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# Wildfire Smoke in the United States

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# About the Authors

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**Matthew Wibbenmeyer** is a fellow at Resources for the Future (RFF). His research studies climate impacts and mitigation within the US land sector, with a special emphasis on wildfire impacts and management. US wildfire activity has accelerated in recent years, leading to increases in property damages, carbon emissions, and health impacts due to smoke. Wibbenmeyer's research studies the impacts of these changes for communities, how these impacts are distributed, and how management choices affect the distribution of impacts. Alongside his work on wildfire, Wibbenmeyer is investigating the role of the US land sector in mitigating climate change, and how policy toward land sector choices may influence the United States' ability to meet climate goals.

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# Abstract

As large wildfires grow more frequent, the United States is seeing increasing impacts from smoke. Wildfire smoke frequently causes particulate matter pollution to exceed federal standards, and these smoke impacts are expected to grow over the century as the climate warms. Drawing from the economics and social science literature, this paper argues that increasing wildfire smoke pollution is a serious threat to health, the economy, and human well-being. The paper identifies areas in which to prioritize policy attention, such as increasing funding for land management activities and leveraging air quality regulations to incentivize wildfire hazard mitigation.

# Contents

# 1. Introduction

Wildfire activity is increasing globally (Jolly et al. 2015; Senande-Rivera et al. 2022), driven by increases in aridity and, in some regions, an overabundance of fire-ready fuels (Marlon et al. 2012). Recently in the United States, fires have produced several deadly and destructive disasters, including those in Paradise, California, in 2018 and Lahaina, Hawaii, in 2023. Despite these notable impacts, there is growing evidence that the overall damages of wildfire smoke emissions may be at least as large as the direct damages from wildfires (Burke et al. 2023; Wang et al. 2021).

As fire consumes biomass, it releases a variety of pollutants, including carbon dioxide, carbon monoxide, methane, volatile organic compounds, nitrous oxide, nitrogen oxides, and particulate matter. Of these, fine particulate matter less than 2.5 in diameter ($PM_{2.5}$) accounts for the third-largest share of emissions, by mass, after carbon dioxide and carbon monoxide (Urbanski et al. 2008).[1] Researchers have found that even short-term exposure to heightened levels of fine particulate pollution can have substantial health impacts because of its effects on cardiovascular and respiratory systems. Heightened $PM_{2.5}$ levels can lead to increased mortality, especially among vulnerable individuals, and to increased hospitalizations and preterm births. $PM_{2.5}$ can also reduce welfare through other channels; for example, it has been found to decrease economic productivity, increase crime rates, and impair educational outcomes.

This paper argues that increasing air pollution due to wildfire smoke is a serious threat to health and human well-being and warrants increased attention from policymakers in the United States. While acknowledging the important role of carbon emissions from wildfires in contributing to climate change, the paper focuses specifically on wildfire smoke—that is, emissions that contribute conventional pollutants.[2] Agricultural burning and prescribed fire, another category of wildland fire, can also contribute to air pollution; however, we restrict our attention to smoke from wildfires—uncontrolled fires burning on wildlands such as forests and shrublands.

The paper proceeds as follows. Section 2 reviews evidence from epidemiologic and economic studies on the impacts of wildfire smoke, mainly focusing on studies that have specifically investigated wildfire smoke but occasionally drawing from a large body of evidence on the effects of $PM_{2.5}$ more broadly. Section 3 then shows, based on

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[1] Some literature has also studied exposure to $PM_1$ and $PM_{10}$, which are particulate matter less than 1 and 10 µg, respectively. Studies generally indicate that exposure to particulate matter less than 2.5 micrograms in diameter is especially harmful. Carbon monoxide and carbon dioxide account for 92–95 percent and 4–7 percent of the composition of wildfire smoke emissions, respectively, depending on forest type; $PM_{2.5}$, which is the third-largest constituent emission, accounts for 0.09–0.8 percent of emissions (Urbanski et al. 2008).
[2] Together with methane emissions, carbon dioxide equivalent emissions from wildfires are substantial; in 2020, only California's transportation sector produced more emissions than the state's wildfires (Jerrett et al. 2022).

recently published results and data, that the impact of wildfire smoke on US air quality has grown substantially in recent years. Finally, Section 4 outlines potential paths for policy to address increasing smoke and discusses the considerations surrounding smoke from prescribed fires, which reduce future wildfire smoke impacts but produce pollution in the immediate term. Section 5 concludes.

# 2. Impacts of Wildfire Smoke

## 2.1. Health

Most studies of the effects of wildfire smoke on health have focused on harmful effects due to particulate pollution. Among air pollutants, fine particulate matter is one of the most harmful to human health. Its small size allows it to easily enter the lungs and eventually escape into the bloodstream, with deleterious effects throughout the body. $PM_{2.5}$ particles cause inflammation in the airway, lungs, and central nervous system, and they change cell chemistry, resulting in decreased function of the respiratory and cardiovascular system (Feng et al. 2016). These effects can exacerbate underlying conditions such as chronic pulmonary disease and asthma and increase the risk of heart attack, congestive heart failure, and dementia, especially among the elderly. $PM_{2.5}$ may also increase the incidence of preterm birth, low birth weight, and infant mortality.[3]

Economists have studied the impacts of $PM_{2.5}$ from wildfire smoke because it generates arguably exogenous temporal variation in fine particulate concentrations, allowing them to econometrically separate the health effects of $PM_{2.5}$ from the effects of variables correlated with both pollution exposure and health, such as race and income. Researchers frequently rely on satellite data to measure the presence of wildfire smoke (e.g., Ruminski et al. 2008). These data do not distinguish between ground-level smoke and smoke at higher altitudes, however, so it is important to couple satellite data with surface-level air quality measures (e.g., Burke et al. 2022; Burkhardt et al. 2019).

The health consequences of exposure to $PM_{2.5}$ from wildfire smoke versus other sources may differ for two reasons.[4] First, $PM_{2.5}$ from wildland fires typically exhibits considerably more temporal variation than $PM_{2.5}$ from the industrial and transportation sectors. Exposure from wildfire smoke is more likely to be acute and is often more severe; for example, during June 2023, New York City's air quality was briefly the worst in the world because of smoke from Canadian wildfires. Second, although $PM_{2.5}$ is defined by diameter, the chemical composition of particulates can vary, and $PM_{2.5}$ emissions from wildfires differ chemically from those of other sources (Wegesser et al.

[3] Kim et al. (2015) and Feng et al. (2016) provide helpful reviews of the physiological mechanisms underlying health effects of fine particulate matter.
[4] For example, Aguilera et al. (2021) find that wildfire smoke increases respiratory hospitalizations more than $PM_{2.5}$ from ambient sources.

2009). Additionally, smoke contains harmful copollutants, including larger-diameter particulate matter and volatile organic compounds (Liu and Peng 2019).

In general, however, epidemiological and econometric studies find health effects from smoke that are broadly consistent with the greater literature on health effects of *acute* $PM_{2.5}$ exposure. There is strong evidence that wildfire smoke increases mortality (Reid et al. 2016; Cascio 2018). Miller et al. (2021) estimate that in the United States, approximately 17,300 elderly adults die prematurely as a result of wildfire smoke each year. Johnston et al. (2012) and Roberts and Wooster (2021) each estimate that globally, landscape fires (including both wildland fires and agricultural burning) cause as many as 600,000 additional deaths per year. However, more research is needed to clarify the magnitude and primary mechanisms that underlie mortality effects (Cascio 2018; Liu et al. 2015; Reid et al. 2016); though there is consistent evidence that wildfire smoke increases hospital visits for respiratory conditions (Heft-Neal et al. 2023; Reid et al. 2016), evidence of smoke's effects on cardiovascular morbidity is mixed (Heft-Neal et al. 2023; Parthum et al. 2017).

Studies have also shown that wildfire smoke affects birth outcomes. For example, in California, Heft-Neal et al. (2022) estimate that each additional day of exposure to wildfire smoke during pregnancy is associated with a 0.49 percentage point increase in the probability of preterm birth. Similarly, using a difference-in-differences approach, McCoy and Zhao (2021) show that exposure to wildfire smoke causes a 3.4 percentage point increase in the probability of low birth weight.

## 2.2. Welfare

In addition to direct health costs, smoke indirectly affects economic welfare through a variety of channels. Sickness due to smoke, or efforts to avoid sickness, can result in reduced work hours and earnings. Smoke can impair cognitive function, which may affect productivity, educational outcomes, and crime. The overall perceived welfare impacts of these various effects can be measured based on survey responses or preferences revealed through individual behavior, such as demand for housing.

Borgschulte et al. (2022) find that wildfire smoke reduces quarterly earnings in the United States by an average of $125 billion per year—similar to mortality losses due to smoke. They attribute approximately 13 percent of observed earnings losses to reduced employment, with the remaining losses presumably from reduced hours or wages. Several studies in the air pollution literature have similarly documented a reduction in working hours due to $PM_{2.5}$ (Aragon et al. 2017; Fan and Grainger 2023).

In addition to reduced hours, particulate matter may impair labor productivity. Although evidence on the effects of particulate matter on productivity is mixed (Chang et al. 2016, 2019; He et al. 2019), there is substantial evidence that particulate pollution negatively affects the *inputs* into productivity. $PM_{2.5}$ has been found to cause declines in performance of various cognitive tasks (Archsmith et al. 2018; Bedi et al. 2021; Graff Zivin and Neidell 2012; La Nauze and Severnini 2021; Lai et al. 2021;

Schmidt 2022). Particulate pollution, including that from wildfire smoke, negatively affects school performance and attendance (Chen et al. 2018; Pham and Roach 2023; Wen and Burke 2022), which may have longer-run effects on productivity. Psychological effects of particulate pollution include increased stress, anxiety, and aggressive behavior (Lu et al. 2018; Power et al. 2015; Sass et al. 2017). Burkhardt et al. (2019, 2020) propose these psychological phenomena as the primary mechanism to explain estimated increases in violent crime due to particulate pollution.

Smoke also has direct effects on agricultural output. Low-density smoke plumes increase the proportion of diffuse light, which can increase crop yields; because wildfires are currently more likely to produce low-density plumes, the net effect is to increase crop yields, but these benefits are expected to dissipate by 2050 as wildfires become more frequent and severe (Behrer and Wang 2022). Nevertheless, smoke can be detrimental to particular crops, such as wine grapes (Whiting and Krstic 2007).

An alternative to studying smoke damages using observational data on market outcomes is to measure the value of damages using survey responses or observed individual behavior. These approaches could potentially undervalue smoke impacts, such as if individuals do not fully appreciate the health consequences of exposure, although they can account for qualitative effects on amenity values or subjective well-being. For example, Jones (2017) compares life satisfaction survey responses across smoky and nonsmoky periods and finds that US adults are willing to pay $373 to avoid one day of wildfire smoke. Similarly, Burke et al. (2022), Du et al. (2022), and Loureiro et al. (2022) examine effects of wildfire smoke on expressed sentiment using high-frequency social media data, with Loureiro et al. (2022) estimating welfare losses in Spain and Portugal at approximately €4 to €7 per day of exposure. Gellman et al. (2023) examine welfare effects using observed recreation behavior, finding that smoke causes welfare losses to outdoor recreation of approximately $2.3 billion per year in the western United States.

Finally, preferences regarding smoke may be visible in home prices and regional demand for housing. Several studies find that air pollution more generally affects willingness to pay for housing (Chay and Greenstone 2005; Freeman et al. 2019; Hamilton and Phaneuf 2015; Nam et al. 2022). In general, it may be difficult to disentangle the effects of smoke from regional shocks to home prices. However, it is reasonable to expect that repeated smoke events might affect housing demand, and some initial evidence indicates that it does (Huang and Skidmore 2024; Lopez and Tzur-Ilan 2023). Since smoke tends to be spatially correlated, reduced demand for homes may result in increased outmigration from heavily affected regions (Chen et al. 2022; Tiwari 2023). While no studies have empirically examined migration due to wildfire smoke specifically, Rubin and Wong-Parodi (2022) find in a survey of California residents that nearly a quarter of those who intended to move within the next five years reported that wildfire and smoke had at least a moderate effect on their migration decision.

## 2.3. Distributional Impacts

Welfare effects from smoke—through either health impacts or other channels—are not borne equally. Although it is well established that disadvantaged and non-white communities are more exposed to overall $PM_{2.5}$, counties with a higher proportion of white people are on average more exposed to $PM_{2.5}$ from wildfire smoke (Burke et al. 2021). However, conditional on exposure, the degree of vulnerability to smoke varies across populations because of differences in impacts on indoor air quality, protective behavior, and time spent outdoors (Liang et al. 2021; Marlier et al. 2022; O'Dell et al. 2022; Wen and Burke 2022).

On average, an increase in outdoor $PM_{2.5}$ of 1 microgram per cubic meter ($\mu g/m^3$) is associated with an increase in indoor $PM_{2.5}$ of 0.15–0.4 $\mu g/m^3$. Indoor air pollution can triple during smoke events, in some cases leading to indoor $PM_{2.5}$ concentrations that exceed the 35 $\mu g/m^3$ standard for daily ambient air quality standards set by the US Environmental Protection Agency (EPA) (Burke et al. 2022, Liang et al. 2021). However, infiltration varies by building type (Burke et al. 2022; Liang et al. 2021; O'Dell et al. 2022) and is higher for older homes, smaller homes, and low-income households (Burke et al. 2022; Chan et al. 2013).

Outdoor workers are more exposed to hazardous air quality than indoor workers. Outdoor workers constitute 10 percent of the US workforce (BLS 2019) and earn substantially less than indoor workers, with the mean at $46,400 per year for outdoor workers and $54,300 per year for indoor workers.[5] Hispanic individuals are overrepresented among outdoor workers (Cox-Ganser and Henneberger 2021).

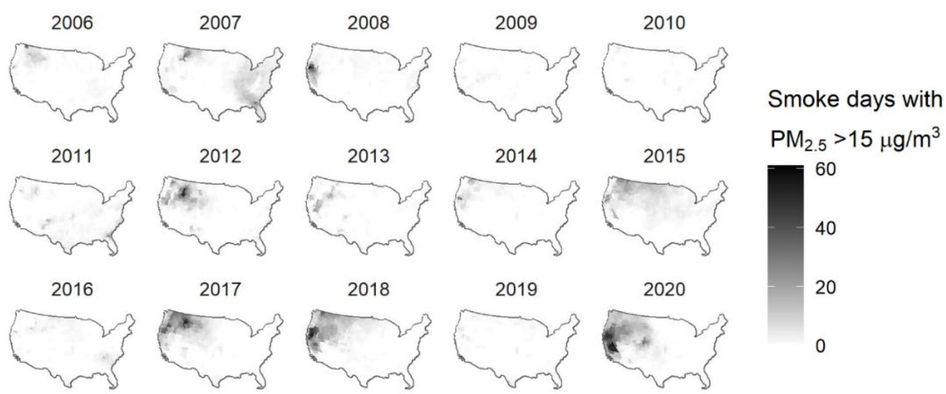
The ability to engage in protective behavior also varies across socioeconomic populations (Burke et al. 2022; Holloway and Rubin 2023; O'Dell et al. 2022). Defensive behaviors, including health-protecting investments like air purifiers (Ito and Zhang 2020; Richardson et al. 2012), and avoidance behaviors, such as reducing short-run labor participation (Aragon et al. 2017; Borgschulte et al. 2022), can both be costly. During smoke events, residents of lower-income areas search the internet less for health-protective information and spend less time at home than those in higher-income areas (Burke et al. 2022). High-income and whiter populations leave their home counties at higher rates than other socioeconomic groups during smoke events (Holloway and Rubin 2023). These results show that adaptive behavior is likely to be unequal across populations, conditional on exposure.

[5] These figures combine data from BLS (2019) with the analysis by Cox-Ganser and Henneberger (2021), which shows the proportions of indoor and outdoor workers by major occupations.

# 3. Wildfire Smoke Trends

As a consequence of the increasing size and intensity of wildfires, pollution from wildfire smoke is rising. This increased smoke pollution is currently undermining federal air quality goals. Wildfire smoke has accounted for up to 25 percent of $PM_{2.5}$ in recent years across the United States and up to half in some areas of the western United States (Burke et al. 2021; O'Dell et al. 2019). Most exposure has been concentrated in the western United States, especially the Pacific Northwest (Burke et al. 2021; Burke et al. 2023). Although overall levels of ambient $PM_{2.5}$ pollution had been declining for several decades, wildfire smoke pollution has reversed those trends in 31 states (Burke et al. 2023). From 2011 to 2022, wildfire smoke accounted for at least 25 percent of exceedances of EPA's 24-hour daily standards for $PM_{2.5}$ in 7 states (Burke et al. 2023). These exceedances are generally not a result of fires burning within the same county: rather, 87 percent of smoke $PM_{2.5}$ is experienced in a different county, while 60 percent comes from fires in other states (Wen et al. 2023).

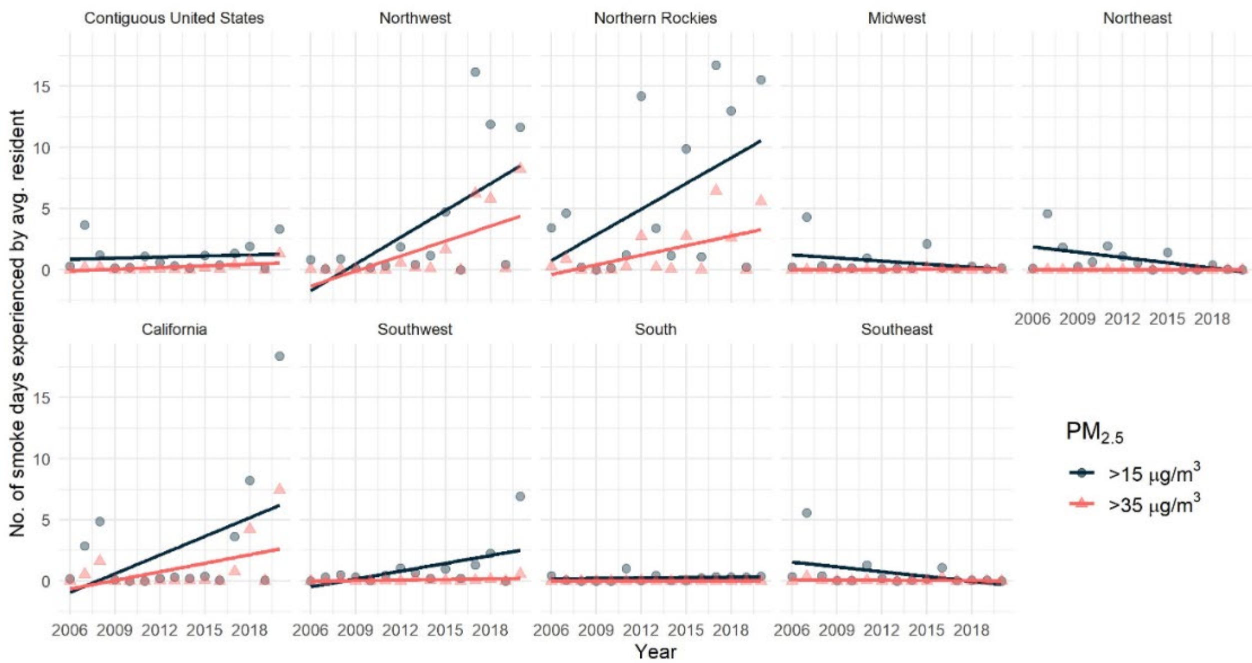
**Figure 1. County Days with Smoke $PM_{2.5}$ > 15 µg/m$^3$**




Source: Data from Childs et al. (2022).

Figures 1 and 2 illustrate trends in days with high wildfire smoke $PM_{2.5}$ using data from Childs et al. (2022). This measure of smoke-specific $PM_{2.5}$ is in addition to any ambient $PM_{2.5}$ from traditional sources. Figure 1 plots the number of days per year that a county, weighted by population, experienced smoke-specific $PM_{2.5}$ greater than 15 µg/m$^3$, the World Health Organization (WHO) threshold for 24-hour exposures to $PM_{2.5}$. Figure 2 shows regional trends for the WHO threshold of 15 µg/m$^3$ and the US National Ambient Air Quality Standards (NAAQS) 24-hour standard for $PM_{2.5}$ of 35 µg/m$^3$ set by EPA. The largest increases in extreme smoke days have been in the Pacific Northwest, Northern Rockies, and California; however, these data do not show more recent events, such as when the eastern United States was affected by large fires across Canada in the summer of 2023.

**Figure 2. Regional Trends in Smoke Days with High $PM_{2.5}$ Experienced by an Average Resident**




Source: Data from Childs et al. (2022).

Note: Regions included in the figure are Northwest (OR, WA); Northern Rockies (ID, MT, WY); Midwest (IL, IN, IA, KS, MI, MN, MO, NE, ND, OH, SD, WI); Northeast (CT, DE, DC, ME, MD, MA, NH, NJ, NY, PA, RI, VT); California (CA); Southwest (AZ, CO, NV, NM, UT); South (TX, OK); Southeast (AL, AR, FL, GA, KY, LA, MS, NC, SC, TN, VA, WV).

Wildfire smoke is expected to further degrade air quality as climate change exacerbates wildfire activity in the United States. Hurteau et al. (2014) estimate that wildfire emissions will increase in California by 19–101 percent by 2100. Similarly, Liu et al. (2021) use a combined climate, vegetation, and fire model to find that smoke emissions will increase by 50 percent in 2050 from the 2000 levels. Burke et al. (2023) also predict large smoke increases based on a projected rise in vapor pressure deficit, a measure of moisture in the air that is highly correlated with wildfire activity.

# 4. Policy Responses

The two primary strategies available to policymakers and managers to reduce smoke impacts are to reduce wildfire hazard and to encourage avoidance behaviors. While air quality regulation is generally EPA's responsibility, wildfire hazard mitigation falls primarily on public land management agencies and private landowners. Land management strategies to reduce wildfire hazard include mechanical treatments, such as thinning and biomass removal, and prescribed burning to reduce dry vegetation. Especially when used together, thinning and prescribed burns can significantly reduce the severity of wildfires, provide increased opportunities for fire containment, and restore fire-adapted ecosystems to historic conditions (Schultz et al. 2019). Prescribed burning is seen as a particularly effective and cost-efficient way to reduce fuels in fire-adapted ecosystems in the United States (Hashida et al. 2024; Kolden 2019). However, as a result of decades of fire exclusion and fuel buildup, fuel treatment needs in the United States are vast; in 2022, the US Forest Service (USFS) estimated that 50 million acres—approximately the area of Nebraska—of public and private land in the western United States needed to be restored over the next 10 years to reduce wildfire hazard in the highest-risk areas.

While recent policy has increased funding for fuel treatments, including for prescribed fire, managing smoke impacts through hazard mitigation nevertheless faces significant challenges. First, capacity and funding are significant barriers to increasing application of prescribed burns (Schultz et al. 2019). In 2021, Clavet et al. estimated that over the next 10 years, $5 billion to $6 billion annually would be needed to achieve USFS targets. The Infrastructure Investment and Jobs Act (IIJA) of 2021 sizably increased the level of federal fuel treatment funding, providing $5.5 billion for wildfire risk reduction and ecosystem restoration over the fiscal years 2022–26, an average of $1.1 billion per year. However, this sum will likely be insufficient to meet USFS goals. Even with further funding, the size of the current wildfire management workforce may limit the ability to dramatically increase the pace and scale of fuels management, at least in the short term. Second, agencies have generally not made smoke impacts a primary criterion for determination of priority fuel treatment locations.[6] Third, on private lands, investment in fuels management is limited by private incentives, which may not take into account the full social benefit of these activities (see, e.g., Busby et al. 2012). Lastly, wildfire hazard reduction may be impeded by narrow burn windows, periods of time when prescribed fire is allowable, because of the risk of escaped fires (Schultz et al. 2019). Combined, these factors incentivize land managers to rely on

[6] For example, priority "firesheds" for initial IIJA landscape investments were identified based on three criteria: potential to reduce fire risk, improved investment in underserved communities, and leveraged community partnerships (USFS 2022). Potential to reduce smoke impacts was not a primary consideration.

wildfires (including managed wildfires) to achieve management goals. However, wildfires are frequently larger than prescribed burns, and they may burn with greater intensity and emit more smoke.

The fact that prescribed fires, which are intended to reduce fire hazard, can affect air quality is known as the "smoke paradox" (Jones et al. 2022; Schweizer and Cisneros 2017). This trade-off presents challenges for US air quality regulation. The Clean Air Act (CAA) functions by penalizing regions when they fail to meet air quality standards. To avoid undue punishment, EPA treats wildfire smoke as an uncontrollable "exceptional event" and exempts smoke events from determinations of air quality attainment. In contrast, showing that prescribed burns should earn the status of exceptional event is more difficult (Williams 2021). These rules implicitly wager that the benefits of reduced smoke from future fires are unlikely to outweigh the damages of certain smoke from prescribed fires. Whether this is true is an empirical question on which there is little available research. If it is not true, the CAA may need to acknowledge that wildfire hazard can be managed—in other words, that wildfires are not uncontrollable acts of God—and to use the framework of the CAA to incentivize appropriate forest management (Williams 2021).[7]

Given the current regulatory framework, though, EPA's role in mitigating wildfire smoke damages has been limited to nonregulatory approaches, such as providing information about smoke impacts to encourage avoidance behaviors. For example, EPA helps communities plan for smoke events by establishing clean air centers and caches of reserve home air filters. The agency has also partnered with the USFS to develop an online tool that provides real-time information on fire locations and air quality (GAO 2023). However, direct evidence of the public health benefits from these nonregulatory activities is lacking, and some findings indicate that benefits may be small. Treves et al. (2023) find that clean air centers are underutilized. While related studies (e.g., Neidell 2009) find that air quality warnings can substantially increase avoidance behavior, evidence on smoke infiltration suggests that even those who avoid outdoor activity will experience large increases in indoor $PM_{2.5}$ exposure. Because of this and evidence that lower-income neighborhoods engage less in protective measures than wealthy neighborhoods, Burke et al. (2022) argue that policies aimed at encouraging self-protection are likely to yield unequal benefits and to be insufficient on their own.

[7] Hyde et al. (2017) provide an international comparison of wildfire-related air quality regulations. Both Canada and Australia have adopted an "exceptional event" framework similar to that of the United States but more actively promote prescribed burns. Greece has more restrictive regulations and currently bans prescribed fire because of concerns over air quality.

# 5. Conclusions

As large wildfires grow more frequent, the United States has seen increasing impacts of smoke. During extreme events, smoke increases pollution above federal attainment standards for particulate matter pollution. Smoke increases are most severe in the western states, especially California, the Pacific Northwest, and the Northern Rockies, but have affected the entire continental United States. These impacts are projected to grow over the century as the climate warms.

The economics and social sciences literatures have documented numerous impacts of wildfire smoke on human health and economic activity, which are borne unequally. These include increases in mortality and severe illness, declines in maternal and infant health, and reductions in labor productivity and perceived well-being. While much remains to be learned about damages from smoke—especially about its longer-term impacts and differences between its impacts and those of other sources of $PM_{2.5}$—existing evidence suggests these damages are potentially even larger than direct damages from wildfires.

Current federal policy is likely insufficient to address the issue of wildfire smoke. Land management to reduce wildfire hazard faces significant challenges, including a lack of funding and regulatory hurdles for both agencies and private landowners. Air quality regulations likely are impediments to greater use of prescribed fire but could be leveraged to incentivize wildfire hazard mitigation. As much of the literature has highlighted, reliance on private adaptation alone is unlikely to adequately mitigate the damages of wildfire smoke.

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