REVIEW

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

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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. Only one study has investigated long-term respiratory health impacts of wildfire smoke, and 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

air pollution, climate change, particulate matter, respiratory system, smoke, wildfires

INTRODUCTION: WILDFIRE SMOKE, CLIMATE CHANGE, AND RESPIRATORY HEALTH

Wildfire activity has increased over the past few decades in the western United States. 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 United States between 1984 and 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 United States 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 μm) concentrations are declining in most of the United States except the Northwest United States 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 to 20 billion/year in the continental United States [14]. In this review, we review the findings from epidemiological studies

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KEY POINTS

- Wildfires and smoke exposures are anticipated to increase in the western United States as climate change progresses.
- A growing body of evidence indicates that exacerbations of asthma are affected by wildfire smoke exposure, whereas recent evidence for COPD 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 because of exposure assessment method, fire characteristics, grouping of ICD-9 codes, underlying population susceptibility, or statistical techniques used.

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.

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 United States, 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 6106 $\mu g/m^3$ and daily concentrations of 394 $\mu g/m^3$ have been documented [15,17]. About 52% of all summertime 24-h $PM_{2.5}$ observations above 35 $\mu g/m^3$ in the continental United States 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 exposure. Although monitoring data is our best estimate of particulate matter 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 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 particulate matter concentrations that people are breathing. AOD data is also missing when clouds are present [22]. Atmospheric models 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 atmospheric models 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, atmospheric models, 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 modeled data alone.

RESPIRATORY HEALTH EFFECTS ASSOCIATED WITH WILDFIRE SMOKE EXPOSURE

Particulate matter 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 particulate matter focus on wildfire sources, of those that do, most find that finer particles are more toxic than coarser particles and that wildfire particulate matter may be more toxic than urban particulate matter [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.

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 10 years later that was not associated with other temporal changes; those exposed as children seemed to have recovered their lung function 10 years later [36▪▪]. A decrease in lung function was also observed in a cohort of 3-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].

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 nonsignificant analyses used estimates of wildfire $PM_{2.5}$ from an atmospheric model that did not account for chemical reactions in the atmosphere nor blended with monitoring data, and the third used a temporal comparison.

Chronic obstructive pulmonary disease

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 atmospheric model data, but not from atmospheric model-derived $PM_{2.5}$ estimates [24▪▪]. Alman *et al.* [38▪] found significant associations between combined hospitalizations and ED visits for COPD and atmospheric model-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 atmospheric model-derived particulate matter exposures for ED visits [33▪,37▪].

Respiratory infections

Previously, we found mixed evidence of an association between wildfire smoke exposure and respiratory infections [11]. At that time, of 14 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 because of 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

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■] [a]	Outpatient presentation	2007 fires San Diego County	Temporal comparison	↑↑
Haikerwal *et al.* [37■] [d]	ED visits	Victoria, Australia Dec 2006–Jan 2007	AM $PM_{2.5}$ output	↑↑
Hutchinson *et al.* [32■] [a]	ED visits	2007 fires San Diego County	Temporal comparison	↑↑
Hutchinson *et al.* [32■] [b]	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, meteorology and land use	↑↑
Tinling *et al.* [33■] [c]	ED visits	2011 fires, North Carolina	AM $PM_{2.5}$ output	↔
Alman *et al.* [38■] [d]	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■] [a]	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, meteorology and land use	↑↑
COPD				
Hutchinson *et al.* [32■] [a]	Outpatient presentation	2007 fires San Diego County	Temporal comparison	↔
Haikerwal *et al.* [37■]	ED visits	Victoria, Australia Dec 2006–Jan 2007	AM $PM_{2.5}$ output	↔
Hutchinson *et al.* [32■] [a]	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, meteorology and land use	↑↑
Tinling *et al.* [33■] [e]	ED visits	2011 fires, North Carolina	AM $PM_{2.5}$ output	↔
Alman *et al.* [38■] [d]	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■] [a]	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, meteorology 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■] [f] ICD-9 codes: 466, 481, 487, and 485 combined	ED visits	2011 fires, North Carolina	AM $PM_{2.5}$ output	↑↑
Upper respiratory infections				
Hutchinson *et al.* [32■] [a] ICD-9 codes 460-464	Outpatient presentation	2007 fires San Diego County	Temporal comparison	↔
Hutchinson *et al.* [32■] [a] ICD-9 codes 460–464	ED visits	2007 fires San Diego County	Temporal comparison	↑↑

Table 1 (*Continued*)

	Health Encounter Type	Study Period and Area	Exposure Assessment Method	Findings
Alman *et al.* [38■] [d] ICD-9 codes 460–465, 466	Hospitalizations and ED visits combined	2012 Colorado fires	AM $PM_{2.5}$ output	↑
Hutchinson *et al.* [32■] [a] ICD-9 codes 460–464	Hospitalizations	2007 fires San Diego County	Temporal comparison	↔
Pneumonia				
Hutchinson *et al.* [32■] [a] ICD-9 codes 480–487	Outpatient presentation	2007 fires San Diego County	Temporal comparison	↑
Hutchinson *et al.* [32■] [a] 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, meteorology and land use	↔
Alman *et al.* [38■] [d] ICD-9 codes 480–486	Hospitalizations and ED visits combined	2012 Colorado fires	AM $PM_{2.5}$ output	↔
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■] [a] 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, meteorology and land use	↔
Bronchitis				
Hutchinson *et al.* [32■] [a] ICD-9 code 466 (acute bronchitis)	Outpatient presentation	2007 fires San Diego County	Temporal comparison	↑↑
Hutchinson *et al.* [32■] [a] ICD-9 code 466 (acute bronchitis)	ED visits	2007 fires San Diego County	Temporal comparison	↑↑
Alman *et al.* [38■] [d] 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■] [a] ICD-9 code 466 (acute bronchitis)	Hospitalizations	2007 fires San Diego County	Temporal comparison	↔
Combined respiratory conditions				
Hutchinson *et al.* [32■] [a]	Outpatient presentation	2007 fires San Diego County	Temporal comparison	↑↑
Hutchinson *et al.* [32■] [g]	ED visits	2007 fires San Diego County	AM $PM_{2.5}$ output	↑↑
Hutchinson *et al.* [32■] [a]	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, meteorology and land use	↑↑
Tinling *et al.* [33■]	ED visits	2011 fires, North Carolina	AM $PM_{2.5}$ output	↑
Alman *et al.* [38■] [d]	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 $PM_{2.5}$	↑↑

Table 1 (*Continued*)

	Health Encounter Type	Study Period and Area	Exposure Assessment Method	Findings
Gan *et al.* [24▪▪]	Hospitalizations	2012 fire season Washington State	Blended model combining kriged monitoring, AOD, and AM data	↑↑
Hutchinson *et al.* [32▪] [a]	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▪] [d]	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, meteorology 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: AM, atmospheric model; AOD, aerosol optical depth; COPD, chronic obstructive pulmonary disease; $PM_{2.5}$, particulate matter with an aerodynamic diameter smaller than 2.5 μm; US, United States.
↔, No association; ↑, suggestive increase; ↑↑, significant increase; ↓↓, significant decrease.
[a]This analysis did not adjust for temperature and relative humidity.
[b]Increase in OR with increasing moving average (48-h and 72-h).
[c]Effect estimate shown is for all adults, but sub-analyses were done for other age groups.
[d]Lag 0.
[e]Called chronic pulmonary conditions using ICD codes: (490, 491, 492, 496).
[f]Called upper respiratory infections.
[g]Increase in OR with increasing moving average (48-h and 72-h).

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. Gan *et al.* [24▪▪] found a significant association between pneumonia hospitalizations and wildfire smoke during the 2012 Washington state fires when assessing exposure from kriged monitoring data, a suggestive relationship with a blended model and no association with exposure assessed with an atmospheric model. The analysis of outpatient presentations (but not hospitalizations or ED visits) by Hutchinson *et al.* [32▪] found a borderline significant relationship.

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].

Combined 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.

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 sex, 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 socioeconomic status [25■,42■].

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].

FUTURE IMPACTS DUE TO CLIMATE CHANGE

Few studies have estimated future population exposures to wildfire smoke because of 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 United States will be exposed to wildfire smoke at least once per 20-year period in the mid-21st and late-21st century under two climate change scenarios. Liu *et al.* [51] estimated that $PM_{2.5}$ exposures because of wildfire smoke in the western United States 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 United States 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 because of 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.

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 because of 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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Conflicts of interest

There are no conflicts of interest.

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