CURRENT OPINION

Measures of forest fire smoke exposure and their associations with respiratory health outcomes

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Purpose of review
Exposure to forest fire smoke is episodic, which makes its health effects challenging to study. We review the newest contributions to a growing literature on acute respiratory outcomes.

Recent findings
Smoke exposure was associated with increases in self-reported symptoms, medication use, outpatient physician visits, emergency room visits, hospital admissions, and mortality. The associations were strongest for the outcomes most specific to asthma.

Summary
Studies with varied approaches to exposure assessment and varied measures of respiratory outcomes were consistent among themselves, and consistent with most previous work.

Keywords
asthma, biomass, forest fire smoke, respiratory

INTRODUCTION

Forest fires occur throughout most of the world, but their frequency, intensity, and size vary according to complex ecologic and human factors [1]. Forest fires also have a complex relationship with the global climate, whereby smoke may contribute to atmospheric warming [2] and cooling [3], but overall warming may increase the fire risk [4,5]. Indeed, there is growing concern about the incidence of so-called mega-fires that resist conventional suppression, transform vast landscapes, and threaten human populations. Such fires also produce large smoke plumes that can affect air quality at local, regional, and global scales [6].

The health effects of forest fire smoke are challenging to assess because large fires are typically sporadic and smoke episodes are typically short-lived. Given that the public health impacts are small, smoke rarely affects populations large enough to support the detection of statistically significant associations. Even so, a growing body of literature indicates that smoke exposure is associated with acute respiratory outcomes ranging from increased reporting of symptoms through to increased risk of mortality. A recent review of the evidence through 2010 [7▪▪] provides an excellent background for this compendium of the newest methods and results. Our review is also limited to studies reporting the respiratory health effects of forest fire smoke in the general population, and it does not cover related work on occupational exposures, periodic agricultural burning, or domestic solid fuel use.

Any epidemiologic study on the health effects of forest fire smoke has two key components: a clear definition of exposure within the population and a clear definition of the measured health outcomes. Here, we summarize eight recent studies (Table 1) [8▪,9▪,10▪▪,11▪▪,12▪,13▪,14▪▪,15▪], classifying the exposure assessment approaches used by each as 'simple' or 'complex' and classifying the health outcomes evaluated as 'mild' or 'severe'. We then generate a matrix of assessment methods and outcome severities to highlight the internal consistency of the results.

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KEY POINTS

- Smoke exposure assessment is challenging, but fire databases and remote sensing are facilitating innovation in both simple and complex approaches.
- Respiratory outcomes ranging from self-reported symptoms through to mortality have been evaluated, with administrative databases and surveillance frameworks facilitating larger studies.
- Smoke exposure is consistently associated with respiratory health outcomes, and it is most clearly associated with outcomes specific to asthma.

A RANGE OF SMOKE EXPOSURE ASSESSMENT METHODS

Forest fire smoke is a complex mixture of solids and gases, the composition of which varies with factors such as fuel type and fire temperature [17]. Most epidemiologic studies have used particulate matter measurements to represent this mixture, recognizing that air quality monitoring networks cannot capture the true spatial and temporal variability of smoke plumes. Recent work builds on this conventional approach by exploring innovative methods to assess smoke exposure, particularly in areas with limited air quality monitoring. We have classified the methods used by each study reviewed as 'simple' or 'complex' (Table 1), where simple approaches used existing data to estimate smoke exposure directly and complex approaches required extensive additional analyses.

Simple methods

Kolbe and Gilchrist [13▪] and Vora *et al.* [15▪] took the most straightforward approach, using particulate matter measurements to identify single smoke episodes caused by known fires. In the absence of particulate matter measurements, Caamano-Isorna *et al.* [9▪] simply used the number of known fires as a proxy for smoke episodes. Analitis *et al.* [8▪] used daily burned area as a similar proxy for daily smoke exposure over a 7-year period, although black smoke (a measure of particulate matter light reflectance) concentrations were also available. Henderson *et al.* [11▪▪] assessed daily smoke exposure over a single fire season using PM_{10} measurements and the footprints of smoke plumes visible from satellite images.

Complex methods

In addition to the simple methods, Henderson *et al.* [11▪▪] entered emissions from fires detected by remote sensing into a pollution dispersion model to estimate smoke-specific PM_{10} concentrations throughout the study area [18]. This approach was intended to improve the spatial scale of the exposure estimates and to focus analyses on the health effects specific to smoke (by removing background particulate matter), which was a common objective among the studies using complex methods. Johnston *et al.* [12▪] took a 14-year time series and defined every day with a 24-h PM_{10} concentration over the 99th percentile as an 'extreme air pollution event'. Multiple sources of information (government records, media reports, and remote sensing data) were then used to determine which events were caused by fire smoke [19▪], and analyses were conducted using the binary variable 'smoke event day' instead of the PM_{10} concentrations. Rappold *et al.* [14▪▪] identified 3 days of high exposure using $PM_{2.5}$ measurements, and classified areas as 'exposed' or 'referent' using aerosol optical depth (AOD, a measure of light reflected by particulate matter in the atmosphere) data collected every 30 min by remote sensing. Remote sensing data were also central to the approach used by Delfino *et al.* [10▪▪] for a single fire season. Although their study area had a dense air quality monitoring network, many of the stations only measured particulate matter every 3 or 6 days, and some stations were incapacitated by the smoke or the fires. Satellite images were used to identify areas of 'no smoke', 'light smoke', and 'heavy smoke', and these classifications were combined with meteorological variables to model the available $PM_{2.5}$ measurements. The resulting regression equations were used to generate a complete set of daily $PM_{2.5}$ data for all the stations, and values were assigned to plume footprints (during the fire period) or interpolated (during the prefire and post-fire periods) to estimate daily exposures across the study area [16].

A RANGE OF RESPIRATORY OUTCOMES

The respiratory health effects evaluated were as diverse as the approaches used for smoke exposure assessment. We have classified the outcomes reported by the eight studies as 'mild' or 'severe' (Table 1), where the potential long-term health risks of mild outcomes were small when compared with those of severe outcomes.

Mild outcomes

Kolbe and Gilchrist [13▪] assessed the self-reported symptoms including coughing, throat irritation,

Table 1. Summary of the reviewed studies

Author, year	Description	Study population	Smoke exposure assessment method(s)	Respiratory health outcome(s)
Analitis *et al.* 2011 [8■]	Time-series analysis of all fires seasons between 1998 and 2004 in Athens, Greece	>3 000 000	Simple: every day in the time series was classified as no fire, small fire, moderate fire, or large fire according to area burned	Severe: respiratory mortality
Caamano-Isorna *et al.* 2011 [9■]	Ecologic assessment of the impacts of the 2006 fire season in Galicia, Spain	~2 040 000	Simple: each of 156 municipalities was classified as having no exposure, medium exposure, or high exposure based on the number of fires in the municipality	Mild: dispensation of drugs for obstructive airway diseases
Delfino[a] *et al.* 2009 [10■■]	Poisson analysis of the prefire, during-fire, and postfire season of 2003 in southern California, USA	~20 500 000	Complex: $PM_{2.5}$ estimates for each of 560 postal codes within the study area. Estimates used particulate matter measurements, visibility, meteorological data, and remote sensing data [16]	Severe: respiratory hospital admissions
Henderson *et al.* 2011 [11■■]	Population-based cohort followed through the 2003 fire season in British Columbia, Canada	281 711	Simple: PM_{10} measurements Simple: smoke plume footprints Complex: PM_{10} dispersion model estimates [14■■]	Mild: respiratory physician visits Severe: respiratory hospital admissions
Johnston *et al.* 2011 [12■]	Case-crossover analysis of all fire seasons between 1994 and 2007 in Sydney, Australia	~3 862 000	Complex: Validated extreme air pollution event days caused by forest fire smoke [17]	Severe: respiratory mortality
Kolbe[a] and Gilchrist, 2009 [13■]	Telephone survey of community residents affected by the 2003 fire season in Albury, Australia	389	Simple: known fire smoke event	Mild: respiratory symptoms
Rappold *et al.* 2011 [14■■]	Poisson analysis of a high exposure period during a 2008 peat fire in South Carolina, USA	~2 670 000	Complex: 3-day period of high exposure identified from particulate matter measurements. Remote sensing aerosol optical depth was used to classify each of 41 counties during the high exposure period	Severe: respiratory emergency department visits
Vora *et al.* 2011 [15■]	Case series of eight asthmatics enrolled in other asthma research studies during the 2007 fires season in San Diego, USA	8	Simple: known fire smoke event	Mild: peak expiratory flow and forced expiratory volume Mild: sputum eosinophils Mild: rescue medication usage

Assessment methods defined as 'simple' used existing data to directly estimate smoke exposure, while those defined as 'complex' required extensive additional analyses (available publications on these methods are cited). The potential long-term health risks of 'mild' outcomes were small when compared with those of 'severe' outcomes.
[a]Although these studies were published before the review period, we include them as illustrative examples that have not been described in previous reviews.

shortness of breath, wheezing, asthma, and bronchitis. Vora *et al.* [15■] measured lung function, sputum eosinophils, and rescue mediation usage in diagnosed asthmatics. Caamano-Isorna *et al.* [9■] used pharmaceutical billings database to evaluate the use of drugs for obstructive airway diseases. Henderson *et al.* [11■■] used an administrative database of outpatient physician visits with respiratory diagnosis codes, including separate analyses for asthma-specific codes.

Severe outcomes

Henderson *et al.* [11■■] repeated their analyses for the more severe outcome of hospital admissions with respiratory diagnoses. Delfino *et al.* [10■■] also used respiratory hospital admissions, including specific analyses for asthma, chronic obstructive pulmonary disease (COPD), acute bronchitis plus bronchiolitis, and pneumonia. Rappold *et al.* [14■■] made use of emergency room data from a real-time public health surveillance system, including specific analyses for asthma, COPD, pneumonia plus acute bronchitis, and upper respiratory infections. Analitis *et al.* [8■] and Johnston *et al.* [12■] both examined mortality with underlying respiratory causes.

CONSISTENT ASSOCIATIONS

To compare the results from these eight disparate studies, we have summarized the reported associations in a matrix of exposure methods and outcome severities (Table 2). The quantitative results of each study are discussed below, ordered by the size of the study population. To further highlight the clearest and strongest associations, we have also summarized the results of all studies reporting on outcomes more specific to asthma (Table 3).

Vora *et al.* [15■] conducted the smallest study on a convenience sample of eight asthmatic patients who had data collected for a separate research project during a coincidental 5-day smoke event in San Diego, California, USA (~1.2 million). The authors did not describe the criteria used to define asthma, nor the underlying severity of asthma in any of the participants. Lung function was not significantly decreased in any of the patients, but five of the eight did demonstrate increasing use of rescue medication. Sputum testing was only conducted on two patients, and both showed increased sputum eosinophils (a marker of pulmonary inflammation) during the smoke event. Although the findings cannot be generalized to all people with asthma, they are consistent with the previously published evidence about the pulmonary toxicology of forest fire smoke [20] and the clinical responses of people with asthma to air pollution from forest fires [21].

Kolbe and Gilchrist [13■] randomly sampled 389 households from Albury, Australia (~40 000) following a 38-day smoke event. They documented a high frequency of self-reported respiratory symptoms in all respondents, but particularly in those who self-identified as having previous diagnoses of a respiratory condition. For example, of the 20% of respondents who reported a history of asthma, 44% reported increased shortness of breath in association with the pollution episode, compared with 24% of all respondents. Overall, 70% of respondents experienced symptoms (respiratory and nonrespiratory) that they attributed to smoke exposure, with 5% seeking healthcare as a consequence. The main limitations of these results are the reliance

Table 2. Summary of associations for general respiratory outcomes

Exposure/outcome	First author	Exposure	Outcome	Association[a]	Notes on age for clear associations (↑↑)
Simple/mild	Vora [15■]	Known event	Lung function	–	
	Henderson [11■■]	Smoke plume footprints	Physician visit	↑	
	Vora [15■]	Known event	Sputum eosinophils	↑	
	Caamano-Isorna [9■]	Number of fires	Obstructive airway drugs	↑↑	Pensioners only (age not specified)
	Henderson [11■■]	Measured PM_{10}	Physician visit	↑↑	All ages, higher in 20–50 years
	Kolbe [13■]	Known event	Respiratory symptoms	↑↑	All ages, higher in 40–74 years
	Vora [15■]	Known event	Medication usage	↑↑	Average age 36 ± 10 years
Complex/mild	Henderson [11■■]	Modeled PM_{10}	Physician visit	↑	
Simple/severe	Analitis [8■]	Measured black smoke	Mortality	–	
	Henderson [11■■]	Smoke plume footprints	Hospital admission	↑	
	Analitis [8■]	Fire size	Mortality	↑↑	All ages, higher in 75+ years
	Henderson [11■■]	Measured PM_{10}	Hospital admission	↑↑	All ages
Complex/severe	Johnston [12■]	Validated smoke event	Mortality	↑	
	Delfino [10■■]	Modeled $PM_{2.5}$	Hospital admission	↑	
	Henderson [11■■]	Modeled PM_{10}	Hospital admission	↑↑	All ages
	Rappold [14■■]	Aerosol optical depth	Emergency visit	↑↑	All ages, higher in <65 years

[a]A dash (–) indicates no association; a single arrow (↑) indicates a suggested association (not statistically significant, where applicable); and double arrows (↑↑) indicate a clear association (statistically significant, where applicable).

Table 3. Summary of associations for outcomes more specific to asthma

First author	Exposure	Outcome	Association[a]	General respiratory measure of association/asthma-specific measure of association
Caamano-Isorna [9■]	Number of fires	Drugs for obstructive airway diseases	↑↑	N/A
Delfino [10■■]	Modeled $PM_{2.5}$	Asthma-specific hospital admission	↑↑	1.03 general/1.05 asthma
Henderson [11■■]	Measured PM_{10}	Asthma-specific physician visit	↑↑	1.05 general/1.16 asthma
	Satellite smoke	Asthma-specific physician visit	↑↑	1.08 general/1.21 asthma
	Modeled PM_{10}	Asthma-specific physician visit	↑↑	1.01 general/1.04 asthma
Kolbe [13■]	Known event	Asthma symptoms in self-reported asthmatics	↑↑	24% overall/44% asthmatics
Rappold [14■■]	Aerosol optical depth	Asthma-specific emergency visits	↑↑	1.66 general/1.65 asthma
Vora [15■]	Known event	Medication usage in diagnosed asthmatics	↑↑	N/A

[a]A dash (–) indicates no association; a single arrow (↑) indicates a suggested association (not statistically significant, where applicable); and double arrows (↑↑) indicate a clear association (statistically significant, where applicable).

on self-reporting and the lack of baseline data to provide context for the findings.

Henderson *et al.* [11■■] identified an administrative, population-based cohort of 281 711 individuals residing in eastern British Columbia, Canada (~640 000), who were exposed to forest fire smoke over a 3-month period. Physician visits for general respiratory diagnoses were significantly associated with measured PM_{10} [30 μg/m^3, odds ratio (OR) = 1.05; 95% confidence interval (CI) = 1.03–1.06], and insignificantly associated with smoke plume footprints (in-plume OR = 1.08; 95% CI = 0.99–1.18) and modeled PM_{10} (60 μg/m^3 OR = 1.01; 95% CI = 0.99–1.03). Point estimates were higher and significant for asthma-specific diagnoses (Table 3). Hospital admissions for general respiratory diagnoses were significantly associated with measured PM_{10} (30 μg/m^3, OR = 1.15; 95% CI = 1.00–1.29) and modeled PM_{10} (60 μg/m^3, OR = 1.11; 95% CI = 1.04–1.18), and insignificantly associated with smoke plume footprints (in-plume OR = 1.60; 95% CI = 0.09–2.81). This is the first study to examine the health effects of forest fire smoke within a cohort. The results are internally consistent within a range of exposure measures and externally consistent with other work [7■■,10■■,22,23].

Caamano-Isorna [9■] examined the association between the number of regional forest fires and dispensations of drugs for obstructive airways diseases (we assume these include asthma and chronic obstructive pulmonary disease). The dispensation billings were converted to a metric of defined daily doses per 1000 people in each of 156 municipal regions of Galicia, Spain (~2 million). There were no significant changes in the 'no exposure' (0–3 fires) and 'medium exposure' (4–10 fires) categories, but daily dispensations were increased by 18 and 12 doses for 'high exposure' (11–58 fires) male and female pensioners, respectively, after the fire season. Pharmacy sales have previously been used to monitor the impact of fluctuations in air pollution [24] and pollen counts [25], providing an informative health outcome whether the drugs are primarily used to treat specific, short-term symptoms. They are also useful in smaller populations in which more severe outcomes are too infrequent to be significantly associated with environmental exposures.

Rappold *et al.* [14■■] studied the public health effects of peat fire smoke in 41 North Carolina counties (~2.7 million) using emergency department visits reported through a syndromic surveillance system that included data from 111 of 114 civilian emergency rooms. The 18 exposed counties had 65–70% increases in cumulative relative risk of visits for asthma, COPD, pneumonia or bronchitis, and upper respiratory infections (insignificant association) during the 3-day smoke episode and within the following 5 days. No changes were observed in the 23 referent counties. Risks were generally increased in women and in those less than 65 years of age. This is the first comprehensive study on the health effects of peat fire smoke, which is different from forest fire smoke in composition (and possibly in its range and magnitude of health impacts) [26].

Analitis *et al.* [8■] assessed how respiratory mortality was associated with black smoke and the area burned by 236 fires over a 7-year period in Athens, Greece (~3 million). There was no association between 'small fire' (0.1–1 km^2, $n = 252$) days and mortality, but 'medium fire' (1–30 km^2, $n = 42$) and 'large fire' (30+ km^2, $n = 7$) days were significantly associated with increases of 16% (95% CI = 1.3–33.4%) and 92% (95% CI = 47.5–150%)

in daily respiratory mortality, respectively. This work is challenging to compare with other mortality studies because fire size is a proxy for smoke exposure, and we do not know whether the particulate matter concentrations were elevated on fire days. Although black smoke measurements were also available, the mean (SD) concentration was 45 (21) $\mu g/m^3$ on the 770 'no fire' days and 36 (10) $\mu g/m^3$ on the seven 'large fire' days. This suggests that black smoke (a measure of particulate matter light reflectance that can only be used to estimate particulate matter mass concentration) did not reliably reflect the air quality impacts of forest fire smoke in Athens.

Johnston *et al.* [12■] more directly assessed how respiratory mortality was affected when forest fire smoke caused 50 extreme air pollution events ($PM_{10} \geq 47\, mg/m^3$) in Sydney, Australia (~3.8 million) over a 14-year period. Although smoke events were significantly associated with all-cause mortality (OR = 1.05; 95% CI = 1.00–1.10), they were insignificantly associated with respiratory mortality (OR = 1.09; 95% CI = 0.88–1.36). The higher point estimate for respiratory mortality compared with all-cause mortality is, however, consistent with the work of Analitis *et al.* [8■] and others [23,27].

Delfino *et al.* [10■■] studied the largest population, associating $PM_{2.5}$ concentrations in 560 postal codes with hospital admissions before, during, and after the 2003 fire season in southern California (~20.5 million). They reported that a 10 $\mu g/m^3$ increase in estimated $PM_{2.5}$ from wildfires was associated with admissions for acute bronchitis (relative risk, RR = 1.10; 95% CI = 1.02–1.18), pneumonia (RR = 1.03; 95% CI = 1.01–1.05), COPD (RR = 1.04; 95% CI = 1.00–1.07), and asthma (RR = 1.05; 95% CI = 1.02–1.08). Similarly to Rappold *et al.* [14■■], the association with COPD was largest in 20–65 years age category. Although asthma admissions were increased overall, the largest association was in adults over 65, which is consistent with other reports of asthma outcomes being higher in adults than in school-aged children [11■■,21,23].

CONCLUSION

Eight studies have used a wide range of exposure assessment methods in a wide range of study designs to examine the associations with a wide range of respiratory outcomes in a wide range of populations. The overall results are markedly consistent, both internally and externally [7■■]. Although readers may place greater confidence in the more rigorous studies, we also want to acknowledge the value of simpler approaches. Forest fire smoke is a challenging exposure to evaluate, and many questions still remain about its health effects. Studies reporting on acute cardiovascular outcomes have been largely null, but recent work has found that out-of-hospital cardiac arrests were increased on smoky days [28], and three studies reviewed here reported other significant associations [8■,12■,14■■]. These results are consistent with the acute cardiovascular effects of urban particulate matter [29], but we need to build internal consistency within the literature on forest fire smoke. Similarly, there is a dearth of evidence about exposures and outcomes in the equatorial regions more regularly affected by smoke from rainforest clearing. Finally, to the best of our knowledge, there is no evidence on the comparative risks of very acute (1–3 h) and acute (24 h) exposures, nor on chronic outcomes associated with acute exposures. Any contributions that help to address these gaps will be valuable additions to a sparse literature, and we believe that simple studies are preferable to no studies at all. Noonan and Balmes [30] recently articulated some specific ideas for interested investigators.

This is an exciting time for research on the health effects of forest fire smoke. Environmental databases and remote sensing products are facilitating new and innovative approaches to exposure assessment. Administrative health databases are facilitating population-based research, thereby improving the statistical power of many analyses. Furthermore, growing interest in the burden of disease [31■■] and health costs associated with smoke exposure [32■] may help to generate future funding for studies of all shapes and sizes.

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Conflicts of interest

There are no conflicts of interest.

REFERENCES AND RECOMMENDED READING

Papers of particular interest, published within the annual period of review, have been highlighted as:
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■■ of outstanding interest
Additional references related to this topic can also be found in the Current World Literature section in this issue (p. 331).

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A recent comprehensive review of the respiratory health effects associated with exposure to forest fire smoke. It is the first review specific to forest fire smoke (as opposed to biomass smoke in general), focusing on work from Australia but including key global examples.

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A novel use of fire size as a proxy for smoke exposure. One of few studies reporting significant associations for mortality outcomes (all-cause, respiratory, and cardiovascular).

9. ■ Caamano-Isorna F, Figueiras A, Sastre I, *et al.* Respiratory and mental health effects of wildfires: an ecological study in Galician municipalities (north-west Spain). Environ Health 2011; 10:48 [10.1186/1476-069X-10-48].

A novel use of fire count as a proxy for smoke exposure. The first study to assess the association between forest fires and pharmaceutical use within an entire population.

10. ■■ Delfino RJ, Brummel S, Wu J, *et al.* The relationship of respiratory and cardiovascular hospital admissions to the southern California wildfires of 2003. Occup Environ Med 2009; 66:189–197.

A rigorous study conducted in a very large population. Excellent PM2.5 exposure assessment at a fine spatial resolution. Clear, population-based health outcome with associations reported for the prefire, during-fire, and postfire periods to differentiate the effects of fire-related particulate matter from background particulate matter.

11. ■■ Henderson SB, Brauer M, MacNab YC, *et al.* Three measures of forest fire smoke exposure and their associations with respiratory and cardiovascular health outcomes in a population-based cohort. Environ Health Perspect 2011; 119:1266–1271.

Rigorous study conducted using a powerful cohort design. Three different measures of exposure were used, two specific to forest fire smoke. Two clear, population-based health outcomes were assessed. Results were internally consistent.

12. ■ Johnston F, Hanigan I, Henderson S, *et al.* Extreme air pollution events from bushfires and dust storms and their association with mortality in Sydney, Australia 1994–2007. Environ Res 2011; 111:811–816.

A careful separation of fire smoke from background sources, and one of few studies reporting significant association with mortality. Some evidence of interaction between smoke and heat.

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A well designed, randomized survey about forest fire smoke exposure, its health effects, and public awareness about outreach messaging.

14. ■■ Rappold AG, Stone SL, Cascio WE, *et al.* Peat bog wildfire smoke exposure in rural North Carolina is associated with cardiopulmonary emergency department visits assessed through syndromic surveillance. Environ Health Perspect 2011; 119:1415–1420.

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The principal estimate was approximately 340 000 deaths annually. Exposure was rigorously assessed using global models and remote sensing data, then evaluated using surface measurements. Mortality was calculated differently for regions affected sporadically and chronically, with multiple sensitivity analyses to explore a wide range of scenarios.

32. ■ Kochi I, Donovan GH, Champ PA, *et al.* The economic cost of adverse health effectsfrom wildfire-smoke exposure: a review. Int J Wildland Fire 2010; 19:803–817.

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