Title: Wildfire smoke exposures and adult health outcomes

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Summary

- Health outcomes attributable to wildfire smoke pollution exposure are an increasingly important global health issue especially as wildfires are increasing in frequency and intensity with climate change.
- In this chapter, we present an up-to-date overview of the literature regarding the health consequences of wildfire smoke pollution exposure experienced by adults, identify research gaps, and propose possible areas for future epidemiological studies.
- We also discuss existing interventions to reduce the negative health outcomes associated with wildfire smoke pollution exposure.

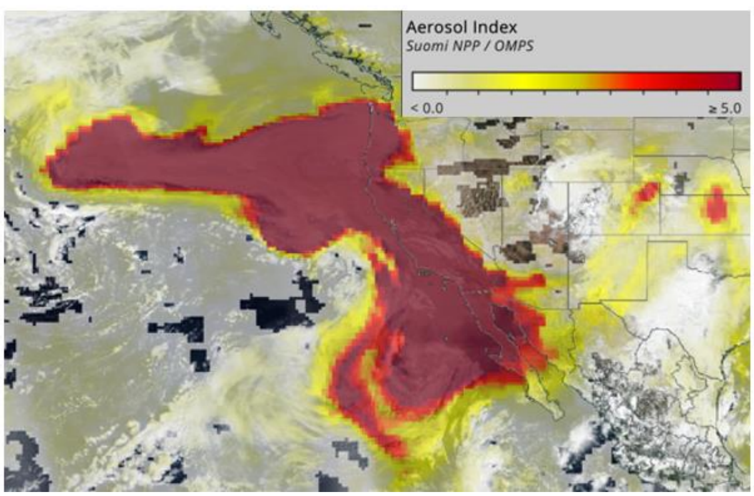
1 Global Background and Significance of the Problem

1.1 Background

Landscape fires can have devastating impacts on human health through contributions to surface air pollution. Fires contribute to enhanced surface concentrations of fine particulate matter ($PM_{2.5}$; particles < 2.5 microns in diameter) and trace gases such as ozone (O_3), carbon monoxide (CO), and other pollutants. Severe fire events in Australia, the western U.S., Indonesia, and the Amazon that recently captured the world's attention have also exposed broad regional populations to dangerous levels of fire-contributed air pollution, hereafter referred to as smoke pollution (Figure 1). In some regions of the world, increases in smoke pollution have negated other air quality improvements over past decades[1].

Understanding and documenting the health outcomes associated with smoke pollution exposure is an important and growing public health issue. First, climate change is increasing the contribution of wildfires to smoke pollution in many regions. In the same vein, while wildfires are traditionally considered as acute events, their staggering increase in prevalence and intensity is gradually constituting a sub-chronic environmental exposure, albeit with limited epidemiological evidence. Second, documenting which communities are particularly exposed and/or impacted and which underlying health conditions (e.g. diabetes, cardiovascular diseases) drive a higher susceptibility to smoke pollution is crucial to inform prevention efforts. Third, although evidence for smoke pollution and health outcomes has grown in the past two decades, this primarily comes from high income countries. Many other regions are exposed to smoke pollution, constituting a critical need for future research.

***Figure 1**. Aerosol Index from September 10th, 2020 showing the presence of absorbing particles in the atmosphere across the western U.S. during a wildfire event. Observations from Suomi Ozone Mapping and Profiler Suite (OMPS)/National Polar orbiting Partnership (NPP) (OMPS-NPP); image courtesy of NASA Worldview.*



1.2 Smoke pollution health burdens around the world

Several studies have estimated global or regional health burdens to smoke $PM_{2.5}$ exposure. This provides useful information across several dimensions: (1) the relative contribution of smoke to the health burden of $PM_{2.5}$ compared to other sources of ambient pollution, (2) geographic and temporal variability in the health burden of smoke $PM_{2.5}$ exposure, and (3) sources of fire emissions that can inform intervention strategies.

Global exposure to smoke $PM_{2.5}$ from landscape fires is responsible for an estimated 340,000-680,000 deaths per year, amounting to between 8 and 21% of the total outdoor air pollution mortality burden (i.e. the total number of premature deaths directly attributable to this exposure) [2,3]. More than 44 million people around the world are exposed to unhealthy annual average $PM_{2.5}$ smoke pollution (> 55 μg/m^3) [3]. However, there is significant spatial variability in smoke pollution sources that contribute to landscape fires (wildfires, deforestation and forest degradation fires, savanna fires, agricultural fires, etc.) and the magnitude of public health burden.

In many tropical countries, fires associated with land use and drought conditions contribute to high levels of smoke pollution exposure. Johnston et al. [2] and Roberts and Wooster [3] highlighted sub-Saharan Africa and Southeast Asia as global hotspots in driving the attributable mortality burden of smoke $PM_{2.5}$ exposure. Recent estimates suggest nearly 10% of premature deaths due to $PM_{2.5}$ exposure in Brazil were linked to smoke pollution [4]. Preventing vegetation fires in the Amazon Basin could avert approximately 17,000 premature deaths due to smoke $PM_{2.5}$ exposure[5]. Another tropical fire hotspot is Indonesia, where severe fires in 2015 were linked to an estimated 44,000-100,000 premature deaths across Equatorial Asia [6,7] and the exposure of nearly 70 million people to unhealthy smoke pollution levels[8].

Landscape fires also contribute to local and regional pollution in non-equatorial regions. Vegetation fires were linked to short-term $PM_{2.5}$ increases in southern and eastern Europe and low-to-moderate increases in daily $PM_{2.5}$ across the continent [9]. Kollanus et al. estimated that 1,483 and 1,080 premature deaths across 27 countries in Europe in 2005 and 2008, respectively, were attributable to smoke $PM_{2.5}$. Across the U.S., fires contribute to approximately 11% of $PM_{2.5}$ and 1% of O_3 on average but play a more important role in western states [10] and during extreme weather events [10,11]. For instance, fires can contribute up to 50% of $PM_{2.5}$ in some parts of the western U.S. [12]. In this region, nearly 50 million people over 2004-2009 were exposed to a ‘smokewave’ event (more than two days with high smoke $PM_{2.5}$), with corresponding increases in respiratory hospital admissions [13]. A recent study estimated the number of asthma hospital admissions, emergency department visits, and premature deaths attributable to acute smoke $PM_{2.5}$ exposure across the U.S. using concentration-response functions (CRFs refer to the estimated dose-response between levels of $PM_{2.5}$ and the risk of observing a given health outcome of interest) specific to smoke $PM_{2.5}$ exposure as well as gas-phase hazardous air pollutants (HAPs) [14]. They estimated that 216,000 deaths were attributable to wildfire smoke and that most of the burden took place outside the western U.S. as smoke typically travelled across the continent impacting a very large population.

Agricultural fires also contribute to consistent seasonal pollution enhancements in many parts of the world. For example, agricultural waste burning in Central and West Africa is the dominant driver of smoke pollution across the continent, linked to 43,000 premature deaths per year [15]. Another important example is in India, where crop residue burning contributes to seasonal extreme pollution above World Health Organization guidelines in rural areas and urban centers [16,17]. In many regions, additional research is required to separate agricultural fire contributions from other sources of pollution to quantify the health burden attributable to agricultural fires. However, it is worth mentioning that most studies described above applied CRFs developed for all-source $PM_{2.5}$ or (more rarely) for smoke $PM_{2.5}$ specifically.

1.3 Scope of the chapter

The aim of this chapter is to provide a current overview of the health consequences of smoke pollution exposure experienced by adults, excluding occupational settings (e.g. among firefighters) [18-21]. The perinatal and child health burden is discussed in the following chapter. We primarily document the health impacts associated with $PM_{2.5}$ smoke pollution exposure, but also briefly address other potentially synergistic consequences associated with the trauma of fire events, such as the emergence of mental health stressors. While $PM_{2.5}$ is the most investigated smoke constituent, it is important to note that other harmful compounds of smoke that impact human health exist such as ozone (O_3), volatile organic compounds (VOCs), carbon monoxide, lead, and other heavy metals and toxins that can be generated by burning biomass and flame contact with built structures. However, such pollutants may primarily impact populations directly impacted by the fire (not only through smoke)[14].

We first present a summary of the epidemiological literature on smoke pollution and adult health outcomes by synthesizing several recent reviews and additional studies. We consider the environmental justice implications of this phenomenon and the need to address differential susceptibility and exposure to biomass burning smoke pollution. We then discuss opportunities to improve our understanding of the adult health burden of smoke exposure more holistically. This includes how smoke pollution exposure estimates are matched to health data through different study designs, settings in which evidence is still lacking, and additional areas of future research, such as repeated smoke exposures and compounded impacts. We then present an overview of existing interventions to reduce the negative health outcomes associated with smoke pollution exposure. We conclude with a summary of research gaps and future directions.

2 Overview of Epidemiologic Evidence on Adult Health Outcomes

2.1 Introduction

In the past few years, several literature reviews have been conducted with regards to the health impacts associated with landscape fire smoke pollution exposure [22-29]. $PM_{2.5}$ is one of the primary constituents of smoke pollution and is the focus of this section. Ambient $PM_{2.5}$ concentrations are monitored and regulated, as such particles are small enough to penetrate the respiratory system, interact with the circulation system, and can further impact any organ in the body. Furthermore, $PM_{2.5}$ also impacts human health through systemic inflammation and activation of the autonomic nervous system[30]. Evidence regarding the health effects of all-source $PM_{2.5}$ is vast, and several reviews have been published in the past decades [31-34], including both acute (e.g. asthma exacerbation, myocardial infarction, etc.) and chronic (atherosclerosis, dementia, lung cancer, etc.) effects. Smoke pollution concentrations are mostly considered as acute exposures in the epidemiological literature but, as we discuss below, some long-term consequences may exist. The repeated nature of such events in the context of climate change makes such exposure more frequent and considering such exposures as sub-chronic in certain regions of the globe may be warranted in future studies.

The mechanisms through which $PM_{2.5}$ can impact human health (such as oxidative stress, alteration of the pulmonary immune system, and chronic inflammation) may differ according to particle composition (for more details, see Chapter 11). While it may seem reasonable to initially assume that smoke pollution may have similar toxicological mechanisms and impacts on human health compared to all-source $PM_{2.5}$, recent research justifies studying smoke as a separate exposure for several reasons. First, $PM_{2.5}$ concentrations during an extreme biomass burning event can be one order of magnitude larger or more when compared to typical exposure levels. This implies that epidemiological evidence from other sources of fine particles regarding the dose-response relationship, the types of symptoms, or which subgroups of the populations are susceptible may not extrapolate to such exposures. Second, recent toxicological evidence suggests that smoke $PM_{2.5}$ may be more toxic than equal doses of $PM_{2.5}$ from other sources due to particle composition[35]. Current air pollution guidelines or regulations do not distinguish by emissions source or chemical composition for $PM_{2.5}$. With these considerations, focusing on studies with specific smoke pollution exposures has led to dozens of epidemiological studies in the past two decades that we summarize below. We describe the types of health outcomes that have been investigated and the state of evidence is regarding these outcomes. In Section 3, we will discuss health outcomes such as mental health for which evidence is still sparse.

2.2 Mortality

The evidence related to the impact of smoke pollution on acute premature mortality is relatively strong. Many studies have consistently found an increase in daily mortality during a wildfire event or in subsequent days [36]. However, most of these studies focused on all-cause mortality or mortality for respiratory or CVD endpoints; studies about other cause-specific mortality outcomes are still lacking [22,23]. In a recently published global analysis, Chen et al.[37] found an annual average of 33,510 all-cause deaths to be attributable to smoke $PM_{2\cdot5}$ pollution exposure using data from 749 cities in 43 countries.

2.3 Morbidity

2.3.1 Respiratory diseases

Respiratory health outcomes have received the most attention in the published epidemiological literature. Various respiratory morbidity outcomes have been studied, including lung function, respiratory medication usage [38] [39], physician visits, and emergency departments (ED) visits or hospital admissions for respiratory problems[25]. When considering ED or physician visits for various respiratory outcomes, published studies strongly suggest a detrimental effect of smoke pollution. Among the specific respiratory outcomes, asthma has been extensively studied. A recent systematic review [25] focusing on asthma-related outcomes found consistent evidence for this outcome.

Fewer studies have examined changes in lung function[25] . Amid mixed results, most studies were not able to identify the effect of smoke pollution. For medication usage, studies focused on various endpoints, such as medication use, initiation of oral steroid use, or medication for obstructive lung disease also have inconsistent results [22]. Finally, there is increasing evidence that wildfire smoke also exacerbates Chronic Obstructive Pulmonary Disease (COPD)[40]. More recent studies also investigated the role of smoke pollution on exacerbating respiratory infections or disease severity such as for seasonal influenza[41]; such connections between respiratory infectious diseases and wildfire are particularly relevant in the context of the COVID-19 pandemic [42,43].

2.3.2 Cardiovascular diseases

Less epidemiological evidence exists for cardiovascular outcomes than for respiratory outcomes. Some studies have considered smoke pollution exposure and cardiovascular diseases (CVD) outcomes such as hypertension [44]. Most CVD studies assessed hospital admissions or ED visits for CVD causes[22]. Fewer studies investigate specific CVD endpoints, like congestive heart failure [45], ischemic heart disease[46], cardiac arrest [47] or myocardial infarction[48]. However, the results of these studies focusing on CVD outcomes are mixed, with some studies identifying an increasing risk and other studies not detecting any effect.

2.4 Vulnerable populations

While most studies conducted to date focused on the health impacts on the entire adult population, several have investigated whether certain population subgroups are more susceptible to the health impacts associated with a specific landscape fire event or smoke pollution more generally[49,50]. Such work investigating effect modification by various socio-demographic characteristics is motivated by the large evidence on differential susceptibility for fine particles in general (i.e. from other sources of emission)[51]. Indeed, the environmental justice literature has found that socioeconomic and racial and ethnic minorities suffer from a disproportionate burden of air pollution exposure in general, and $PM_{2.5}$ in particular[52].

However, studies assessing the extent to which certain socio-demographic characteristics modify the smoke pollution-health risk remain limited. Most studies investigating such differential susceptibility questions conducted stratified analyses or included an interaction term between smoke pollution exposure and the socio-demographic variable of interest [53]. Among these studies, most focused on age as a susceptibility factor [48,54,55]. Some studies have shown that the risk for most health outcomes was higher among older populations (with various cutoffs across the studies such as > 65 or > 75 years old), but other studies found the opposite pattern or no evidence of such effect modification by age [22]. Several studies assessed potential gender heterogeneity, but the results are mixed[22].

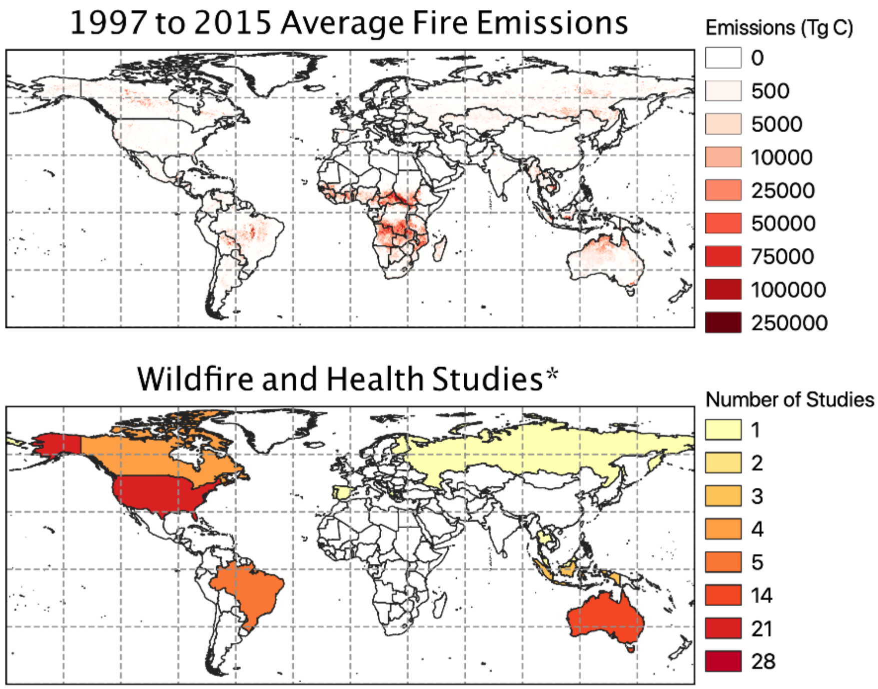
Differential susceptibility across socioeconomic and racial/ethnic groups, including individual race or ethnicity [50], neighborhood SES [57], indigenous status [58] or proxies such as district-specific food consumption [59] have also been considered. However, results from these studies were mixed, with some studies finding that low SES groups were more susceptible to wildfire and other studies found no differences among groups. Finally, other vulnerability factors included pre-existing health conditions (using different proxies such as number of physician visits in the previous year[57]) but available evidence is inconclusive to date.

3. Considerations for future epidemiological studies

3.1 Geographic disparities in health studies

More studies are needed in geographically underrepresented areas where wildfire smoke pollution is common and/or projected to increase in the future, especially where the public health infrastructure is more vulnerable [60]. This emphasis should be placed on developing exposure and health operational capacity in parts of the world with high levels of smoke pollution, particularly in sub-Saharan Africa, given the majority of existing studies examined these impacts in North America or Australia [61,62]. The geographical distribution of existing epidemiological studies highlighted an important gap, which is not unique to smoke pollution [63]. In Figure 2 below, we illustrate the discrepancies between where studies have been conducted thus far and where most wildfire emissions take place. Epidemiological evidence is lacking in several regions where fires are an important source of emissions, especially in Lower Middle Income Countries (LMICs).

Figure 2. *Maps comparing the number of all-source smoke pollution-health studies conducted in each country with the average fire emissions from 1997 to 2015 from the Global Fire Emissions Database* [64,65].



**** The included studies are extracted from 4 recent systematic reviews*** [22-25]

3.2 Exposure estimates for epidemiological studies

Fire contributions to smoke pollution are estimated with various approaches, including atmospheric modeling, satellite-based techniques, ground station data, or blended methods that merge multiple information sources. Here, we briefly review the primary smoke exposure methods through the lens of providing recommendations for use in epidemiological studies. For an in-depth discussion of each of these methods, we refer the reader to Chapters 6-9.

The first category of exposure assessment is atmospheric models, which can be applied at global to local scales. Lelieveld et al. [66] and Johnston et al. [2] used global atmospheric models to quantify the smoke pollution health burden from multiple fires around the world compared to non-fire pollution sources. At smaller scales, atmospheric dispersion models can be used to track smoke pollution from individual fire events [67]. Second, satellite observations can monitor pollution during fire events. Satellite-based products include the National Environmental Satellite, Data, and Information Service (NESDIS) Hazard Mapping System (HMS) smoke plume data in North America connects observed smoke plumes to active fires [12,68,69]. Aerosol Optical Depth (AOD) from the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument on the Terra and Aqua satellites and the TROPOspheric Monitoring Instrument (TROPOMI) have been used to map atmospheric aerosol loading and infer surface $PM_{2.5}$ concentrations during fire events [70 71]. Third, ground station observations have been used as an input into blended models to replicate the spatial and temporal variability of smoke pollution. Low-cost sensor networks also show promise for informing the statistical relationship between satellite column aerosol optical depth and surface-level $PM_{2.5}$ during wildfire events due to their dense spatial coverage [72].

Each of these exposure methods have their own strengths and weaknesses to consider for use in epidemiological studies. The first consideration is the spatial scale of exposure datasets. With coarser models or sparse ground station data, the ability to resolve peak smoke pollution concentrations may be reduced, which could result in an underestimate of health outcomes. An additional consideration is the assignment of a single exposure variable to an entire population, despite significant individual-level differences in exposure, such as across zip codes [73], and whether an individual spends the majority of their time indoors or outdoors. Second, when possible, we recommend that epidemiological studies use multiple exposure estimates to test the sensitivity of the studies to exposure methods. Blended models consider multiple sources of information to represent smoke $PM_{2.5}$ concentrations. For example, ground station monitors provide surface-level estimates of $PM_{2.5}$ at specific locations and/or time points. Satellite-based observations can be used to fill in some of the gaps in this spatial or temporal coverage. Cleland et al.[74] recently compared the smoke pollution health burden using multiple exposure estimates (ground monitor, modeled, and blended). The authors found that the choice of exposure dataset drove uncertainty in the resulting health burden estimate. In a review of 28 studies around the world that estimated PM associated with open burning, Johnson et al. [62] found that blended approaches tend to have the best results by at least partially compensating for limitations associated with each individual approach. Lassman et al. [75] also found more accurate wildfire $PM_{2.5}$ predictions from monitors relative to satellite AOD or atmospheric modeling simulations, but that blended techniques were more accurate if ground monitor density was low. Exploring multiple exposure datasets may not always be possible due to data or computational limitations. For example, in regions of the world that lack dense ground station networks, modeling or satellite studies are particularly useful [15]. Finally, recognizing the implications of exposure method for issuing public health guidance is critical. Fadadu et al. [76], for example, found substantial variability with the magnitude and timing of peak smoke pollution derived from HMS satellite-derived smoke polygons of low, medium, and high intensity and ground station monitors.

3.3 Epidemiological study designs

It is first important to distinguish two approaches to evaluate the health impacts of smoke pollution, including: i) single events and ii) repeated effects of long-term smoke pollution exposure over a long-time span (e.g. multiple years).

First, several studies focused on an individual or a handful of major fire events and then evaluated whether health outcomes changes were observed in affected areas (with or without control groups). Examples of such events include the October 2007 Southern California wildfires[77], summer Russian wildfires in 2010[78], or Indonesia's forest fires of 1997 [59]. In such settings, authors relied on various study designs including case crossover designs [77], interrupted time series designs[79] or panel analyses [80]. Such designs capitalize on the specific location and timing of the event of interest and formulate an identification strategy to compare observed outcome in the exposed group to a substitute for the counterfactual population (that was not exposed to the smoke pollution). Quasi-experimental designs, such as difference-in-differences, can also be employed for such research questions but remain underused for such type of events. Yet, they are a powerful alternative strategy to address various confounders that may or may not be measured while checking identification assumptions, such as parallel trends [81]. In addition, simpler approaches have been implemented where excess events were estimated by comparing observed outcomes during the event of interest to outcomes rates on a given calendar dates from previous years [78]. This technique has been frequently used in the context of extreme weather events, like extreme heat, hurricanes to estimate excess mortality[82,83]. However, such approaches do not typically control for any time-varying confounders, such as temperature or other sources of air pollution, which may lead to biased estimates of exposure.

Second, other studies focus instead on estimating the overall impact of smoke pollution by considering multiple years and focusing on various spatial scales (from single cities to an entire country). In this setting, studies rely on various techniques to estimate exposure to smoke pollution, such as atmospheric models or statistical techniques (for more details, see previous chapters). Accordingly, various study designs have employed, including ecological time series models or case crossover designs [84,85] and individual designs based on existing cohorts, nested case-control designs or ad hoc surveys [86].

Finally, several studies [73,87] have investigated the spatial variability in the health impacts associated with wildfires events and found important heterogeneity of the geographical distribution of the impacts. Such studies remain rare as compared to studies that aggregate the estimates spatially but can provide estimates that can be particularly useful to identify vulnerable communities.

3.4 Understudied health outcomes

Certain health outcomes have been understudied. These include mental health outcomes in the adult population, such as psychological distress, solastalgia (i.e. the distress caused by environmental change) [88], changing psychological outcomes [89] or mental and emotional well-being [90]. Investigating the short- and long-term impacts of landscape fires on mental health is particularly important to design interventions following such events and improve the resilience of affected communities. In a random digit dial survey of an area affected by multiple wildfires, Felix & Afifi[91] found that those who were exposed to wildfire and were evacuated had poorer measured mental health and greater total fire stress than those who were not evacuated; relative to men, women had poorer mental health and greater total fire stress. More evidence regarding these links is currently needed and future studies capitalizing on self-reported mental health symptoms or medical claims are critical to the development of this field. Other issues such as diabetic [92] or ophthalmologic [93] outcomes, as well as injuries [94] were investigated by few studies and more evidence is definitively warranted. Furthermore, given the emerging literature linking exposure to $PM_{2.5}$ and incident diabetes[95] and dementia[96], there is a need to further investigate the impact of smoke pollution and these outcomes.

It is also particularly important to better understand which pre-existing medical conditions constitute susceptibility factors for smoke pollution exposure. Apart from respiratory, CVD, or other chronic conditions, such as diabetes, it is necessary to investigate the extent to which individuals with dementia, Alzheimer's Disease Related Dementias (ADRD) or cancer survivors, for example, are more susceptible to poor health outcomes as compared with the general population. Documenting such pre-existing susceptibility factors will inform existing preventive policies such as early warning systems by identifying which priority populations for interventions. Other plausible susceptibility factors have also received little attention to date and future epidemiological studies are critically needed. Such factors include metrics of health care access, background exposure to other sources of pollution, occupation (e.g. outdoor workers), and populations with physical disabilities.

3.5 Fires and the built environment

Landscape fires have the capacity to not only burn vegetation but the built environments in which people live, work and function[97], as well. As a variety of substances are used in the construction and maintenance of these structures, these materials have varying capacity as fuel and have differing toxic potential when burned. Carratt et al.'s review[98] noted that there was a spatial overlap of burned area and the prior application of pesticides in California—fire combatting chemical also can be found in these locations. Epidemiological data regarding the health effects of these ignited, potentially-combined chemical exposures is lacking. Studies that address the acute and chronic health outcomes after landscape fire events generally do not address the chemical species of $PM_{2.5}$. More developed is the literature addressing the protection of the built environment from biomass burning events Penman et al.[99] used a Bayesian Network model to analyze the strategic use of "fuel breaks", among other factors, in San Diego County, California. Found to be an effective strategy, the use of this model determined that high density communities, which tend to be at low elevations, were more susceptible to burning than were those at higher elevations, which tended to be less densely populated. Weather, too, contributed substantially to the wildfire's size and ability to travel and affect communities; the treatment of potential fuel had a minimal effect on the fire's ability to spread and endanger property. Housing density in wildfire vulnerable areas in the United States increased 1350% between 1940 and 2010[100], increasing the likelihood of the built environment's involvement in wildfire events. Wildfire adaptation has been investigated at the individual[101] and community[102] level, both of which address the necessity of managing vulnerability at the wildland-urban interface.

3.6 Future research needs

Apart from knowledge gaps in relation to health outcomes and susceptibility factors, there are multiple avenues for future research. First, while most studies focused on $PM_{2.5}$ as the main component of biomass burning smoke exposure, other pollutants, such as O_3 or polycyclic aromatic hydrocarbons (PAHs) are generated in fire plumes. Recent studies have shown that wildfires generate increases in tropospheric O_3 levels through processes distinct from $PM_{2.5}$ [103,104]. In future studies, it will be particularly important to understand how smoke pollutants other than $PM_{2.5}$ impact population health and study potential synergies among these pollutants.

Another important area of research relates to whether $PM_{2.5}$ smoke pollution affects health outcomes differently from $PM_{2.5}$ from other sources. While this pattern has been suggested by toxicological studies where differences in the composition led to higher effects of smoke $PM_{2.5}$ compared to ambient sources [35,105-107], evidence at the population level is lacking. To the best of our knowledge, only two studies [108,109] focusing on asthma addressed this research question. Furthermore, in a recent study, it has also been shown that smoke $PM_{2.5}$ can cause a greater impact on respiratory health than $PM_{2.5}$ from other sources [110]. While further studies are needed to confirm these emerging findings, such patterns point to the need for air quality policies to consider the variability in $PM_{2.5}$ impacts on human health according to the sources of emissions.

Another area of research that deserves more attention is related to improvement in the understanding the long-term impacts of smoke pollution on various outcomes (besides mental health as described above). Indeed, while wildfire has been considered traditionally as an acute environmental exposure, such instances are rapidly evolving in the context of climate change and variability [12,111]. As the length of wildfire seasons increases[112], the duration of exposure to extreme smoke pollution and corresponding health outcomes will likely increase. For example, in the western U.S., future smoke $PM_{2.5}$ concentrations under multiple climate change scenarios suggests an increasing threat to public health, particularly for many vulnerable subpopulations [111,113,114]. This motivates the need to better understand individual actions to reduce exposure as well as larger scale interventions to reduce wildfire emissions in order to reduce negative human health outcomes (see Section 4 of this chapter) [115].

It is also important to better understand the compounded impacts of smoke pollution with other contemporaneous risks. For example, smoke pollution and extreme heat events may co-occur as recently illustrated by Australian fires and the western U.S. in 2020. Smoke pollution and extreme heat share similar mechanisms through which they impact human health and several studies have demonstrated the synergistic effects of air pollution (not specific to smoke) and extreme heat [116]. In addition, evidence about heat-related vulnerability identified similar population subgroups as for smoke pollution. Characterizing joint exposures to extreme heat and smoke pollution, as well as associated impacts, constitutes an important area for future research, especially while both events are expected to increase in intensity and frequency in our changing climate.

Finally, an important (and timely) area of investigation is related to the interactions between smoke pollution and infectious diseases. As discussed above, some recent studies have shown that biomass burning smoke may influence seasonal influenza incidence rates. For example, Landguth et al. concluded that increases in $PM_{2.5}$ concentrations during the wildfire season led to an increase in the influenza incidence in the following winter influenza season in Montana[41]. In parallel, experimental studies also showed that exposure to air pollutants, including PM[117] increased susceptibility to viral lung infections by affecting the immune system. A recent study suggested that other infectious agents, such as pathogenic fungus (e.g. causing coccidioidomycosis), may be transported by smoke pollution [118]. The interaction between air pollution and infectious diseases such as tuberculosis [119] and coronavirus infection (e.g. SARS[120]) constitutes a novel area of research that is judicious in the context of the COVID-19 pandemic [42,121,122]. Notably, a recent study by Zhou et al.[43] found that the 2020 wildfires in Washington, Oregon and California counties amplified the effect of short-term exposure of $PM_{2.5}$ on COVID-19 cases and deaths.

4. Interventions to reduce the wildfire's impact on public health

Our current understanding of the health outcomes associated with smoke pollution can help inform potential preventive strategies to protect public health. In this section, we provide a brief overview of several types of actions that exist to mitigate this health exposure.

4.1 Pre-emptive power outages

Certain strategies to reduce fire risk can also bring second-order health effects. For example, pre-emptive de-energization policies in California to reduce ignition sources associated with power lines during extreme fire weather conditions can disproportionately impact the health of communities with lower adaptive capacity[123]. Power outages may lead to unintended health consequences, such as mental health outcomes, injuries, or heat-related illnesses (through air conditioning interruption, for example). However, to the best of our knowledge, there is no empirical evidence regarding these issues, and we encourage future studies to address such connections.

4.2 Land management

Another important area of future research is how land management interventions could reduce the public health burden of wildfire smoke pollution exposure through fuel and prescribed burning management [124,125]. These land management strategies will likely change health outcomes by altering the magnitude, frequency, timing, and duration of smoke exposure. For example, prescribed fires typically take place during lower atmospheric ventilation conditions to help control fire behavior, which can increase local exposure, whereas intense wildfires may be more likely to be injected higher into the atmosphere, with broader regional effects [126]. Across broader spatial and temporal scales, implementing low level prescribed burning strategies could reduce the risk of extreme wildfire events and minimize large-scale smoke pollution impacts [127]. New research is needed to focus on the unique characteristics of prescribed fires as a coupled human-natural system [128].

Schweizer et al. [69] compared wildfire and prescribed burning smoke plumes in California using HMS observations and found that larger and more intense fires exposed more people per area burned because the smoke was transported over larger distances. Preliminary studies find worse health outcomes in children exposed to smoke from wildfires compared to prescribed burning [129]. However, quantifying the health benefits of prescribed burning remains highly uncertain [130]. One primary source of this uncertainty is accurately estimating how low level prescribed burns could offset the risk of future, higher emissions from extreme wildfire events [131]. Another is due to measurement differences between wildfire and prescribed burning exposure estimates, with the proximity of sensors to fires often closer to prescribed burns than extreme wildfire events [130].

4.3 Public health interventions

Limiting the number of people directly exposed to smoke pollution through evacuations is perhaps the most obvious intervention to protect public health [123,132]. In addition to populations directly exposed to wildfire threats, most of the smoke pollution health burden will be driven by regional exposures due to smoke transport. In this context, early warning systems (EWS) that aim to reduce a population's exposure to smoke pollution by collective or individual behavioral changes are crucial. Several models provide near-real time or forecasted smoke $PM_{2.5}$ concentrations in the U.S. For example, the CDC's National Environmental Public Health Tracking Network provides short-term smoke pollution forecasts to identify at-risk populations and strengthen public health preparedness [133]. Prior studies suggest that intervention advisories about low $PM_{2.5}$ concentration thresholds, coupled with strong public adherence, can effectively reduce risk[134] in susceptible populations. In southern Australia, the Air Quality Visualization (AQVx) combines data to assess landscape fire-health effects from smoke exposure and to evaluate dispersion models, allowing targeted warning messages at a local scale [135]. For a discussion of other real-time and operational smoke forecasting systems, we refer the reader to Chapter 9.

Actions that take place during such EWS include modifications to work plans, school or business closures and event cancelations. Individual behavioral changes are also urged when EWS are activated such as usage of individual protections (N95 masks or respirators that filter particles), recommendations to stay indoors, limit physical activity, and reduce other activities that impact air quality, such as smoking, wood burning, or traffic emissions[136]. Other long-term structural actions also exist to improve building resilience by improving mechanical ventilation systems to filter incoming air or providing air purifiers with a high efficiency (HEPA) filter.

Studies that have evaluated the potential effectiveness of some of these interventions are rare [137] and more evidence is urgently needed. We strongly encourage future experimental studies that would compare the effectiveness of different actions on various populations as well as quasi-experimental studies as done in the context of other EWS [138,139].

5. Conclusions

In the context of climate change and variability, health outcomes associated with exposure to smoke pollution are an increasingly important global health issue. Understanding such outcomes in various locations, populations, and for different multiple health endpoints is an urgent priority. In this chapter, we provide a contemporary overview of the epidemiological evidence for adult health outcomes related to smoke pollution exposure. While stronger evidence exists for associations between short-term exposures and all-cause mortality or respiratory morbidity, for example, additional studies are needed to address cardiovascular outcomes, the mental health burden, and vulnerable populations. Geographic disparities exist in existing adult epidemiological studies, which requires additional information to better understand potential regional differences in health outcomes. We discuss how exposure to smoke pollution has been estimated, various methodological considerations for epidemiological study designs, and emerging evidence for several understudied health outcomes. Several opportunities exist to reduce smoke pollution exposure through land use interventions, early warning systems, and behavioral modifications. Taken together, while strong evidence exists for certain health outcomes and regions of the world, future studies will allow us to comprehensively understand the adult health burden of smoke pollution exposure by considering additional health outcomes, interactions among exposures, and additional opportunities to protect health.

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