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The economic cost of adverse health effects from wildfire-smoke exposure: a review

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Abstract. The economic costs of adverse health effects associated with exposure to wildfire smoke should be given serious consideration in determining the optimal wildfire management policy. Unfortunately, the literature in this research area is thin. In an effort to better understand the nature of these economic costs, we review and synthesise the relevant literature in three areas: studies that estimated the health-related economic costs of wildfire-smoke exposure; epidemiology studies related to the health risk of wildfire smoke; and general economic studies that estimated the monetary value of preventing the specific adverse health outcomes. Based on the findings from this literature review, we identify the need for a better understanding of the effect of wildfire smoke on major and minor adverse health outcomes. It would also be useful to know more about averting behaviours among residents exposed to smoke during a wildfire event. Finally, we suggest investigating the unique health effects of wildfire smoke compared with conventional air pollution to determine whether it is appropriate to extrapolate from previously estimated conventional pollution dose–response functions.

Additional keywords: epidemiology studies, forest fires, health damage, non-market valuation, particulate matter.

Introduction

The economic costs associated with the adverse health effects of wildfire-smoke exposure can be an important consideration in wildfire management. For example, concerns about adverse health effects from 2008 wildfires in northern California prompted the USDA Forest Service to actively suppress all wildfires in California. However, despite the emphasis placed on reducing the health risk, the science demonstrating health effects from wildfire-smoke exposure is incomplete and at times contradictory. In addition, there are few monetary estimates of the economic costs associated with the adverse health effects of wildfire-smoke exposure.

Evaluating the health-related economic costs of wildfire smoke involves two steps. First, the total adverse health outcomes associated with a wildfire event are quantified (such as 10 excess deaths or 100 excess hospital admissions for a particular illness during wildfire events). The quantified adverse health outcomes are then monetised by multiplying each health outcome by per-unit cost. In this paper, we review and synthesise the literature related to the health-related economic costs of wildfire-smoke exposure in an effort to understand the nature of this cost, to provide a comprehensive list of available studies in related fields, and to identify the key issues worthy of future investigation. We summarise three research literatures: studies that estimated the health-related economic cost of wildfire-smoke exposure; epidemiology studies related to the health effect of wildfire smoke; and general economic studies that estimated the monetary value of preventing the specific adverse health outcomes (premature mortality and various cardio-respiratory symptoms). We also discuss how the health risk of wildfire smoke could be considered in wildfire management decisions.

The rest of the article is organised into six sections. The first section describes the study methodology. The second section reviews studies that estimated the health-related economic costs of wildfire-smoke exposure. The third section summarises the epidemiology literature related to health effects of wildfire smoke. Specifically, we compare and contrast studies that examined the health effect of particulate matter (PM) exposure from industrial sources (urban PM exposure) with studies that

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examined the health effect of wildfire-smoke exposure.[A] The fourth section reviews the economic valuation literature on health outcomes related to air pollution. The fifth section highlights some potential policy considerations, and the last section provides a conclusion.

Study methodology

Systematic literature reviews were conducted in economics, epidemiology and wildfire policy research fields to identify relevant published and unpublished papers. Searching the published literature was straightforward as there are many web-based databases such as Econlit and Medline. We also relied on previously published review papers and references from recent articles in the related fields. In addition, we contacted individuals who have published in the relevant literature to inquire about recent publications and unpublished papers. On-line search engines, such as Google, were also used. For the epidemiology literature, we only summarised studies that conducted tests to determine the statistical significance of the results.

Health-related economic cost of wildfire-smoke exposure

Studies that estimated health-related economic costs of wildfire-smoke exposure are sparse. Our literature search turned up six relevant studies worldwide. The magnitude of estimated health-related economic costs depends on the scale of the wildfire event, demographic characteristics of the exposed population (residents of developed or developing countries), and the type of adverse health outcomes considered. Table 1 summarises the location of wildfires, the measured adverse health outcomes, the type of dose–response function used to quantify the level of adverse health outcomes, and estimated economic costs in each study. The economic costs are estimated either by a willingness to pay (WTP) approach or a cost of illness (COI) approach. The WTP approach measures the comprehensive economic cost, whereas the COI approach measures only direct cost associated with illness. The characteristics of each approach are discussed further in the fourth section.

When estimating health-related economic costs, the selection of adverse health outcomes to be quantified is somewhat subjective. The United States Environmental Protection Agency (US EPA) has identified an extensive list of possible health effects from PM, one of the major pollutants associated with wildfire smoke, that ranges from acute minor symptoms to premature mortality (US EPA 1999). As shown in Table 1, common adverse health outcomes considered in previous studies are hospital admission for respiratory and cardiac symptoms, hospital outpatient visits for respiratory symptoms, work loss days and restricted-activity days. Only Rittmaster *et al.* (2006, 2008) included the economic cost of premature mortality due to wildfire-smoke exposure.[B] This estimated cost of premature mortality is substantially larger than any of the other costs reported in Table 1, while the number of estimated excess deaths is very small (0.4–0.5 estimated excess deaths). Although the method employed in Rittmaster *et al.* (2006, 2008) to quantify the number of excess deaths from a wildfire event has its limitations, and could cause overestimation of the mortality impact of wildfire smoke, the studies of Rittmaster *et al.* suggest that the omission of mortality costs in the other studies summarised in Table 1 may results in substantial underestimates of total health costs.

Work days lost, restricted-activity days, and minor restricted-activity days contribute substantially to total morbidity-related costs, and account for 36 to 74% of total estimated health costs in the studies that did not consider premature mortality. The studies summarised in Table 1 also suggest that hospital admissions, respiratory symptoms and self-treatment are major health-cost components.

The approach used to quantify adverse health impacts from wildfire-smoke exposure could have important implications for the validity of the estimates. There are two approaches to quantify the level of adverse health outcomes. One approach is to use original health data such as vital statistics or hospital discharge data to measure the adverse impact of a wildfire event. The other approach is to extrapolate existing dose–response functions between air pollution and adverse health outcomes. The latter approach is commonly used in policy analysis by the US EPA (1999, 2005) because it only requires air pollution data to estimate the level of adverse health effects of any event.

Martin *et al.* (2007) and Rittmaster *et al.* (2006, 2008) use existing dose–response functions based on urban air pollution PM and adverse health outcomes. Although wildfire smoke contains substantial amounts of PM, the problem of this approach is that exposure to PM from wildfire smoke may result in different health effects. Most existing PM dose–response functions, including ones employed in Martin *et al.* (2007) and Rittmaster *et al.* (2006, 2008), are based on low to moderate concentration levels of PM exposure from urban air pollution sources such as fossil-fuel burning (hereafter referred as conventional PM studies). Wildfires often result in short-lived, but very high levels of PM from vegetation burning. As discussed later, some researchers have argued that the different chemical properties and circumstances of urban air pollution and wildfire smoke may result in different health effects. Therefore, although it is convenient to use conventional PM studies to estimate the level of adverse health outcomes of wildfire smoke, it is not clear that this approach is appropriate. In the next section, we compare the findings from conventional PM and wildfire-specific epidemiology studies in an effort to understand whether it is appropriate to extrapolate results from conventional PM studies to estimate health effects from wildfire-smoke exposure.

Epidemiology studies: urban air pollution *v.* wildfire smoke

In this section, we review and summarise the findings from conventional PM studies and wildfire-specific epidemiology

[A]Particulate matter (PM) is categorised as PM_{10}, which is particles less than 10 μm in diameter, and $PM_{2.5}$, which is particles less than 2.5 μm in diameter.
[B]The estimate of mean health-related cost in Rittmaster *et al.* (2006) was corrected in Rittmaster *et al.* (2008).

Table 1. Previous economic analysis of wildfire-smoke-induced health damage

COI denotes values obtained from Cost of Illness approach, WTP denotes values obtained from willingness to pay approach, $PM_{2.5}$ denotes particulate matter with particles less than 2.5 µm in diameter, and PM10 denotes particulate matter with particles less than 10 µm in diameter. Total cost may not be same as sum of all cost due to rounding

	Name of fire and description	Health outcomes	Source of dose–response function	Estimated economic cost (central estimate unless specified, 2007 $US value)
Cardoso de Mendonça *et al.* (2004)	Fires in Amazon between 1996 and 1999	In-patient treatment (respiratory)	Original	$2 100 000 (annual average COI)
				$9 400 000 (annual average WTP)
Martin *et al.* (2007)	Hypothetical prescribed fire in Kaibab National Forest in USA	Hospital admissions (respiratory and cardiac)	Conventional dose–response functions	$52 490 (COI)
		Lower respiratory symptoms (children)		$25 510 (WTP) (both children's health effects)
	Affected city: Flagstaff	Acute bronchitis (children)		
		Work-loss days (WLD)		$106 996 (WLD and RAD: COI; MRAD: WTP)
	Worst-case scenario: total 1935 $\mu g\,m^{-3}$ $PM_{2.5}$ increase	Restricted-activity days (RAD)		
		Minor restricted-activity days (MRAD)		
		Total		**$185 002 (COI and WTP mix)**
Rittmaster *et al.* (2006, 2008)[A]	2001 Chisholm fire in Canada	Mortality	Conventional dose–response function	$2 292 224 (WTP)
		Hospital admissions (respiratory)		$1901 (COI)
		Hospital admissions (cardiac)		$2038 (COI)
	7 days fire, 2 days of heavy smoke	Emergency room visits		$761 (COI)
		Restricted activity days		$289 306 (WTP, COI)
		Asthma symptom days		$17 341 (WTP)
	Peak $PM_{2.5}$: 55 $\mu g\,m^{-3}$ daily average; 261 $\mu g\,m^{-3}$ hourly average	Bronchitis admissions		$9580 (COI)
		Acute respiratory symptom events		$93 630 (WTP)
		Total		**$2 706 782 (COI and WTP mix)**
Shahwahid and Othman (1999)	1997 Asian Haze in Malaysia	Hospital admissions	Original	$610 725 (COI)
	Smoke period: August–November 1997. Air pollution index reached dangerous level. Declared state of emergency for 10 days	Outpatient		$1 820 346 (COI)
		Self-treatment		$768 754 (COI)
		Work-loss days		$294 003 (COI)
		Restricted activity days		$1 928 967 (COI)
		Total		**$5 422 798 (COI)**
		Adjusted total[B]		**$10 845 597 (WTP)**
Hon (1999)	1997 Asian Haze in Singapore	Hospital admissions	Original	$123 010–$512 544 (COI)
	14 days unhealthy 24-h average air quality level	Outpatient (less severe)		$642 549–$1 606 372 (COI) (all outpatient and self-treatment)
		Outpatient (severe)		
		Self-treatment (less severe symptoms)		
		Work-loss days		$1 964 550–$6 527 998 (COI)
		Total		**$2 730 109–$8 646 916 (COI)**
		Adjusted total[B]		**$5 460 220–$17 293 831 (WTP)**
Ruitenbeek (1999)	1997 Asian Haze in Indonesia. PM_{10} in Jambi recorded 1864 $\mu g\,m^{-3}$ (Kunii *et al.* 2002)	Hospitalisation	Shahwahid and Othman (1999)	$380 160 000 (all medical costs)
		Outpatient		
		Self-treatment		
		Work-loss days		$215 820 000 (COI)
		Total		**$595 980 000 (COI)**
		Adjusted total[B]		**$1 191 960 000 (WTP)**

[A]Canadian dollar is converted to US dollar using 1996 average exchange rate (CAN$: US$ = 1 : 0.73).
[B]Adjusted total is obtained by multiplying the total cost estimated from the COI approach and WTP/COI ratio of 2.

Table 2. Summary of conventional particulate matter (PM) health impacts

Weighted average is obtained in the following manner. First, we obtain the average relative risk and 95% confidence interval for each selected study. Then we calculate weighted average from $\bar{x} = \sum_{i=1}^{n} x_i/\text{s.e.}_i / \sum_{i=1}^{n}\text{s.e.}_i$ where x is estimated relative risk, s.e. is standard error of estimated relative risk and i denotes different study

Health outcomes	50-μg m^{-3} increase of daily PM_{10} (weighted average)	25-μg m^{-3} increase of daily $PM_{2.5}$ (weighted average)	Source
Mortality	1.1–8.3% (2.9%)	1.5–9.7% (3.5%)	Based on US EPA (2004)
Respiratory	13.9%	5.5%	
Chronic obstructive pulmonary disease (COPD)	5.5–9.9% (7.0%)	–	
Pneumonia	11.5–16.5% (14.0%)	–	
Cardiovascular	2.2–9.7 (5.5%)	2.6–19.1% (4.6%)	
Cardiorespiratory	–	5.1–6.2% (5.6%)	
Hospital admission			
Respiratory	5.8%	2.8–4.6% (3.78%)	
COPD	5–8.8% (6.8%)		
Pneumonia	2.9–18.6% (8.2%)	10.1–10.5 (10.3%)	
Asthma	9.5–16.2% (12.9%)	1.4–8.7% (2.4%)	
Cardiovascular (>65 years old)	2.7–5.0% (4.0%)	2.9–3.9% (3.4%)	
Heart failure	3.9%	6.8–8% (7.4%)	
Emergency department visit			
Cardiovascular		6.1%	
Asthma	13.2–34.7% (21.1%)		
		1-μg m^{-3} increase of daily $PM_{2.5}$	
Restricted-activity days		1.58%	Ostro and Rothschild (1989)
Minor restricted-activity days		0.82%	

literature. Most published conventional PM studies find significant health effect of PM in terms of mortality and morbidity. If urban PM and wildfire smoke PM exposures have same health effect, we expect to find a significant health effect from wildfire smoke as outdoor PM concentration levels generally increase substantially during the wildfire period. We focus our review to examine the following: (1) if wildfire-specific epidemiology studies found significant health effects associated with wildfire-smoke exposure, and (2) if the findings in wildfire-specific epidemiology studies are consistent with the findings in conventional PM studies. First, we review the findings from the conventional PM studies, followed by wildfire-specific studies, and discuss the potential uniqueness of wildfire-smoke-specific health effects.

Conventional PM studies

Table 2 summarises the results from selected conventional PM studies that were reviewed by the US EPA (2004).[C] Conventional short-term PM studies estimate the marginal effect of PM on adverse health outcomes using a daily time-series model. They generally find a small but statistically significant impact of short-term exposure to PM on the levels of mortality, cardiorespiratory-related hospital admissions and emergency department visits. For example, a 50-μg m^{-3} increase in coarse particles, PM_{10}, is associated with a 2.9% increase of mortality risk, a 5.8% increase of respiratory-related hospital admission and a 21% increase of asthma-related emergency department visits.[D] Also, Ostro and Rothschild (1989) found that a 1-μg m^{-3} increase of fine particles, $PM_{2.5}$, resulted in a 1.58% increase in respiratory-related restricted-activity days and a 0.82% increase in minor restricted-activity days among a sample of 18- to 65-year-olds.[E]

Wildfire health impact studies

This section first summarises the findings from epidemiology studies that examine the health effects of wildfire smoke, and then discusses the consistency with findings from conventional PM studies. Tables 3, 4 and 5 summarise studies that examined the relationship between wildfire smoke and the levels of mortality, hospital admissions, and emergency department visits

[C] US EPA (2004) reviewed the PM-health studies published after 1996 to re-evaluate the relevance of the PM standard established in 1996. Table 2 summarises US studies that met selection criteria outlined in US EPA (2004) and had statistically significant results.

[D] All values are based on the weighted average of mean estimate among selected studies listed in US EPA (2004). The weighted average was calculated by our research group and is detailed in Table 2.

[E] A respiratory-related restricted-activity day is defined as ‘any day on which a respondent was forced to alter his or her normal activity and an acute respiratory condition was reported. It includes days of work lost or bed disability as well as more minor restriction’. A minor restricted-activity day is defined as ‘a restricted-activity day that does not result in either work loss or bed disability and therefore involves more minor conditions and reductions in activity’ (Ostro and Rothschild 1989, p. 239).

Table 3. Wildfire-induced mortality impact summary (ordered by maximum PM_{10} level)

Study	Location	Name and studied period of wildfire	Maximum PM_{10} average level ($\mu g\,m^{-3}$)	Effect on mortality
By historical control method				
Emmanuel (2000)	Singapore	1997 Asian Haze Sep–Oct 1997	100 (monthly)	No change
Phonboon *et al.* (1999)	Hatyai, Thailand	1997 Asian Haze Sep–Oct 1997	218 (daily)	No change
By time-series method				
Cardoso de Mendonça *et al.* (2006)	Amazon, Brazil	Burning of Amazon forest between 1996 and 1999	PM level not available. Substitute with acres of area burned	No change
Vedal and Dutton (2006)	Colorado, USA	Hayman Fire 9 and 18 June 2002	91 (daily) 372 (hourly)	No change
Morgan *et al.* (2010)	Sydney, Australia	32 bushfire days between 1994 and 2002	117 (daily)	No change
Sastry (2002)	Kuala Lumpur, Malaysia	1997 Asian Haze Sep–Oct 1997	423 (daily) Number of low visibility days = 14	Increase of PM by 100 $\mu g\,m^{-3}$ is associated with relative risk of total mortality 1.07 High risk: 65–74-year-old age groups
Sastry (2002)	Kuching, Malaysia	1997 Asian Haze Sep–Oct 1997	Number of low visibility days = 33	Cardiorespiratory related mortality: Significant only for age >75 years

Table 4. Wildfire-induced morbidity impact (hospital admission) summary ordered by maximum PM_{10} level

Respiratory symptoms include general respiratory symptoms, upper respiratory infection or obstructive respiratory disease. NA indicates that estimate is not available

Study	Location	Name of wildfire	Maximum PM_{10} level ($\mu g\,m^{-3}$)	Effect on asthma	Effect on respiratory symptoms	Effect on cardiovascular system
By historical control method						
Phonboon *et al.* (1999)	Thailand	1997 Asian Haze	218 (daily) 69 (monthly)	No change	7% increase (net)	No change
	Thailand (Hatyai)	1997 Asian Haze	218 (daily) 69 (monthly)	No change	49% increase (net, bronchitis and chronic obstructive pulmonary disease)	NA
Duclos *et al.* (1990)	California, USA	Large fire in Aug–Sep 1987	237 (daily)	No change	NA	NA
Delfino *et al.* (2009)	Southern California	2003 southern California fire	>240 (daily $PM_{2.5}$)	26–33% increase during post-wildfire period	48–58% increase during post-wildfire period	6% increase during post-wildfire period
Emmanuel (2000)	Singapore	1997 Asian Haze	100 (monthly)	NA	No change	NA
By time-series method						
Cardoso de Mendonça *et al.* (2004)	Brazil, Amazon	Burning of Amazon forest in 1996–99	Not reported	NA	1 unit of increased burned area is associated with 0.2961 cases of hospitalisation (panel model)	NA
Chen *et al.* (2006)	Brisbane, Australia	Bushfires in July 1997–Dec 2000	60 (daily)	NA	Increased PM_{10} from low to medium, or to high is associated with 9 and 19% increase of admissions respectively	NA
Johnston *et al.* (2007)	Darwin, Australia	Bushfires in 2000, 2004 and 2005	70 (daily)	13% increase associated with 10 $\mu g\,m^{-3}$ increase of PM_{10}	8% increase associated with 10-$\mu g\,m^{-3}$ increase of PM_{10}	No change
Cançado *et al.* (2006)	Piracicaba, Brazil	Sugarcane burning in April 1997–March 1998	87.7 (daily average) during burning period	NA	Children: increased (10% significance level) Elderly: increased	NA
Morgan *et al.* (2010)	Sydney, Australia	32 bushfire days between 1994 and 2002	117 (daily)	5.02% increase of adult asthma associated with 10 $\mu g\,m^{-3}$ increase of PM_{10}	1.24% increase associated with 10-$\mu g\,m^{-3}$ increase of PM_{10}	No change
Phonboon *et al.* (1999)	Thailand (region-wide)	1997 Asian Haze	218 (daily) 69 (monthly)	1 $\mu g\,m^{-3}$ increase of monthly average PM_{10} is associated with 13 excess admissions per month	1-$\mu g\,m^{-3}$ increase of PM_{10} is associated with 85 excess admissions (significant at 10% level)	NA
Delfino *et al.* (2009)	Southern California	2003 Southern California Fire	>240 in San Diego (daily $PM_{2.5}$)	4.8% increase associated with 10 $\mu g\,m^{-3}$ increase of $PM_{2.5}$	2.8% increase associated with 10-$\mu g\,m^{-3}$ increase of $PM_{2.5}$	No change
Shahwahid and Othman (1999)	Malaysia	1997 Asian Haze	Air pollution index = 831	NA	1 unit of increased air pollution index measure is associated with 0.000055 cases per 10 000 people[A]	NA
Mott *et al.* (2005)	Kuching, Malaysia	1997 Asian Haze	852 (daily)	All ages: increased	All ages: increased	No change

[A]The original classification of disease is 'cardiorespiratory illness'.

respectively.[F,G] In these tables, we only include studies that tested for the statistical significance of the results.[H] All the studies use either the time-series method or historical control method. The historical control method is used to evaluate the health effects of a particular event at an aggregate level, such as the total or average levels, by comparing the levels of adverse health outcomes during wildfire period with an appropriate control period.[I] The studies summarised in Tables 3, 4 and 5 are listed by estimation method and the maximum PM level recorded during the wildfire events (from the lowest to the highest).

In contrast to conventional PM studies, wildfire studies were less likely to find a significant positive mortality effect in spite of the substantial increases in PM levels during the wildfire period (Table 3). Only two of the seven studies found a significant mortality effect. [J] Table 4 lists studies that examine the impact of a wildfire event on hospital admissions related to asthma, general respiratory symptoms, and cardiovascular symptoms. Studies found consistent increases of general respiratory-related and asthma-related admissions during wildfire events. Twelve out of the thirteen relevant studies for general respiratory symptoms, and six out of the nine relevant studies for asthma-related admissions found a significant increase during wildfire events. However, only one of the six relevant studies found a significant increase in the number of cardiovascular-related admissions during wildfire events.

Morbidity effects can also be measured by the number of visits to hospital emergency departments.[K] Table 5 summarises studies that examine the impact of wildfire-smoke exposure on the number of asthma, general respiratory symptoms and cardiovascular symptoms-related emergency department visits. A significant increase in the number of emergency department visits was found in seven of the thirteen studies that considered asthma-related effects, nine out of the thirteen studies that considered respiratory-related symptoms, and none of the three studies that considered cardiovascular symptoms.

In summary, significant adverse health effects from wildfire smoke were consistently found in limited health outcomes, such as respiratory-related hospital admissions. The adverse health effects of wildfire smoke on respiratory-related emergency department visit were found but less consistently. Very few studies found a significant positive association between wildfire smoke and mortality or cardio-related morbidity outcomes. Even among the studies that found a significant adverse health effect from wildfire-smoke exposure, the findings are somewhat inconsistent with conventional PM studies. For example, Sastry (2002) found a positive association between levels of PM_{10} and mortality among the elderly in Malaysia during the 1997 South-east Asian Haze. The magnitude of this mortality effect is consistent with the mortality effect found in conventional PM studies. However, the mortality effect was found to be significant only after very high pollution days (daily PM $>200\ \mu g\ m^{-3}$), whereas conventional PM studies find significant mortality effects at lower levels of PM. Johnston *et al.* (2002) also found non-linear health effects associated with PM exposure during wildfire periods.[L]

However, there are studies that show a higher adverse health effect of wildfire smoke than non-wildfire-related PM exposures. For example, Chen *et al.* (2006), Cançado *et al.* (2006) and Delfino *et al.* (2009) found a higher marginal effect of PM on the level of respiratory-related hospital admissions during wildfire event periods than non-wildfire event periods.

Differences between conventional and wildfire PM studies

Contrary to expectations based on the findings from conventional PM studies, significant adverse health effects of wildfire have been found consistently only with the limited respiratory-related morbidity outcomes, and not with mortality or cardio-related morbidity outcomes. However, studies that examined respiratory-related hospital admissions indicated that wildfire-smoke exposure imposed more health risk than conventional PM exposure. Five reasons have been put forth as the possible causes of the differences in observed health effects from conventional PM studies and wildfire smoke studies (Lipsett *et al.* 1994; Kunii *et al.* 2002; Künzli *et al.* 2006; Vedal and Dutton 2006). In this section, we discuss briefly each of the five reasons.

Reason 1. The choice of the statistical model

Conventional PM studies typically use daily time-series models with a long period of observation. This large sample size likely enables researchers to detect a small health effect

[F]In these tables, 'No change' means that there was no statistically significant increase of adverse health outcomes during a wildfire event at the 5% significance level.

[G]Naeher *et al.* (2007) also provide a comprehensive review of epidemiology studies of vegetation fires as well as controlled laboratory studies of wood smoke, health effects of residential wood burning, toxicology, and the chemical and physical nature of wood smoke. Our study expands their epidemiology literature review of mortality, hospital admission and emergency room visits by adding studies that are not included as well as by adding the analytical structure.

[H]The related health studies that were excluded from these tables owing to the lack of statistical tests or the examination of other types of health outcomes include: Frankenberg *et al.* (2005), Kunii *et al.* (2002), Künzli *et al.* (2006), Mott *et al.* (2002), Moore *et al.* (2006), Mott *et al.* (2003), Ovadnevaitė *et al.* (2006), Shusterman *et al.* (1993) and Sorensen *et al.* (1999).

[I]Studies categorised under 'historical control analysis' in this paper include studies that control confounding factors by selecting appropriate reference period using sample design or through econometric modelling.

[J]We count the estimate from a different location or from a different estimation method (historical control or time-series model) in the same study as separate studies in Tables 3–5.

[K]For convenience, we categorise emergency department, health centres, or urgent-care and outpatient facilities as 'emergency departments'.

[L]Kunii *et al.* (2002) also report a weaker mortality impact from wildfire smoke than urban air pollution. They attributed 527 deaths during the 1997 South-east Asian Haze episode to wildfire smoke, while they predicted 15 000 deaths based on the conventional PM-mortality study. Kunii *et al.* (2002) is not included in Table 3 owing to a lack of statistical tests.

Table 5. Wildfire-induced morbidity impact (emergency department (ED) or other outpatient facility visit) summary ordered by maximum PM_{10} level

Respiratory symptoms include general respiratory symptoms, upper respiratory infection, or chronic obstructive pulmonary disease (COPD). NA indicates that estimate is not available. (P) indicates that analysis was conducted using proportion of the number of patients in a certain diagnosed category over total patients

Study	Location	Name of wildfire	Maximum PM_{10} level ($\mu g\,m^{-3}$)	Patient type	Effect on asthma	Effect on respiratory symptoms	Effect on cardiovascular symptoms
By historical control method							
Churches and Corbett (1991)	Sydney, Australia	Burning of firebreaks, May 1991	Nephelometry reading = 7.5 (hourly)	ED	No change	NA	NA
Cooper *et al.* (1994)	Sydney, Australia	Bushfire, Jan 1994	Nephelometry reading = 2.3 (daily)	ED	No change	NA	NA
Smith *et al.* (1996)	Sydney, Australia	Bushfire, Jan 1994	250 (hourly)	ED	No change	No change	NA
Phonboon *et al.* (1999)	Thailand (region-wide)	1997 Asian Haze	218 (daily) 69 (monthly)	Outpatient	NA	8% increase (net)	No change
Davidson *et al.* (2003)	Colorado	Hayman Fire	91 (daily) 372 (hourly)	ED Urgent care Outpatient	No change 22% decrease (P) No change	40% increase (P) No change NA	NA NA NA
Phonboon *et al.* (1999)	Thailand (Hatyai)	1997 Asian Haze	218 (daily) 69 (monthly)	Outpatient	No change	7% increase (net, all respiratory disease)	No change
Duclos *et al.* (1990)	CA, USA	Large fire, Aug–Sep 1987	237 (daily)	ED	40% increase (P)	20–50% increase (P)	NA
Viswanathan *et al.* (2006)	CA, USA	2003 southern CA fire	294 (daily)	ED (chief complaints)	Increased by 5% (P)	Increased by 4–5% (P)	No change
Kene *et al.* (2008)	San Diego, USA	2003 southern CA fire (San Diego)	Not reported	ED (chief complaints)	NA	Increased (P)	NA

By time-series method							
Smith *et al.* (1996)	Sydney, Australia	Jan 1994 (2 weeks)	250 (hourly)	ED	No change	No change	NA
Johnston *et al.* (2002)	Darwin, Australia	Long bushfire between 1 April and 31 October 2000	70 (daily)	ED	Linear model: 18% increase with 10-$\mu g\,m^{-3}$ increase of PM_{10} Categorical model: from base ($<10\,\mu g\,m^{-3}$) to high ($>40\,\mu g\,m^{-3}$) PM_{10} level is associated with 92–156% increase of admissions	NA	NA
Chew *et al.* (1995)	Singapore	1994 forest fire in Indonesia	More than 158 (daily)	ED, children	Significant increase	NA	NA
Phonboon *et al.* (1999)	Thailand (region-wide)	1997 Asian Haze	218 (daily) 69 (monthly)	Outpatient	NA	No change	NA
	Thailand (Hatyai)	1997 Asian Haze	218 (daily) 69 (monthly)	Outpatient	NA	1-$\mu g\,m^{-3}$ increase of daily average PM_{10} is associated with 0.2 excess visits	NA
Emmanuel (2000)	Singapore	1997 Asian Haze	100 (monthly)	Outpatient	19% increase with 100-$\mu g\,m^{-3}$ increase of PM_{10} (50 $\mu g\,m^{-3}$ to 150 $\mu g\,m^{-3}$)	12% increase with 100-$\mu g\,m^{-3}$ increase of PM_{10} (50 $\mu g\,m^{-3}$ to 150 $\mu g\,m^{-3}$)	NA
Shahwahid and Othman (1999)	Malaysia	1997 Asian Haze, Aug–Oct 1997	Air pollution index = 831	Outpatient	NA	1 unit of increased air pollution index measure is associated with 0.0125 cases per 10 000 people[A]	NA

[A]The original classification of disease is ‘cardiorespiratory illness’.

from short-term PM exposure.[M] In contrast, the historical control method that is often employed in wildfire studies compares aggregate adverse health outcome levels between the study and control periods. This method is not ideal for detecting relatively small health impacts (Vedal and Dutton 2006). However, despite the drawbacks of the historical control method, using a time-series model to evaluate the health effects of wildfire smoke is generally problematic. Smoke from wildfires does not typically last for a long period of time, particularly in the USA. Thus the wildfire event period is too short to have sufficient statistical power for a time-series analysis to be performed.[N]

Reason 2. Urban air pollution and wildfire smoke have chemical differences

Another possible explanation for the observed difference between findings in conventional PM and wildfire smoke studies is the chemical differences between urban air pollution and wildfire smoke. Vedal and Dutton (2006) argue that fossil-fuel combustion usually contains toxic particles such as metal, and may be more hazardous than vegetation burning. However, Wegesser *et al.* (2009) found that PM samples collected during a wildfire event were more toxic than the same amount of PM from normal ambient air.[O]

Reason 3. Non-linearity of the PM dose–response function

Wildfires usually result in large, but short-lived increases in PM levels. In contrast, urban air pollution is often less intense. The US EPA (2004) concludes that the PM dose–response function is linear at low to moderate levels. However, several wildfire studies (Sastry 2002; Chen *et al.* 2006; Martin *et al.* 2007) suggest that the dose–response function is non-linear for higher levels of PM exposure. If this is the case, using a dose–response function derived from low- to moderate-level PM exposure to estimate the health effects of wildfire-smoke exposure would give biased estimates.

Reason 4. Averting behaviour might be different for urban air pollution than for wildfire smoke

Vedal and Dutton (2006) and Kunii *et al.* (2002) suggest the possibility of different averting behaviours among residents in smoke-affected areas during wildfire events as a potential cause of discrepancy between findings of conventional PM studies and wildfire studies. Bresnahan *et al.* (1997) and Künzli *et al.* (2006) found that individuals, particularly those who are sensitive to air pollution, take averting measures when the air pollution level is high. As large wildfire events are highly publicised, and smoke is clearly visible, individuals may take more measures to avoid air pollution from wildfires than from other sources. If that is the case, we would expect fewer observed adverse health outcomes for a given level of PM during a wildfire.[P]

Reason 5. Perceptions about the health risk

People may perceive that air pollution from wildfires imposes a greater health risk than pollution from other sources. Lipsett *et al.* (1994) found that approximately four times as many people without physical evidence of illness visited an emergency department during a large urban fire event than usual. Although the perception of wildfire smoke as a more serious health threat is unlikely to affect the levels of mortality or hospital admissions, it may result in more minor adverse health outcomes such as emergency department visits and perceived symptoms of cardiorespiratory illness.

Future research

There is still significant uncertainty about the health effects of wildfire smoke. Many mortality and cardio-related morbidity studies and some respiratory-related emergency department visit studies found no significant health effect due to wildfire events, in contrast to what would be predicted based on conventional PM studies.

Given the different study design, sample and limited information available about each study, it is difficult to rigorously compare the findings from these two types of studies. More studies are needed that use time-series analysis to understand the potentially unique health effects of wildfire-smoke exposure, as this method allows researchers to compare the health effect of air pollution during wildfire event and non-wildfire event periods using the same study design and sample.[Q] Another benefit of using time-series analysis is that the dose–response function obtained from this method could easily be extrapolated to evaluate the health impact of different wildfire events.

More research is also needed to investigate the impact of wildfire smoke on minor adverse health outcomes that do not require hospital visits, such as coughs and headaches that restrict daily activity. Such studies are sparse in general, and particularly in the area of health impact of wildfire smoke. The per-unit cost of these symptoms may be small, but the potential number of people who experience these health outcomes could be large. As a result, the total cost of minor symptoms may be substantial.

[M]See also Vedal and Dutton (2006) for the discussion of potential bias in conventional time-series PM models. Naeher *et al.* (2007) also provide a discussion about the limitation of several studies with short-observation and few reference periods.

[N]Studies that implemented a time-series approach and found a significant increase in mortality and emergency department visits during a wildfire event tended to involve long observation periods. For example, Sastry (2002) uses 13 to 33 smoke days and Chen *et al.* (2006) use 452 smoke days.

[O]A related issue of this topic is that wildfire smoke has different PM sizes than urban air pollution. According to Ward (1999), wildfire smoke mainly contains $PM_{2.5}$. Some studies suggest that $PM_{2.5}$ is more hazardous than PM_{10} (US EPA 2004). If this is the case, wildfire smoke would be more hazardous than urban air pollution.

[P]Vedal and Dutton (2006) and Kunii *et al.* (2002) provide a discussion of the effectiveness of averting behaviours during wildfire events.

[Q]There are only four hospital admission or mortality studies, Chen *et al.* (2006), Cançado *et al.* (2006), Delfino *et al.* (2009) and Morgan *et al.* (2010), that have taken such an analytical approach.

Finally, no studies have estimated the scale of averting behaviour during a wildfire event. Information on averting behaviour would provide a more complete picture of the health costs of wildfire and might help explain the disparity between conventional PM and wildfire PM studies.

Economic values of health effects

In this section, we review the economic valuation studies related to adverse health outcomes. Adverse health outcomes caused by wildfire smoke impose direct and indirect costs on society. Freeman (2003) divides the types of health costs into four categories: (1) medical costs, (2) labour loss, (3) averting costs, and (4) utility loss (discomfort, suffering). From an economic efficiency standpoint, the total cost associated with health damage should be estimated by the individual's WTP to avoid such health damages. Unfortunately, to our knowledge, there is no economic valuation study that estimated WTP to avoid adverse health outcomes associated with wildfire smoke. Thus we review economic studies that estimated the value of avoiding adverse health outcomes in general.

The widely cited US EPA (1999) report used the health valuation literature to estimate per-unit costs of different adverse health outcomes. In this section, we review the EPA's estimates and the more recent health valuation literature. We also discuss whether the EPA values should be revised based on the new literature or whether there is little difference between new and old estimates of health damages. Table 6 presents a summary of valuation estimates used in the US EPA report (1999).

Mortality valuation

The per-unit cost of premature mortality is measured by the value of a statistical life (VSL), which is society's aggregated willingness to pay to save one anonymous person's life. Viscusi (1992) provides one of the first comprehensive reviews of VSL literature. The US EPA (1999) uses the average value of Viscusi's selected 26 VSL estimates, US$7.6 million,[R] to evaluate the benefit of air-pollution control to prevent premature mortality. Out of 26 VSL estimates, 21 estimates are based on labour-market data, and five estimates are based on survey studies. Later, the US EPA revised the VSL to $6.8 million based solely on the labour-market studies (US EPA 2005).

Recent research suggests that labour-market studies used in the US EPA (1999, 2005) analysis overestimate VSL owing to incorrect model specifications. Kniesner *et al.* (2010) and Kochi (2006) correct this bias and report VSL estimates of $8 million–$14 million and $2 million respectively. A recent survey-based study in the USA found that the mean VSL is between $1.8 and $5.7 million (Alberini *et al.* 2004). Taken as a whole, the recent literature suggests that VSL may range between $2 million and $14 million.

Morbidity valuation

Estimating per-unit cost of morbidity is more complex than estimating per-unit cost of premature mortality, as the severity and duration of adverse health outcomes varies (for a detailed review of morbidity valuation methodologies, see Tolley *et al.* (1994) and Dickie and Gerking (2002)). The US EPA (1999) estimates morbidity costs of air pollution based on existing literature using the COI method or the contingent valuation (CV) method. The COI method is often used to value the cost of health outcomes that involve some type of medical care, such as hospitalisation or emergency department visits, and only includes the direct expenses associated with illness, such as medical costs and lost wages.[S] The CV method uses surveys to measure individuals' WTP to prevent an adverse health outcome, which includes the utility loss from illness and averting costs, as well as direct costs.

A full economic accounting of morbidity costs should be in terms of WTP, but COI is easier to measure. Consequently, a common practice is to convert individual COI to WTP using a WTP/COI ratio. Chestnut *et al.* (1999) provide a summary of four studies that estimated WTP as well as COI using the same study population and the same health endpoint.[T] When a COI estimate accounts for the cost incurred by the individual and a third party, such as a health insurance company, it is called a social COI and the estimated WTP/social COI ratio is between 1.3 to 2.4 for asthma symptoms, cataract and angina symptoms. Chestnut *et al.* (1999) recommend a conservative WTP/social COI ratio of 2.0 for non-fatal morbidity treatment except for cancers, and 1.5 for non-fatal cancer treatment.[U]

Several studies have estimated WTP to avoid relatively minor symptoms, such as acute cardiorespiratory symptoms. Dickie and Gerking (2002) and Dickie and Messman (2004) provided a list of studies and estimates. As Dickie and Messman (2004) noted, WTP values used by the US EPA (1999) are generally lower than more recently estimated values (selected results from the Dickie and Messman (2004) study are presented

[R]All dollar values are in 2007 US dollar values converted using the Consumer Price Index.

[S]Conventional Cost of Illness (COI) generally estimates only medical costs and lost wages during a hospital stay or hospital visit. However, a recent study by Chestnut *et al.* (2006) found that the time lost during recovery from a hospital stay is also an important source of cost, which increases conventional COI estimates by 9 to 32%. The COI during this recovery period includes: additional medical costs, lost wages, and lost productive and recreational activities. The COI per hospitalisation also depends on the age of the patient and category of illness. The elderly (over 65 years old) have lower COI than younger individuals owing to the smaller value of lost work days.

[T]These four studies either directly elicited the dollar value of willingness to pay (WTP) and cost of illness (COI), or they asked respondents to rate the share of COI components as a share of perceived total health cost. For example, Chestnut *et al.* (1988) asked respondent to rate each component of WTP associated with an increase in angina episode with a scale of 'bothersomeness'. WTP components include COI consequences (medical costs and labour loss), and non-COI consequences, such as less leisure and more concern.

[U]If the cost of illness (COI) estimate only accounts for the cost incurred by an individual (called individual COI), the WTP/individual COI ratio (WTP, willingness to pay) could be significantly higher than the WTP/social COI ratio. It is important to remember that WTP/COI ratios may vary significantly across different health outcomes, as Adamowicz *et al.* (2004) indicated.

Table 6. Per-unit economic value used in US EPA (1999)
Created from table 6-1, p. 70 and table H-3, pp. H-21–H-26, US EPA (1999). Monetary value adjusted to year 2007 level

	US EPA value (US$ 2007)	Dickie and Messman (2004)
Mortality	$7 600 000	
Hospital admissions		
All respiratory	$10 971	
All cardiovascular	$15 105	
Emergency department visits for asthma	$308	
Respiratory illness and symptoms		
Acute bronchitis	$71	$202 (adult) $380 (child)
Asthma attack or moderate or worse asthma day	$50	
Acute respiratory symptoms	$28	1-day symptom $90 (adult) $190 (child)
Upper respiratory symptoms	$30	
Lower respiratory symptoms	$19	
Shortness of breath, chest tightness or wheeze	$8	1-day shortness of breath $190 (child)
Work days loss	$131	
Mild restricted-activity days	$60	

in Table 6). For example, the US EPA uses $71 per acute bronchitis case, whereas Dickie and Messman (2004) estimated the median WTP to prevent a 6-day-long acute bronchitis case as $202 for an adult.[V] Similarly, the US EPA uses $28 per day for acute respiratory symptoms, whereas Dickie and Messman (2004) estimated $90 a day for an adult.

It is not clear why more recent studies report generally higher WTP estimates than older studies. However, recent studies incorporate improvements in non-market valuation methods and so may warrant more weight than older studies. Finally, many studies (Liu *et al.* 2000; Navrud 2001; Dickie and Messman 2004) consistently find that WTP estimates for the prevention of children's morbidity are substantially higher than the WTP estimates for the prevention of adults' morbidity. This underlines the importance of valuing adults' and children's morbidity impacts separately.

Wildfire policy considerations

Quantifying the health effects of wildfire smoke

If wildfire-management decisions are going to take into consideration the potential mortality impacts of wildfire smoke, we do not recommend using results from conventional PM epidemiology studies to estimate the mortality effects of wildfire. Although conventional PM studies generally show a statistically significant mortality risk of short-term PM exposure, the majority of wildfire-PM studies do not. Extrapolating mortality impact results from conventional PM studies to wildfire may substantially overestimate mortality-related costs. If a wildfire is of short duration, or results in only moderate increases in PM levels, then analysts might consider assuming no mortality effect, while noting that this assumption may underestimate true cost. If mortality effects are to be included, it should be noted that there is still great uncertainty in the VSL estimates.

Consideration of respiratory-related morbidity effects in wildfire-management decisions based on results of conventional PM studies might be reasonable if wildfire-specific study results are not available. However, this recommendation comes with the caveat that the health effects of urban air pollution may be somewhat different from wildfire smoke. The cost of severe morbidity that involves major medical care could be estimated based on the social COI method. To convert social COI to WTP, a WTP/social COI ratio of 2 is generally accepted. Dickie and Messman (2004) is a good source to find WTP to avoid less severe respiratory symptoms, as they used a relatively large USA sample. Finally, we again emphasise the importance of accounting for adults and children separately.

Consideration of health effects of wildfire smoke in policy options

During a wildfire event, there are two main ways to reduce the adverse health impacts of wildfire smoke: wildfire suppression to reduce PM emissions or temporarily moving susceptible people away from smoke-affected areas. The appropriate response depends on the impact wildfire smoke is likely to have on air quality, the number of people who will be exposed to the smoke, and the likely efficacy of wildfire suppression actions. For example, in the introduction, we noted that improving air quality was a major reason that the USDA Forest Service decided to suppress all wildfires in California during the summer of 2008. In the weeks leading up this decision, wildfires had a significant impact on air quality.[W] As total health costs are

[V]Dickie and Messman (2004) found that the average acute bronchitis symptom lasts an average of 7 days among the sample.

[W]The US EPA classifies wildfires as exceptional events and, therefore, does not penalise states if wildfire smoke causes federal air-quality standards to be breached.

determined largely by the magnitude of the population exposed to the smoke, all else equal, deploying a higher suppression effort is more likely warranted when wildfire smoke drifts into highly populated areas. Fire managers need to recognise that air pollution does not affect all segments of the population equally. People with pre-existing respiratory problems are far more likely to suffer adverse health outcomes. Therefore, moving a relatively small fraction of the population away from smoke-affected areas may significantly reduce the health impacts of a wildfire. However, if a wildfire affects a large metropolitan area, then moving even a small fraction of the affected population may be difficult and expensive. In such an urban area, higher levels of wildfire suppression may be cost-effective when compared with the cost of relocating thousands of people.

Another important factor to consider in wildfire smoke and suppression decisions is the marginal impact of suppression on air quality. During periods of severe fire weather, suppression may have little impact of fire behaviour. Under these circumstances, increased suppression effort would have little effect on PM levels and could not be justified on the basis of reducing health-related costs.

Reducing PM from wildfires and reducing conventional PM pollution differ in a crucial way. If urban PM is reduced by closing down a coal-fired power plant permanently, for example, then this does not increase the probability of PM emissions in the future (indeed, it does the opposite). However, suppressing wildfires to reduce PM may increase the potential for future PM emissions if a wildfire occurs years later. That is, if a wildfire is successfully suppressed, then the fuel that would have burned remains in the forest. This increased fuel load means that, in the future, severe wildfires – which emit more PM – are more likely. Wildfire suppression does not eliminate PM pollution; it may shift it into the future.[X] Thus true wildfire smoke prevention requires long-term fuel reduction.

The literature reviewed in this article suggests that prescribed burning, which reduces the probability of future severe wildfires, should result in a net reduction in health damages relative to wildfires for two reasons. First, prescribed fire generally burns less intensely, resulting in lower emissions than wildfires. If the dose–response function is non-linear, there are likely to be substantially smaller health effects at these lower PM concentrations. Second, prescribed burning can be conducted when the winds will not direct the smoke into densely populated areas, again minimising the health damages while reducing fuel loads and future PM emissions.

The wildfire–air pollution relationship also strengthens the rationale for mechanical fuel reduction. Forest thinning can be done to reduce the emissions per acre that would result if a wildfire were to occur. Thus health costs avoided should be included as one of the benefits of mechanical fuel reduction. Although mechanical fuel reduction costs more per acre compared with prescribed burning, in densely populated wildfire-prone areas, the total economic costs, including health costs, could be lower for mechanical fuel reduction than prescribed burning.

Conclusions

In this paper, we summarise the available literature related to economic analysis of adverse health impacts from wildfire smoke, identify the key issues to be investigated in the future to improve this research area, and discuss how concerns about the health effects of smoke could be considered in wildfire management decisions. We find that the available literature on the economic analysis of adverse health impacts from wildfire smoke and wildfire-specific epidemiology studies are still limited. We identify several potentially productive research areas. First, investigating the unique health effects of wildfire smoke compared with conventional air pollution would be helpful to better quantify the adverse health impacts of wildfire smoke, as well as to determine whether it is appropriate to extrapolate from existing conventional air pollution dose–response functions. Second, quantifying the relatively minor adverse health impacts that do not require major medical care could be very important as the total cost associated with these health outcomes could be substantial. Last, understanding averting behaviour during wildfire events could be important as the opportunity costs of avoiding wildfire smoke through evacuation, avoidance of outdoor activity, or other preventive measures may be substantial.

The health-related cost of wildfire-smoke exposure should undoubtedly be an important consideration for wildfire management policy. However, we still have limited knowledge about the nature of this cost. We encourage more research as such information will have increasing importance as the number and scale of future wildfire events is predicted to increase.

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[X]Shifting the adverse health effects of wildfire smoke into the future would provide some benefit, as these costs would be discounted.

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