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Wildfire smoke exposure under climate change: impact on respiratory health of affected communities

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Abstract

Purpose of review—In this review, we describe the current status of the literature regarding respiratory health related to wildfire smoke exposure, anticipated future impacts under a changing climate, and strategies to reduce respiratory health impacts of wildfire smoke.

Recent Findings—Recent findings confirm associations between wildfire smoke exposure and respiratory health outcomes, with the clearest evidence for exacerbations of asthma. Although previous evidence showed a clear association between wildfire smoke and chronic obstructive pulmonary disease, findings from recent studies are more mixed. Current evidence in support of an association between respiratory infections and wildfire smoke exposure is also mixed. The only study to investigate long-term respiratory health impacts of wildfire smoke demonstrated decreases in lung function ten years after exposure though this finding was only in males who were young adults during the 1997 Indonesian fires. Few studies have estimated future health impacts of wildfires under likely climate change scenarios.

Summary—Wildfire activity has been increasing over the past several decades and is likely to continue to do so as climate change progresses, which, combined with a growing population, means that population exposure to and respiratory health impacts of wildfire smoke is likely to grow in the future. More research is needed to understand which population subgroups are most vulnerable to wildfire smoke exposure and the long-term respiratory health impacts of these high pollution events.

Keywords

Wildfires; smoke; air pollution; climate change; respiratory system; particulate matter

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1 Introduction: Wildfire Smoke, Climate Change, and Respiratory Health

Wildfire activity has increased over the past few decades in the western United States (US). This can be at least partly attributed to climate change and historical fire suppression [1–3]. Anthropogenic contributions to climate change are estimated to have led to a doubling of the total area burned by forest fires in the western US between 1984–2015 [1]. Wildland fires contribute to increases in air pollution locally and regionally [4, 5*, 6–9]. An estimated 26% of summertime organic aerosols in the western US come from wildfires; this fraction is expected to increase as wildfires become more prevalent while urban air pollution continues to decline [10]. $PM_{2.5}$ (particulate matter with an aerodynamic diameter smaller than 2.5 microns) concentrations are declining in most of the US except the Northwest US where the increasing concentrations are attributed to wildfires [7]. Recent review papers have highlighted the health impacts of population exposure to air pollution from wildfires [11–13], with consistent evidence of an association with exacerbations of asthma and chronic obstructive pulmonary disease (COPD) [11]. Current estimates of the health costs of wildfire smoke exposure range from $11–20 billion/year in the continental US [14]. In this review, we review the findings from epidemiological studies published between January 2016 and August 2018 in English in peer-reviewed journals on the association between wildfire smoke and population respiratory health. We also review proposed strategies to decrease population exposure to wildfire smoke and papers that project future air quality and health impacts of wildfires in a changing climate.

2 Exposure Assessment During Wildfires

Wildfire smoke contains a variety of chemical components [9, 15–17] and can significantly impact air quality locally and regionally [4, 5*, 18*]. Population exposure levels from wildfires vary widely, depending on the area burned, fuels, fire intensity, rate of burning, dispersion, and population location [9,19].

$PM_{2.5}$ is the component in wildfire smoke of most concern for health. In the US, the daily average National Ambient Air Quality Standard for $PM_{2.5}$ is 35 $\mu g/m^3$, however, the World Health Organization recommends that daily $PM_{2.5}$ not exceed 25 $\mu g/m^3$.

Ambient concentrations of $PM_{2.5}$ in the vicinity of a wildfire can be extremely high. Hourly concentrations of 6,106 $\mu g/m^3$ and daily concentrations of 394 $\mu g/m^3$ have been documented [15,17]. About 52% of all summertime 24-hr $PM_{2.5}$ observations above 35 $\mu g/m^3$ in the continental US occur when a smoke plume is present [20].

Exposure assessment methods of $PM_{2.5}$ from wildfires have improved in recent years. Many early studies used temporal comparisons, in which the health outcomes from one time period are compared with similar time periods without wildfire smoke. Temporal comparisons may be confounded by temporally-varying factors such as temperature and relative humidity and do not allow quantification of the exposure-response function. Other early studies relied on monitoring data to assess particulate matter (PM) exposure. Although monitoring data is our best estimate of PM exposure at that location, air pollution varies spatially, especially during wildfires. This can lead to exposure misclassification likely biasing effect estimates towards the null [21]. In our previous review [11], some studies began to use atmospheric models (AMs) and/or satellite aerosol optical depth (AOD) data to help assess exposure. These data can improve spatiotemporal information about $PM_{2.5}$, but both have uncertainties. AOD measures total particles in the atmospheric column, and does not directly represent ground-level PM concentrations that people are breathing. AOD data is also missing when clouds are present [22]. AMs are physically-based and can provide information related to emissions, transport, and chemistry in locations that lack monitors but are often inaccurate compared to monitors. Research demonstrates that statistically merging AMs with monitoring data improves accuracy [23]. Recent wildfire smoke and health studies often statistically 'blend' data (e.g. Gan et al. [24!] and Reid et al. [25*] from multiple sources such as satellites, AMs, monitors, meteorology, and land use. There is yet no consensus on which of the various blending methods is 'best', however, these methods likely improve understanding of wildfire smoke exposures beyond the use of monitoring or modelled data alone.

3 Respiratory health effects associated with wildfire smoke exposure

PM from wildfire smoke is thought to affect the lungs by contributing to oxidative stress, inflammation, and cell toxicity [26]. Studies of the toxicity of wildfire smoke tend to focus on *in vitro* assessments of release of inflammatory proteins, concentrations of species that indicate oxidative stress, biomarkers of the body's response to oxidative stress and inflammation, evidence of genotoxicity, or levels of macrophages and monocytes denoting activation of the immune system [27*]. A recent review finds that although few toxicity studies of PM focus on wildfire sources, of those that do, most find that finer particles are more toxic than coarser particles and that wildfire PM may be more toxic than urban PM [27*]. Previous research shows that respiratory symptoms are associated with exposure to wildfire smoke [28, 29], and current evidence is consistent with this conclusion [30*–34*].

We review the recent evidence for respiratory health impacts associated with wildfire smoke exposure, noting that many studies explored a variety of respiratory health outcomes but are assessed here separately. One recent study [35] is not included in our discussion as it did not adjust for any appropriate confounding factors and therefore we consider the findings inaccurate. Information on study location, exposure assessment method, and findings are shown in Table 1. Table 1 also highlights methodological concerns in the studies reviewed.

3.1 Lung Function

As discussed in Reid et al. [11], multiple studies have found a decrease in lung function associated with wildfire smoke exposure among individuals without asthma or bronchial hyperreactivity. It is hypothesized that medication use among these individuals prevents a decrease in lung function [11]. A recent study is the first to demonstrate potential long-term health impacts from wildfire smoke exposures in humans [36!]. Males who were adults during the 1997 Indonesian wildfires showed decreased lung function ten years later that was not associated with other temporal changes; those exposed as children seemed to have recovered their lung function ten years later [36!]. A decrease in lung function was also observed in a cohort of three year-old (adolescent) Macaque monkeys who were infants during the 2008 California wildfires that was not observed in an unexposed cohort (born a year later) [40].

3.2 Asthma

A growing body of evidence documents an association between exacerbations of asthma and wildfire smoke exposure [11]. Since 2016, this evidence is corroborated by significant positive associations between hospitalizations, ED visits, and outpatient visits for asthma exacerbations and wildfire smoke exposure in nine of 12 analyses reviewed here [24!, 25*, 32*, 37*, 38*], see Table 1. Two more found suggestive, if not statistically significant associations [32*, 33*], and another found a null association [33*]. It is notable that two of these non-significant analyses used estimates of wildfire $PM_{2.5}$ from an AM that does not account for chemical reactions in the atmosphere or blend with monitoring data, and the third used a temporal comparison.

3.3 Chronic obstructive pulmonary disease (COPD)

In our previous review [11], we showed that the consensus of the literature showed a consistent positive association for exacerbations of COPD and wildfire smoke exposure. The current literature, however, is less consistent with only four statistically significant positive associations of 11 analyses. Significant associations were observed between wildfire smoke exposure and COPD ED visits but null results for hospitalizations during the 2008 northern California wildfires [25*]. An analysis of the 2012 Washington state fires found significant associations between hospitalizations for COPD when using kriged monitoring data or $PM_{2\ 5}$ exposures from a model that blended monitoring, AOD, and AM data, but not from AM-derived $PM_{2\ 5}$ estimates [24!]. Alman et al. [38*] found significant associations between combined hospitalizations and ED visits for COPD and AM-derived $PM_{2.5}$ levels during the 2012 Colorado fire season. Analyses using temporal comparisons were null for outpatient visits, ED visits, and hospitalizations [32*], as were results from two analyses using AM-derived PM exposures for ED visits [33*, 37*].

3.4 Respiratory Infections

Previously, we found mixed evidence of an association between wildfire smoke exposure and respiratory infections [11]. At that time, of fourteen analyses of all respiratory infections combined or pneumonia and bronchitis combined, eight showed a significantly positive relationship, two showed a suggestive positive relationship, and four found null associations. We have found 18 new analyses of the relationship between wildfire smoke exposure and respiratory infections, however different studies group respiratory infections differently (see Table 1), making comparisons across studies difficult. Different findings could be due to outcome grouping or other methodological choices.

In a study of the impacts of wildfires in Indonesia on air pollution and health in Singapore, clinic visits for acute respiratory infections increased significantly during weeks with high fire levels (as estimated from satellite-derived fire radiative power) in Indonesia during 2010–2016 [5*]. During a 2008 peat fire in North Carolina, ED visits for a set of acute respiratory infections that included acute bronchitis and pneumonia were significantly positively associated with $PM_{2.5}$ [33*].

Hutchinson et al. [32*] found significantly elevated risk of ED visits, but not outpatient or inpatient presentations at hospitals, for upper respiratory infections during a wildfire event compared to reference periods among the Medi-Cal (Medicaid) population in San Diego. Alman et al. [38*] found a borderline significant association for combined hospitalizations and ED visits for upper respiratory infections and $PM_{2.5}$ during wildfires in 2012 in Colorado.

We found four recent studies [24!, 25*, 32*,38*] with seven different analyses of the association between wildfire smoke and pneumonia, of which, all were null except two. The analysis of outpatient presentations (but not hospitalizations or ED visits) by Hutchinson et al. [32*] found a borderline significant relationship. Gan et al. [24!] found a significant association between pneumonia hospitalizations and wildfire smoke during the 2012 Washington state fires only when assessing exposure from kriged monitoring data, but not from an AM or a blended model.

The studies that have investigated the association between wildfire smoke and acute bronchitis show mixed findings, and the only significant findings come from one study that used only temporal comparisons and found statistically significant associations for ED visits and outpatient presentations, but not for hospitalizations among Medi-Cal patients in San Diego [32*]. A study of the 2012 Washington State wildfires found no significant associations between acute bronchitis hospitalizations and wildfire smoke using three different methods to estimate wildfire smoke [24!]. No association was found for hospitalizations and ED visits combined for bronchitis, not otherwise specified, during the 2012 wildfire season in Colorado [38*].

The null findings associated with pneumonia and bronchitis are in contrast to previous papers that collectively hinted at an association between wildfire smoke and pneumonia and bronchitis [11]. It is notable that most of the previous studies had grouped pneumonia and bronchitis together rather than separating them as is the norm in these recent studies. One earlier study that did separate pneumonia and bronchitis found a significant association between $PM_{2.5}$ and pneumonia but not acute bronchitis during the 2003 wildfires in southern California [41].

3.5 Grouped Respiratory Outcomes

Several recent papers investigate the relationship between wildfire smoke exposure and all respiratory health outcomes grouped together. Studies consistently find significant associations for hospitalizations [24!, 25*, 39*], hospitalizations and ED visits combined [38*], ED visits [25*, 32*], and outpatient presentations [32*]. A few studies, however, did not observe significant relationships [18*, 32*, 33*]. It should be noted that one of these [18*] examined long-range transported smoke rather than fresh smoke, which could have different chemical composition.

4 Vulnerable Populations

Understanding if specific population subsets experience differential impacts from wildfire smoke is important for targeting public health messages to more vulnerable groups. Yet few studies have investigated effect modification by population subgroups and, of those, the results are not consistent across studies. When investigating differential effects by gender, some find larger effect sizes in women [25*, 37*,42*], some in men [24!, 36!], but many find no differences [24!, 32*, 33*, 43*]. Many studies investigate differential impacts by age groups [24!, 25*, 32*, 33*, 37*, 38*], but no consistent conclusions can be drawn. Other population subgroups have been insufficiently studied with only one recent study investigating race [42*], and only two investigating socio-economic status [25*,42*].

5 Strategies to Reduce Smoke Exposure and Associated Health Impacts

Fire is a feature of the landscape that we cannot remove [3, 19, 44], therefore we have to learn to live with fire and its associated air pollution impacts. We can, however, aim to decrease population health harms. Changes to land and fire management practices could help balance the ecological need for fires with the need to minimize population exposure to wildfire smoke [3, 19, 44]. Prescribed fires can be used to decrease the risk of catastrophic wildfires. To our knowledge, no studies have quantified potential differential health impacts of smoke from wildfires and prescribed fires, though the question has been raised [9].

In communicating risk to the public, recent research highlights the need for consistent messages using simple language across several channels of communication, with attentiveness to the particular at-risk population [45]. Clean air shelters and portable air cleaners may reduce individual exposure to wildfire smoke [34*, 46]. Hospitals should prioritize the increased risk of wildfires in their planning related to climate change [47].

6 Future Impacts Due to Climate Change

Few studies have estimated future population exposures to wildfire smoke due to climate change, despite many studies projecting higher wildfire risk [48–50]. Mills et al. [50] project that tens of millions of people in the continental US will be exposed to wildfire smoke at least once per 20-year period in the mid- and late-21st century under two climate change scenarios. Liu et al. [51] estimated that $PM_{2.5}$ exposures due to wildfire smoke in the western US for 2046–2051 under moderate climate change will be 160% higher than currently observed.

Combining modeled estimates of future wildfire-specific $PM_{2.5}$ concentrations for the western US with projected population changes and current exposure-response curves for the association between “smoke waves” and respiratory hospitalizations, Liu et al. [52!] found that both climatic changes and projected increases in population will increase the number of respiratory hospitalizations due to wildfire smoke exposure. Ford et al. [53!] estimate that premature deaths attributable to fire-related $PM_{2.5}$ will double by late 21st century compared to early 21st century under climate change scenarios.

7 Conclusion

As climate change progresses, the probability of wildfires is likely to increase in many places, making it more important than ever to understand the health effects of wildfire smoke exposure. Growing evidence suggests respiratory health is impacted by wildfire smoke. Further research is needed to elucidate causes of inconsistent findings among studies, which could be due to exposure assessment methods, fire characteristics, groupings of ICD-9 codes, population susceptibility, or statistical techniques. Additionally, research is needed to investigate effective measures for reducing population exposure, including clean air shelters, portable air cleaners, and land management practices.

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[24]**. Gan RW, Ford B, Lassman W, et al. Comparison of wildfire smoke estimation methods and associations with cardiopulmonary-related hospital admissions. GeoHealth. 2017;1:122–136. [PubMed: 28868515] This study used three separate methods of estimating population exposure to wildfire smoke in Washington State, US. They found that some of their results were not consistent among the three exposure estimation methods, highlighting the importance of carefully considering exposure estimation methods.

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interesting findings related to mental health that should influence future quantitative epidemiological investigations.

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[36]**. Kim Y, Knowles S, Manley J, Radoias V. Long-run health consequences of air pollution: Evidence from Indonesia's forest fires of 1997. Economics and Human Biology. 2017;26:186–198. [PubMed: 28460366] This study observed a long-term (10-years) decrease in the lung function associated with smoke exposure to the 1997 Indonesian Fires. This is the first study to analyze long-term health consequences of landscape smoke exposure.

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[38]*. Alman BL, Pfister G, Hao H, et al. The association of wildfire smoke with respiratory and cardiovascular emergency department visits in Colorado in 2012: a case crossover study. Environ Health. 2016;15:64. [PubMed: 27259511] This study conducted case crossover analyses of several respiratory outcomes for wildfire smoke exposure and stratified by age to examine effect modification.

[39]*. Liu JC, Wilson A, Mickley LJ, et al. Wildfire-specific Fine Particulate Matter and Risk of Hospital Admissions in Urban and Rural Counties. Epidemiology (Cambridge, Mass). 2017;28:77–85.This study conducted a large-scale study both in terms of geographic extent and time. Liu et al. used the concept of smoke waves to analyze the risk of respiratory hospital admissions among the Medicare population and wildfire-specific PM2 5, and found a positive association for the western US from 2004–2009.

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[42]*. Liu JC, Wilson A, Mickley LJ, et al. Who among the elderly is most vulnerable to exposure and health risks of PM2.5 from wildfire smoke? Am J Epidemiol. 2017;186:730–735. [PubMed: 28525551] This is one of the few recent studies to investigate effect modification of the smoke-

health relationship by population subgroups (age, sex, race), which is an area that needs more research.

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[53]**. Ford B, Val Martin M, Zelasky SE, et al. Future Fire Impacts on Smoke Concentrations, Visibility, and Health in the Contiguous United States. GeoHealth. 2018;2:229–247.This study projects future air pollution impacts from wildfires under two climate change scenarios. It then estimates the number of deaths that would be expected from those changes in air pollution.

Key Points

- Wildfires and smoke exposures are anticipated to increase in the western US as climate change progresses.
- A growing body of evidence indicates that exacerbations of asthma are affected by wildfire smoke exposure, while evidence of COPD was clear but recent research is not as consistent.
- Inconsistent results among studies examining associations between wildfire smoke exposure and respiratory infections indicate that more research is necessary to achieve consensus.
- Inconsistencies in the findings among studies considering differential health impacts of smoke exposure among various subsets of the population indicate that more research is needed to understand which populations are most vulnerable to smoke exposure.
- Further research is needed to better understand the reasons for inconsistency in findings among studies, which could be due to exposure assessment method, fire characteristics, grouping of ICD-9 codes, underlying population susceptibility, or statistical techniques used.

Table 1:

Summary of studies examining respiratory health impacts of wildfire smoke exposure by respiratory outcome.

	Health Encounter Type	Study Period and Area	Exposure Assessment Method	Findings
Lung Function				
Kim et al. [36!]	Pulmonology tests	Indonesia ten years after 1997 fires	Interpolated satellite data	↓↓
Asthma				
Hutchinson et al. [32*][NEW1OLD2]	outpatient presentation	2007 fires San Diego County	Temporal comparison	↿↿
Haikerwal et al. [37*]	ED visits	Victoria, Australia Dec2006-Jan2007	AM $PM_{2.5}$ output	↿↿
Hutchinson et al. [32*][NEW1OLD2]	ED visits	2007 fires San Diego County	Temporal comparison	↿↿
Hutchinson et al. [32*][NEW2OLD7]	ED visits	2007 fires San Diego County	AM $PM_{2.5}$ output	↿
Reid et al. [25*]	ED visits	Northern California 2008 fires	Blended model combining monitoring data, AOD, AM output, meterology and land use	↿↿
Tinling et al. [33*][NEW3OLD6]	ED visits	2011 fires, North Carolina	AM $PM_{2.5}$ output	↔
Alman et al. [38*][NEW4OLD5]	Hospitalizations and ED visits combined	2012 Colorado fires	AM $PM_{2.5}$ output	↿
Gan et al. [24!]	Hospitalizations	2012 fire season Washington State	AM $PM_{2.5}$ output	↿↿
Gan et al. [24!]	Hospitalizations	2012 fire season Washington State	Kriged $PM_{2.5}$	↿↿
Gan et al. [24!]	Hospitalizations	2012 fire season Washington State	Blended model combining kriged monitoring, AOD, and AM data	↿↿
Hutchinson et al. [32*][NEW1OLD2]	Hospitalizations	2007 fires San Diego County	Temporal comparison	↿
Reid et al. [25*]	Hospitalizations	Northern California 2008 fires	Blended model combining monitoring data, AOD, AM output, meterology and land use	↿↿
COPD				
Hutchinson et al. [32*][NEW1OLD2]	outpatient presentation	2007 fires San Diego County	Temporal comparison	↔
Haikerwal et al. [37*]	ED visits	Victoria, Australia Dec2006-Jan2007	AM $PM_{2.5}$ output	↔
Hutchinson et al. [32*][NEW1OLD2]	ED visits	2007 fires San Diego County	Temporal comparison	↔
Reid et al. [25*]	ED visits	Northern California 2008 fires	Blended model combining monitoring data, AOD, AM output, meterology and land use	↿↿
Tinling et al. [33*][NEW5OLD9]	ED visits	2011 fires, North Carolina	Modelled predictions of daily wildfire $PM_{2.5}$ from emissions and HYSPLIT trajectories	↔

	Health Encounter Type	Study Period and Area	Exposure Assessment Method	Findings
Alman et al. [38*] NEW4OLD5	Hospitalizations and ED visits combined	2012 Colorado fires	AM $PM_{2.5}$ output	↑↑
Gan et al. [24!]	Hospitalizations	2012 fire season Washington State	AM $PM_{2.5}$ output	↔
Gan et al. [24!]	Hospitalizations	2012 fire season Washington State	Kriged $PM_{2.5}$	↑↑
Gan et al. [24!]	Hospitalizations	2012 fire season Washington State	Blended model combining kriged monitoring, AOD, and AM data	↑↑
Hutchinson et al. [32*] NEW1OLD2	Hospitalizations	2007 fires San Diego County	Temporal comparison	↔
Reid et al. [25*]	Hospitalizations	Northern California 2008 fires	Blended model combining monitoring data, AOD, AM output, meterology and land use	↔
Respiratory Infections (combined)				↔
Sheldon & Sankaran [5*] no ICD codes reported	outpatient presentation	Singapore, 2010–2016	Predicted pollution based on regression of fire radiative power from satellites, monitoring data, and meteorology	↑↑
Tinling et al. [33*] NEW6OLD10 ICD-9 codes: 466,481, 487, and 485 combined	ED visits	2011 fires, North Carolina	Modelled predictions of daily wildfire $PM_{2.5}$ from emissions and HYSPLIT trajectories	↑↑
Upper Respiratory Infections				
Hutchinson et al. [32*] NEW1OLD2 ICD-9 codes 460–464	outpatient presentation	2007 fires San Diego County	Temporal comparison	↔
Hutchinson et al. [32*] NEW1OLD2 ICD-9 codes 460–464	ED visits	2007 fires San Diego County	Temporal comparison	↑↑
Alman et al. [38*] NEW4OLD5 ICD-9 codes 460–465, 466	Hospitalizations and ED visits combined	2012 Colorado fires	AM $PM_{2.5}$ output	↑↑
Hutchinson et al. [32*] NEW1OLD2 ICD-9 codes 460–464	Hospitalizations	2007 fires San Diego County	Temporal comparison	↔
Pneumonia				
Hutchinson et al. [32*] NEW1OLD2 ICD-9 codes 480–487	outpatient presentation	2007 fires San Diego County	Temporal comparison	↑
Hutchinson et al. [32*] NEW1OLD2 ICD-9 codes 480–487	ED visits	2007 fires San Diego County	Temporal comparison	↔
Reid et al. [25*] ICD-9 codes 480–486	ED visits	Northern California 2008 fires	Blended model combining monitoring data, AOD, AM output, meterology and land use	↔
Alman et al. [38*] NEW4OLD5 ICD-9 codes 480–486	Hospitalizations and ED visits combined	2012 Colorado fires	AM $PM_{2.5}$ output	↔↔

	Health Encounter Type	Study Period and Area	Exposure Assessment Method	Findings
Gan et al. [24!] ICD-9 codes 480–486	Hospitalizations	2012 fire season Washington State	AM $PM_{2.5}$ output	↔
Gan et al. [24!] ICD-9 codes 480–486	Hospitalizations	2012 fire season Washington State	Kriged $PM_{2.5}$	↑↑
Gan et al. [24!] ICD-9 codes 480–486	Hospitalizations	2012 fire season Washington State	Blended model combining kriged monitoring, AOD, and AM data	↑
Hutchinson et al. [32*]*NEW1OLD2* ICD-9 codes 480–487	Hospitalizations	2007 fires San Diego County	Temporal comparison	↔
Reid et al. [25*] ICD-9 codes 480–486	Hospitalizations	Northern California 2008 fires	Blended model combining monitoring data, AOD, AM output, meterology and land use	↔
Bronchitis				
Hutchinson et al. [32*]*NEW1OLD2* ICD-9 code 466 (acute bronchitis)	outpatient presentation	2007 fires San Diego County	Temporal comparison	↑↑
Hutchinson et al. [32*]*NEW1OLD2* ICD-9 code 466 (acute bronchitis)	ED visits	2007 fires San Diego County	Temporal comparison	↑↑
Alman et al. [38*]*NEW4OLD5* ICD-9 code 490 (bronchitis, not otherwise specified)	Hospitalizations and ED visits combined	2012 Colorado fires	AM $PM_{2.5}$ output	↔
Gan et al. [24!] ICD-9 code 466 (acute bronchitis)	Hospitalizations	2012 fire season Washington State	AM $PM_{2.5}$ output	↔
Gan et al. [24!] ICD-9 code 466 (acute bronchitis)	Hospitalizations	2012 fire season Washington State	Kriged $PM_{2.5}$	↔
Gan et al. [24!] ICD-9 code 466 (acute bronchitis)	Hospitalizations	2012 fire season Washington State	Blended model combining kriged monitoring, AOD, and AM data	↔
Hutchinson et al. [32*]*NEW1OLD2* ICD-9 code 466 (acute bronchitis)	Hospitalizations	2007 fires San Diego County	Temporal comparison	↔
Combined Respiratory Conditions				
Hutchinson et al. [32*]*NEW1OLD2*	outpatient presentation	2007 fires San Diego County	Temporal comparison	↑↑
Hutchinson et al. [32*]*NEW7OLD3*	ED visits	2007 fires San Diego County	Modelled predictions of daily wildfire $PM_{2.5}$ from emissions and HYSPLIT trajectories	↑↑
Hutchinson et al. [32*]*NEW1OLD2*	ED visits	2007 fires San Diego County	Temporal comparison	↑↑
Reid et al. [25*]	ED visits	Northern California 2008 fires	Blended model combining monitoring data, AOD, AM output, meterology and land use	↑↑
Tinling et al. [33*]	ED visits	2011 fires, North Carolina	Modelled predictions of daily wildfire $PM_{2.5}$ from emissions and HYSPLIT trajectories	↑

	Health Encounter Type	Study Period and Area	Exposure Assessment Method	Findings
Alman et al. [38*] *NEW4OLD5*	Hospitalizations and ED visits combined	2012 Colorado fires	AM $PM_{2.5}$ output	↑↑
Gan et al. [24!]	Hospitalizations	2012 fire season Washington State	AM $PM_{2.5}$ output	↑↑
Gan et al. [24!]	Hospitalizations	2012 fire season Washington State	Kriged $PM_{2.5}$	↑↑
Gan et al. [24!]	Hospitalizations	2012 fire season Washington State	Blended model combining kriged monitoring, AOD, and AM data	↑↑
Hutchinson et al. [32*] *NEW1OLD2*	Hospitalizations	2007 fires San Diego County	Temporal comparison	↔
Kollanus et al. [18*]	Hospitalizations	Helsinki metro area 2001–2010	Binary smoke days determined from monitoring data	↔
Liu et al. [39*] OLD4	Hospitalizations	Western US 2004–2009	Binary smoke waves determined from AM	↑↑
Reid et al. [25*]	Hospitalizations	Northern California 2008 fires	Blended model combining monitoring data, AOD, AM output, meterology and land use	↑↑

When analyses were stratified by subgroups (i.e., age), we are only showing results in this table for all groups combined.

Abbreviations: US = United States; COPD = chronic obstructive pulmonary disease; $PM_{2.5}$ = particulate matter with an aerodynamic diameter smaller than 2.5 μm; AM = Atmospheric Model; AOD = Aerosol Optical Depth

↔ No association.

↑ Suggestive increase.

↑↑ Significant increase.

↓↓ Significant decrease.

NEW1OLD2: This analysis did not adjust for temperature and relative humidity.

NEW2OLD7: Increase in OR with increasing moving average (48-hour and 72-hour)

NEW3OLD6: effect estimate shown is for all adults, but sub-analyses were done for other age groups

NEW4OLD5: lag 0

NEW5OLD9: called chronic pulmonary conditions using ICD codes: (490, 491, 492, 496)

NEW6OLD10: Called upper respiratory infections

NEW7OLD3: Increase in OR with increasing moving average (48-hour and 72-hour)