.*, 2004[13]	January 1994	Sydney	PM_{10}	Evening recorded symptoms (wheeze, dry cough and wet cough) and beta agonist use in 32 children from three schools in Sydney with a history of wheeze	Time series analysis adjusted for temperature, humidity, number of hours spend outdoors, pollen count and inhaled corticosteroid use	Increase of 35 $\mu g/m^3$ same day bushfire PM_{10} was associated with an evening wet cough (OR 2.04, 95% CI: 1.37–3.04). None of the other symptoms were significant and neither was medication use.
New South Wales fires 1994–2002	Morgan *et al.*, 2010[14]	1994–2002	Sydney	PM_{10}	Hospital admissions for respiratory disease	Time series analysis adjusting for temperature, humidity, day of week and flu epidemic	A 10 $\mu g/m^3$ increase in bushfire PM_{10} was associated with a 1.24% (95% CI: 0.22–2.27%) increase in all respiratory hospital admissions.
Queensland fires	Chen *et al.*,2006[15]	July 1997–December 2000	Brisbane	PM_{10}	Hospital admissions for respiratory disease	Time series analysis adjusted for average temperature, day of the week, seasonality, long-term trends (years) and influenza	Comparing hospital admission on high PM_{10} days (>20 $\mu g/m^3$) to low PM_{10} days (<15 $\mu g/m^3$) showed an increase in respiratory hospital admissions of 19% (95% CI: 9–30%) for bushfire days and of 13% (95% CI: 6–23%) for background days.

Table 2 *Continued*

Location	Study	Study period	Study area	Exposure variable	Health outcome and study population	Analytical methodology	Study result
				Australia			
Northern Territory fires	Johnston *et al.*, 2002[16]	April–October 2000	Darwin	PPM_{10}	ED presentations for asthma	Time series analysis adjusting for weekly influenza and weekday versus weekend day	There was an increase in asthma presentations when average daily $PM_{10} \geq 40\ \mu g/m^3$ was compared to the baseline category of $<10\ \mu g/m^3$ (Rate ratio: 2.39, 95% CI: 1.46–3.90).
	Johnston *et al.*, 2007[17]	April–November of 2000, 2004 and 2005	Darwin	PM_{10}	Hospital admissions for respiratory diseases	Case-crossover analysis adjusted for weekly influenza rate, days with rainfall >5 mm, temperature and humidity for same day and previous 3 days and public holidays	An increase of $10\ \mu g/m^3$ in PM_{10} was non-significantly associated with hospital admissions for all respiratory conditions (OR 1.08, 95% CI: 0.98–1.18), and significantly associated with COPD admissions (OR 1.21. 95% CI: 1.00–1.47). For indigenous people all effect sizes were larger, in particular for COPD presentations (OR 1.98, 95% CI: 1.10–3.59).
	Hanigan *et al.*, 2008[18]	April–November from 1996 to 2005	Darwin	PM_{10} (measured and estimated)	Hospital admissions for respiratory diseases	Time series analysis adjusted for indigenous status, influenza epidemics and holidays	An increase of $10\ \mu g/m^3$ same day (estimated) PM_{10} was associated with a non-significant 4.81% (95% CI: −1.04–11.01%) increase in total respiratory admissions. However this association was significant for indigenous people with a 9.40% increase (95% CI: 1.04–18.46%).
	Johnston *et al.*, 2006[23]	April–October 2004	Darwin	PM_{10} and $PM_{2.5}$	Asthma symptoms and medication use in 251 adults and children with asthma	Time series analysis adjusted for temperature, humidity, pollen and spore counts, weekly influenza rates, weekends and holiday periods	An increase in $10\ \mu g/m^3$ was associated with an increase in risk of becoming symptomatic of 24% (95% CI: 11–39%) and 15% (95% CI: 7–23%) for PM_{10} and $PM_{2.5}$ respectively. PM_{10} and $PM_{2.5}$ were significantly associated with starting a course of oral steroids and $PM_{2.5}$ with starting reliever medication.

† No confounding factors, like temperature and humidity included in the analysis.

API, Airborne Particle Index; ED, emergency department; PEFR, peak expiratory flow rate; $PM_{2.5}$, particles with a median aerodynamic diameter less than 2.5 μm; PM_{10}, particles with a median aerodynamic diameter less than 10 μm.

Table 3 Peer-reviewed studies investigating the association between bushfire smoke events and respiratory health effects in Asia

Asia							
Location	Study	Study period	Study area	Exposure variable	Health outcome and study population	Analytical methodology	Study result
1997 Indonesian fires	Aditama, 2000[26]	September 1997–June 1998	Indonesia	—	Routine data from governmental health facilities	Comparing cases between September 1997 and June 1998 with the same period in 1995–1996[†‡]	Increase in cases of acute respiratory infection and bronchial asthma.
	Emmanuel, 2000[27]	August–November 1997	Singapore	PM_{10}	ED presentations, out-patient attendance, hospital admissions for haze-related conditions and mortality	Time series analysis adjusting for temperature, relative humidity, rainfall and wind speed	An increase in 100 $\mu g/m^3$ PM_{10} was significantly associated with a 12% increase in outpatient attendance for upper-respiratory tract illness, 19% for asthma and 26% for rhinitis. There were also increases in ED attendances for haze related conditions (no risks presented in paper). No increase in hospital admission or mortality was found.
	Mott *et al.*, 2005[28]	January 1995–December 1998	Kuching, Malaysia	—	Hospital admission to seven hospitals for respiratory disease	Time series analysis comparing 1997 bushfire period with forecasted estimates using pre-fire periods, adjusting for monthly seasonal components	Increase in respiratory hospitalizations during the bushfire period, particularly due to asthma.
	Sastry *et al.*, 2002[29]	1996–1997	Kuala Lumpur and Kuching, Malaysia	PM_{10}[§]	Mortality	Time series analysis[†]	Daily increase in haze levels associated with increased mortality rates for older individuals, although not significant for respiratory mortality.[§]
	Kunii *et al.*, 2002[24]	September 1997	Jambi, Indonesia	—	Respiratory symptoms in 492 children and adults	Reporting of percentage of respondents with respiratory symptoms[†‡]	A total of 91% of respondents reported respiratory problems due to the smoke haze caused by the bushfires.
	Brauer and Jamal, 1998[30]	August and September 1997	Kuala Lumpur, Malaysia	—	Hospital admissions to major hospitals for asthma and respiratory infection	Comparing September admissions to August[†‡]	Increase in hospital admission for asthma and acute respiratory infection.
	Awang *et al.*, 2000[31]	September 1997	Selangor, Malaysia	—	Hospital admissions for respiratory disease	Comparing September figures to June figures[†]	Increase in hospital admissions for total respiratory disease, and in particular asthma and acute respiratory infection.
1994 Indonesian fires	Chew *et al.*, 1995[32]	September–October 1995	Singapore	PM_{10}	ED presentations for acute childhood asthma in children <12 years in two large hospitals in Singapore	Time series analysis adjusted for meteorological variables and 'other factors' (not further specified)	Increase in daily PM_{10} associated with increase in asthma emergency presentations (no risks presented in paper).

† No confounding factors, like temperature and humidity included in the analysis.
‡ No statistical significance testing.
§ PM_{10} was only used to identify high air pollution days (hence no risks presented for increases in PM).
ED, emergency department; PM, particulate matter; $PM_{2.5}$, particles with a median aerodynamic diameter less than 2.5 μm; PM_{10}, particles with a median aerodynamic diameter less than 10 μm.

Table 4 Peer-reviewed studies investigating the association between bushfire smoke events and respiratory health effects in North America and Europe

Location	Study	Study period	Study area	Exposure variable	Health outcome and study population	Analytical methodology	Study result
North America							
1987 Californian fires	Duclos *et al.*, 1990[33]	August 1987	California	TSP, PM_{10}	ED presentations to 15 hospitals in 6 Californian counties	Compared the 2.5 weeks of bushfire smoke to a control period†	Increase in ED presentations during the fire period for asthma, COPD, laryngitis, sinusitis and other respiratory infections.
1999 Californian fires	Mott *et al.*, 2002[34]	August–November 1999	Humboldt County, California	—	Medical visits for respiratory illnesses to a local medical centre	Comparing the bushfire period visits to the previous year†	Medical visits for respiratory illnesses increased by 52% (217) visits during the fire period compared to the previous year.
2003 Californian fires	Viswanathan *et al.*, 2006[35]	October–November 2003	San Diego County	PM_{10}	ED presentations to 15 hospitals in San Diego County for respiratory diseases	Comparing 2 weeks during and following the bushfire to 1 week before the fire†‡	Increase in ED presentations during the fire period for asthma, respiratory problems (without fever) and smoke inhalation.
	Kunzli *et al.*, 2006[38]	October–November 2003	California	PM_{10} and retrospective reporting on smell of fire indoors	Respiratory symptoms (including wheeze, cough and asthma attacks), medication usage and physician visits during the 2-week fire period for 4609 participants in the Children's Health Study in 16 communities	Mixed effects models adjusted for gender, ethnicity, educational levels of the parents, asthma status	Increase in all respiratory symptoms for those who reported an indoor fire smell of more than 6 days.
1998 Florida fires	Sorenson *et al.*, 1999[39,40]	June–July 1998	Volusia and Flagler counties in Florida	—	ED presentations and hospital admissions at eight hospitals for respiratory conditions	Comparing bushfire period (1 June–6 July 1998) to the same period the year before†‡	ED presentations during the bushfire period increased by 91% for asthma (from 77 to 147), 132% for bronchitis with acute exacerbation (from 28 to 65), 37% for chest pain (from 218 to 299). Changes in the number of hospital admissions were minimal.
2003 British Columbia fires	Moore *et al.*, 2006[41]	1993–2003	Regions of Kelowna and Kamloops in British Columbia, Canada	PM_{10} and $PM_{2.5}$	Physician visits billed to respiratory disease diagnosis code	Comparing three weeks forest fire period with aggregated rates of same weeks in 10 previous years†	Significant increase in weekly physician visits for respiratory diseases during the fire period compared to same weeks in previous year for the Kelowna region. No significant effects were found for Kamloops (Kamloops experienced lower PM concentrations than Kelowna).
Europe							
2002 Lithuanian fires	Ovadnevaite *et al.*, 2006[42]	August–September 2002	Vilnius City, Lithuania	—	Presentations at eight Vilnius health centres for respiratory diseases	Comparing increase in presentations from 1–18 September 2002 to July 2002†‡	The number of presentations for respiratory diseases on average over all eight health centres was 3.1 times higher in September compared to July (ranging from 1.5 times in one health centre to 20.5 times in another).

† No confounding factors, like temperature and humidity included in the analysis.

‡ No statistical significance testing.

ED, emergency department; PM, particulate matter; $PM_{2.5}$, particles with a median aerodynamic diameter less than 2.5 μm; PM_{10}, particles with a median aerodynamic diameter less than 10 μm. TSP, total suspended particles.

week the previous year. Considering the small effects found in other studies, there was not enough power to detect an effect.

Another study conducted during the same period investigated the effect of bushfire smoke on respiratory symptoms and peak expiratory flow rate (PEFR) in children.[12,13] This longitudinal study was conducted in Sydney during January 1994 when children (average age 9 years) were measuring their PEFR and reporting on symptoms (wet cough, dry cough and wheezing) and medication use. Bushfire PM_{10} was calculated by subtracting the average PM_{10} concentration for January 1994 excluding the bushfire period from total daily PM_{10}. The PEFR analyses in 32 children with a history of wheeze found no association. An increase of 35 $\mu g/m^3$ in same day bushfire PM_{10} was significantly associated with a twofold increase in evening wet cough. Although no associations were found with dry cough, wheezing or medication use, this might have been expected as these symptoms have shown to be associated with urban background PM_{10}. The study findings may have been influenced by limited statistical power.

A more recently published study by Morgan *et al.*[14] investigated respiratory hospital admissions with an extended time series analysis from 1994 to 2002. They divided PM_{10} into bushfire PM_{10} and 'non-bushfire' (background) PM_{10}. It was assumed that on days where city-wide 24-h average PM_{10} was greater than the 99th percentile for the study period, the PM_{10} was primarily from bushfires. On these days bushfire PM_{10} was calculated to be the difference between total PM_{10} and estimated background PM_{10}. Over the 8.5-year study period, 32 bushfire days were identified, resulting from 14 different bushfire events. Analyses were done for three age groups, and models adjusted for temperature, humidity, day of the week and presence of an influenza epidemic.

Both bushfire and background PM_{10} were associated with small but significant increases in respiratory hospital admissions for Lag 0 (24-h average concentration on the day of the hospital admissions). However, no significant associations were found with 24-h average concentration on 1, 2 and 3 days before the hospital admission. When the analysis was restricted to respiratory admissions of people over 65 years of age, bushfire PM_{10} showed a more consistent association than background PM_{10}. The greatest differences in effect between bushfire PM_{10} and background PM_{10} were in admissions for COPD among those over 65 years of age and for asthma admissions for those between 15 and 64 years of age. No associations were found with background PM_{10}, but significant associations were found for both outcomes with bushfire PM_{10}. The COPD admissions for those over 65 years were consistently associated with bushfire PM_{10}, with a 10 $\mu g/m^3$ increase in bushfire smoke resulting in an increase in hospital admissions of 3.3%. Asthma admissions for the 15–64 year age group increased by 5.0% for a 10 $\mu g/m^3$ increase in bushfire PM_{10}. Perhaps surprisingly, no association was found for asthma admissions among children 1–14 years of age.

In the same study, no association was found between bushfire PM_{10} and respiratory mortality. However, the number of daily respiratory deaths in Sydney was low (with a median of 5) and this limited the power of the analysis to find an effect even if one was present. Background PM_{10} did not show an association with respiratory mortality either, even though this analysis had more power to detect an effect.

Queensland

Another time series study from Brisbane investigated the association between bushfire PM_{10} on respiratory hospital admissions.[21] The authors used three categories for average daily PM_{10} in the analysis. A bushfire day included an event where more than 1 ha of area was burnt in the Brisbane region. During the study period there were 452 bushfire days (35% of all days). The daily average PM_{10} concentration over 452 bushfire days was 18 $\mu g/m^3$ (range 8–61 $\mu g/m^3$) and for the 828 background days 15 $\mu g/m^3$ (range 5–58 $\mu g/m^3$). These mean values were well below the current Australian air quality standards (see Table 1). There was an increase in respiratory hospital admissions of 19% for bushfire days and of 13% for days without the presence of bushfire smoke. A limitation of this study is that data were obtained from a PM_{10} monitor which was upwind of most bushfires, therefore probably underestimated the exposure on bushfire days. Nonetheless, on bushfire days the association with respiratory hospital admission was at least as great as with urban background PM_{10}. There was a suggestion of a greater effect of bushfire PM_{10}, but this would need further confirmation.

Northern Territory

Darwin provides a unique opportunity to study the effects of bushfire PM because approximately 95% of PM_{10} is due to fire smoke for up to 8 months a year, and only 5% is made up of industrial and motor vehicle emissions.[22] The first study examined the association between ED presentations for asthma and PM_{10} during the 2000 bushfire period.[16] The average daily PM_{10} was 21 $\mu g/m^3$ (range 2–70 $\mu g/m^3$), and there were 7 days in which the National Environment Protection Measures (NEPM) for PM_{10} was exceeded during this period. Four categories of PM_{10} concentrations were studied and analyses were adjusted for weekly rates of influenza and for weekday versus weekend. There was a 1.2-fold increase in asthma presentations for every 10 $\mu g/m^3$ increase in PM_{10}.

Another study by Johnston and colleagues[17] from Darwin investigated the association between hospital admissions for all respiratory diseases and bushfires during the 2000, 2004 and 2005 seasons combined. Unfortunately, no PM_{10} measurement data were available for the years 2001 to 2003. This is the only study on bushfire smoke which has used the case-crossover design that eliminates confounding by day of week and seasonal trends in the exposure variables. An increase of 10 $\mu g/m^3$ in PM_{10} was most strongly associated with COPD and asthma. For indigenous people all effect sizes were larger, in particular for COPD presentations.

Hospital admission for respiratory diseases in Darwin were further investigated by Hanigan *et al.*[18] who used indirect estimates of PM_{10}, derived from visibility data for the bushfire periods in Darwin (when no direct PM measurements were available). They analysed 1996 to 2005 data and found that a 10 μg/m^3 increase in estimated PM_{10} was associated with a non-significant increase in total respiratory admissions on the same day. However, this association was significant for indigenous people with a 9.4% increase. Asthma, COPD and respiratory infections did not show significant associations, but this could be due to small numbers and a lack of statistical power.

A cohort study from Darwin followed 251 adults and children with asthma over the 2004 bushfire period.[23] Participants kept a daily diary where they recorded their asthma symptoms, medication use, missed school or work days and health-care visits for asthma. Analyses were adjusted for temperature, humidity, pollen and spore counts, weekly influenza rates, weekends and holiday periods. PM_{10} levels were rather low and there were no occasions when the NEPM were exceeded during the study period. Significant associations were found with PM_{10} and $PM_{2.5}$ and development of symptoms. An increase in 10 μg/m^3 was associated with an increase in asthma symptoms of 24% for PM_{10} and 15% for $PM_{2.5}$. PM_{10} and $PM_{2.5}$ were also significantly associated with the need for a course of oral steroids and $PM_{2.5}$ with increased reliever medication. Due to the low PM concentrations, high correlations and small effects it was not possible to distinguish between PM_{10} and $PM_{2.5}$ effects.

ASIA

One of the largest forest fire episodes for which effects on community health have been reported occurred in Indonesia in 1997. Approximately 5.3 million hectares were burned during these fires[24] and the severity and extent of the associated smoke haze affected about 300 million people across the region.[25] Several studies investigated the effect on respiratory health of the populations living in cities across South-East Asia (Table 3). However, only one study was done in Indonesia, where the actual fires occurred.[26] Routine data from government health facilities were used to compare cases between September 1997 and June 1998 with the same period in 1995–1996 and increases were reported for acute respiratory infection and bronchial asthma. For example, in south Kalimantan the number of acute respiratory infections increased by 1.8 times, and in south Sumatra this was 3.8 times.

A further seven published studies were done outside Indonesia.[24,26–32] For example, across the strait in Singapore, an increase of 100 μg/m^3 in PM_{10} was associated with a 19% increase in asthma and 12% increase in upper respiratory tract illnesses. However, this study did not find an association with hospital admissions or mortality.[27] A study looking at hospital admission in the Kuching region of Malaysia found significant increases in respiratory hospitalizations particularly due to asthma, during the bushfire period compared to previous year[28] but no air pollution concentrations were measured in this study.

As Table 3 shows, even studies done outside Indonesia and some distance away from the fires found an effect on respiratory health during smoke haze episodes in South-East Asia. Increases were found for emergency admissions for all respiratory diseases or asthma alone, and in most cities increases were found for hospital admissions for respiratory diseases but there was no significant effect on respiratory mortality.

NORTH AMERICA

Hospital emergency or local medical centre visits increased after the California wildfires in 1987,[33] 1999[34] and 2003.[35] There was a unique opportunity during the 2003 California fires, when regions that participated in the Children's Health Study[36,37] were affected by bushfire smoke. The resulting analysis found that the smell of bushfire penetrated indoors for more than 6 days, respiratory symptoms (sore throat, cough, bronchitis, wheezing and asthma attacks) and medication usage were significantly increased. An important limitation was that both exposure and outcome were reported by participants which could lead to interrelated reporting. Associations were strongest for those without asthma, perhaps because those with asthma were more likely to stay indoors and wear masks during the smoke episode. This study measured 5-day average PM_{10} concentrations during the fire period in each of the 16 participating communities, with concentrations ranging from 30 μg/m^3 to 210 μg/m^3. An increase in 5-day average PM_{10} was associated with dry cough, sore throat and medication use, but no significant associations were found with wet cough, bronchitis, wheezing or asthma attacks.[38]

During the 1998 fires in Florida, increases in weekly respiratory ED presentations were found compared to the same weeks in 1997. This effect was strongest for asthma and acute exacerbations of bronchitis. However, this was not associated with increases in weekly hospital admissions, although the number of hospital admissions during the bushfire period was small. The results from this study should be interpreted with caution as no air quality measurements were reported.[39,40]

The 2003 fires in British Columbia resulted in an increase in weekly rates of physician visits for respiratory diseases in the Kelowna region, but not in the Kamloops region.[41] The absence of effects in Kamloops, could be due to less power to detect an effect as the population is smaller than in Kelowna. Alternatively, it could be due to lower levels of PM_{10} in Kamloops (maximum daily average 150 μg/m^3 cf. 200 μg/m^3). In Kelowna, the largest increases in physician visits for respiratory diseases were observed in the fifth week after the fires began, when PM_{10} levels returned to background levels. This could be either because the respiratory symptoms may take several weeks to develop, or suggest that patients may initially try to manage their symptoms on their own before visiting a physician.

EUROPE

In a study from Lithuania where there was a bushfire episode in 2001, the number of visits to eight health centres in Vilnius for respiratory diseases increased 2.8-fold compared to 1 month when there were no fires.[42] Given the serious bushfires in Greece and elsewhere in southern Europe in recent years, it is surprising that more research has not been reported from this part of the world (Table 4).

DISCUSSION

The peer-reviewed literature to date suggests that there is a modest association between bushfire smoke and respiratory health. For example, a comprehensive Australian study over several years found an increase in hospital admissions of 1.2% for each 10 μg/m^3 increase in PM_{10} from bushfire smoke.[14] Estimating the overall effects of bushfire smoke on asthma, COPD or mortality is complicated because of the different methods used in the studies.

The association between exposure to bushfire smoke and respiratory morbidity is consistent with the associations found with urban air pollution. All studies looking at ED presentations found associations, with either increases during the bushfire period compared to a control period, or when appropriate statistical modelling was used and confounding factors were taken into account. However, only a few studies have attempted to differentiate between the effects of bushfire PM_{10} and background PM_{10}.[14,21] It would be too difficult to perform a meta-analysis of the studies reviewed here, due to the large differences in study design and statistical methods used. Most studies did not directly measure PM concentrations or used estimates of PM. Some studies investigated all respiratory effects and others only looked at asthma. The time period of analysis also differed between studies. Of all the studies carried out, only three from Sydney did not find an association.[10–12] All these have statistical limitations. However we accept the likelihood of publication bias, with positive studies being more likely to be published.

A limitation of studies investigating the health effects of bushfire smoke is that the smoke episodes are usually of short duration. Statistical power could be increased by studying larger populations and/or over longer periods. For example, Tham *et al.*[9] investigated respiratory hospital admissions both in Melbourne and Gippsland during a bushfire season. The average PM_{10} concentrations over the study period for the two locations were similar, but the maximum daily concentrations in Gippsland were larger. The study found a small but significant effect of PM_{10} in Melbourne, but not in Gippsland, likely due to the much larger population in Melbourne and hence greater power to detect an effect. A similar result was seen in two regions in Canada.[41] A significant increase in respiratory physician visits during the fire period was found in the town with the larger population and higher PM_{10} concentrations. Several studies with rather low PM_{10} concentrations did find an effect, but these studies were carried out over years rather than weeks or months.[14,16,21]

The studies of respiratory effects of bushfires have usually focused on outcomes that can be obtained shortly after the bushfire smoke event, simply because episodes are difficult to predict in advance. As a result most research has focused on emergency presentations, hospital admissions or mortality. However, these outcomes are at the tip of the health effects pyramid (Fig. 2). Only a few studies have been carried out on more subtle outcomes, often in relation to studies which were ongoing at the time of an event.[12,13,38] Another issue with studying health effects of bushfire smoke is that they tend to occur in rural areas and if there is not a large city nearby, the population is usually not large enough to determine with confidence whether an effect has occurred.

Some ambient air pollutants are regulated because they are thought to be harmful to health at certain concentrations. In Australia, the National Environment Protection Council sets ambient air quality goals for six pollutants in the NEPM for ambient air quality. These six pollutants are ozone, particles, carbon monoxide, nitrogen dioxide, sulphur dioxide and lead. In Australia, the NEPM for acceptable daily average PM_{10} is 50 μg/m^3. Currently, the NEPM PM_{10} standard is allowed to be exceeded 5 days per year, to accommodate for bushfire smoke. However, during bushfire episodes the standards are often exceeded more than the 'allowable' 5 times.[3] For example, the PM_{10} NEPM target was exceeded on a total of 6 days in the 7-month bushfire period in Darwin in 2000.[16]

There are very clear effects on mortality in urban air pollution studies,[5] but these are not found in the bushfire smoke studies. This could very well be due to a lack of power in mortality analyses. The number of deaths are smaller than the number of ED presentations or hospital admissions (Fig. 2). In addition, bushfire smoke episodes are usually of short duration, compared to the urban air pollution studies which are usually carried out over several years. For example, Vedal and Dutton[44] did not find an association with mortality and exposure to $PM_{2.5}$ or PM_{10}. Even though they studied a population of 2 million people, very high PM concentrations due to wildfire smoke only occurred for 2 days. To be able to detect an effect in this study wildfire smoke $PM_{2.5}$ would have to be more than 10 times more toxic then urban background $PM_{2.5}$.[45] Hanninen *et al.*[46] found a consistent, but non-significant association between mortality and $PM_{2.5}$ during a 2-week bushfire smoke episode This suggested that an effect could be present, but the power of the study was such that significance could not be achieved.

From the evidence available to date, it is difficult to determine whether bushfire smoke PM_{10} is more toxic than background PM_{10}. However, the two studies that attempted to separate bushfire PM_{10} from background PM_{10} suggest that bushfire PM_{10} may have a greater impact on respiratory health than urban background PM_{10},[14,21] in particular for hospital admissions

Box 1 Bushfire: asthma management tips, adapted from the Asthma Foundation of Victoria Information Sheet.

- If you live in a fire danger area, or are likely to be visiting one, discuss the dangers with your local general practitioner and update your personal written Asthma Action Plan accordingly. You should also include asthma management in your fire safety survival plan.
- Always follow your personal written Asthma Action Plan. These instructions help you, your family, carers and neighbours recognize signs of worsening asthma and what action to take to prevent further deterioration.
- Always ensure you have plenty of medication on hand, particularly blue reliever medication. Continue use of your preventer as well.
- If you decide to evacuate, make sure your blue reliever medication goes with you.
- Listen to your local radio station or watch television for updates on fire and smoke conditions in the area.
- When smoke is in the air but a fire is not directly threatening you, minimize the time you spend outdoors in the smoke. Where practical, stay indoors and close all windows and doors.
- Turn on your air conditioner (if you have one) and switch it to 'recycle' or 'recirculate'. This will reduce the amount of smoke coming inside.
- If possible stay in air-conditioned premises. If your home gets uncomfortably hot or is letting in outside air, take an air-conditioned break at a local community library or shopping centre.
- If you are particularly susceptible to bushfire smoke, consider staying with a friend or relative whose house has clean indoor air.
- Everyone should rest indoors and avoid outdoor activity as much as possible. Increased physical activity causes deeper breathing, and a greater number of fine particles are breathed deep into the lungs.
- If the bushfire event lasts a long time, take advantage of any breaks in smoky conditions to air out your home, but remember to close off the house again when conditions deteriorate.
- If you develop symptoms such as shortness of breath, coughing or wheezing, chest tightness follow your written Asthma Action plan. If your reliever medication is not reducing your asthma symptoms, seek medical attention without delay and start Asthma First Aid.

in those over 65 years of age, and asthma admissions in younger adults.[14] These results are consistent with a review of studies of PM_{10} and asthma that found greater risks when wood combustion was considered to be the main source of PM.[47]

Bushfires are expected to increase in the future as a result of climate change, and this will result in a larger public health issue. Only a few thorough population studies have been carried out on the issue of bushfire smoke and respiratory health, and more research is needed to be able to properly advise policy makers and clinicians of appropriate public health messages and measures to put in place. However, the evidence in this review supports the current advice given by the Asthma Foundation (Box 1).

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