Feature

Wildfire Smoke in the United States

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Introduction

Wildfire activity is increasing globally (Jolly et al. 2015; Senande-Rivera, Insua-Costa, and Miguez-Macho 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 (Wang et al. 2021; Burke et al. 2023).

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 microns in diameter ($PM_{2.5}$) accounts for the third-largest share of emissions, by mass, after carbon dioxide and carbon monoxide (Urbanski, Hao, and Baker 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 article argues that increasing air pollution due to wildfire smoke is a serious threat to health and human well-being and warrants increased attention from policy makers in the United States. Although acknowledging the important role of carbon emissions from wildfires in contributing to climate change—for example, in 2020, only California's transportation sector produced more emissions than the state's wildfires (Jerrett, Jina, and Marlier 2022)—this

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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 μm in diameter, respectively. Studies generally indicate that exposure to particulate matter less than 2.5 microns 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, Hao, and Baker 2008).

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article focuses specifically on wildfire smoke, that is, emissions that contribute conventional pollutants. 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 article proceeds as follows. "Impacts of Wildfire Smoke" 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. "Wildfire Smoke Trends" then shows, based on recently published results and data, that the impact of wildfire smoke on US air quality has grown substantially in recent years. Finally, "Policy Responses" 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. The final section concludes.

Impacts of Wildfire Smoke

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 (for reviews of the physiological mechanisms underlying health effects of fine particulate matter, see Kim, Kabir, and Kabir 2015 and Feng et al. 2016).

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., Burkhardt et al. 2019; Burke et al. 2022).

The health consequences of exposure to $PM_{2.5}$ from wildfire smoke versus other sources may differ for two reasons. 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, Pinkerton, and Last 2009). In addition, smoke contains harmful co-pollutants, including larger-diameter particulate matter and volatile organic compounds (Liu and Peng 2019). Aguilera et al. (2021) found that wildfire smoke increases respiratory hospitalizations more than $PM_{2.5}$ from ambient sources.

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). Qiu et al. (2024) estimate that from 2011 to 2020 there were approximately 15,800 excess deaths per year due to wildfire smoke. 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 (Liu et al. 2015; Reid et al. 2016; Cascio 2018). Although there is consistent evidence that wildfire smoke increases hospital visits for respiratory conditions (Reid et al. 2016; Heft-Neal et al. 2023), evidence of smoke's effects on cardiovascular morbidity is mixed (Heft-Neal et al. 2023).

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.

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, Molitor, and Zou (2024) 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, Miranda, and Oliva 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, Liu, and Salvo 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 on various cognitive tasks (Graff Zivin and Neidell 2012; Archsmith, Heyes, and Saberian 2018; Bedi et al. 2021; Schmidt 2022). Particulate pollution, including that from wildfire smoke, negatively affects school performance and attendance (Chen, Guo, and Huang 2018; Wen and Burke 2022), which may have longer-run effects on productivity. Psychological effects of particulate pollution include increased stress and anxiety (Power et al. 2015; Sass et al. 2017). Burkhardt et al. (2019) 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—for example, if individuals do not fully appreciate the health consequences of exposure. An advantage of both survey and observational data, however, is that they can account for effects on the subjective value of amenities (such as smoke-free air) or 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) and Du et al. (2024) estimate effects of wildfire smoke on expressed sentiment using high-frequency social media data, with Du et al. (2024) translating these effects to reductions in wages in Southeast Asia. Gellman, Walls, and Wibbenmeyer (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; Hamilton and Phaneuf 2015; Freeman et al. 2019; 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). Because smoke tends to be spatially correlated, reduced demand for homes may result in increased outmigration from heavily affected regions (Chen, Oliva, and Zhang 2022). Although 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.

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 one 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 μg/m^3 standard for daily ambient air quality set by the EPA (Liang et al. 2021; Burke et al. 2022). However, infiltration varies by building type (Liang et al. 2021; Burke et al. 2022; O'Dell et al. 2022) and is higher for older homes, low-income neighborhoods, and Black and Hispanic neighborhoods (Burke et al. 2022).

Outdoor workers are more exposed than indoor workers to hazardous air quality. 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.[2] 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; O'Dell et al. 2022). Defensive behaviors, including health-protecting investments like air purifiers (Richardson, Champ, and Loomis 2012; Ito and Zhang 2020), and avoidance behaviors, such as reducing short-run labor participation (Aragon, Miranda, and Oliva 2017; Borgschulte, Molitor, and Zou 2024), 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). These results show that adaptive behavior is likely to be unequal across populations, conditional on exposure.

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 (O'Dell et al. 2019; Burke et al. 2021). Most exposure has been concentrated in the western United States, especially the Pacific Northwest (Burke et al. 2021, 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 days exceeding the EPA's 24-hour daily standards for $PM_{2.5}$ in seven states (Burke et al. 2023). These poor air quality days 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, whereas 60 percent comes from fires in other states (Wen et al. 2023).

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 exposure 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 24-hour standard for $PM_{2.5}$ of 35 μg/m^3 set by the EPA. The largest increases in

[2] 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.

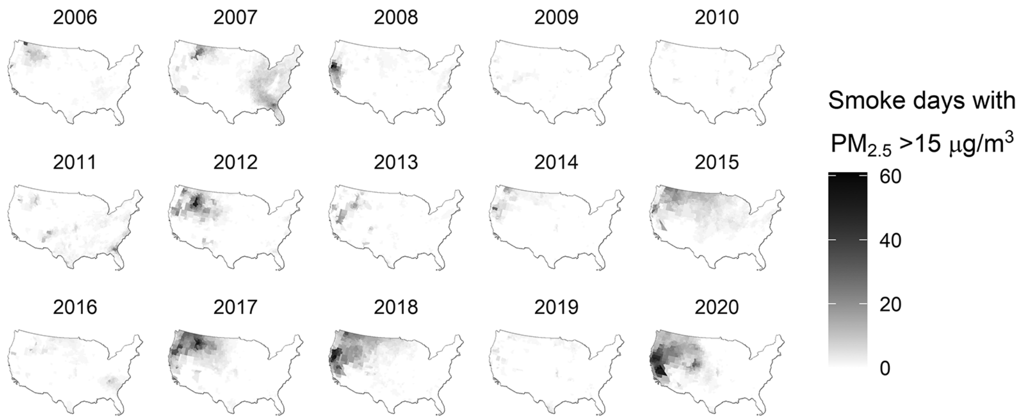

Figure 1 County days with smoke $PM_{2.5} > 15\ \mu g/m^3$. Data from Childs et al. (2022).

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.

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

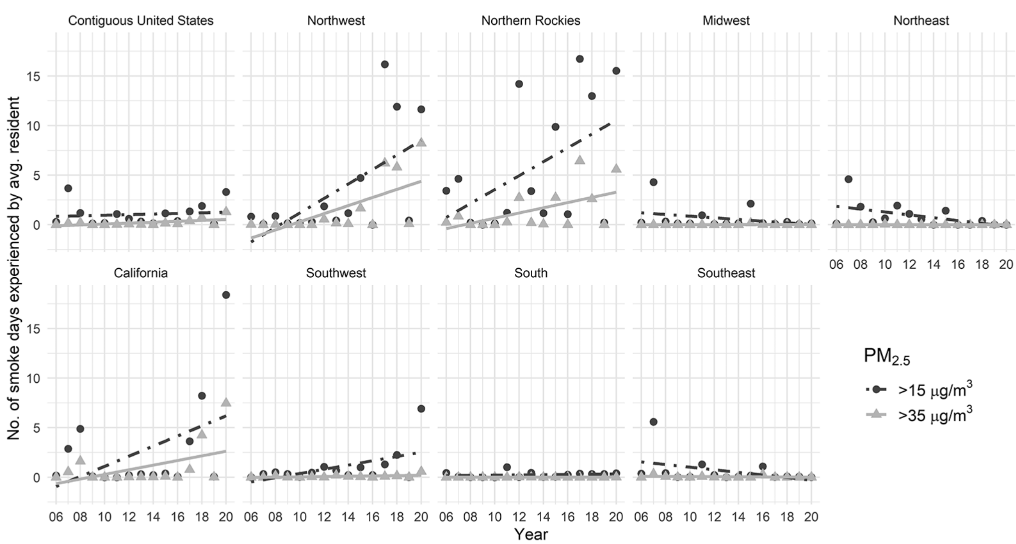

Figure 2 Regional trends in smoke days with high $PM_{2.5}$ experienced by an average resident. Data from Childs et al. (2022). Regions included in the figure are Northwest (OR, WA); Northern Rockies (ID, MT, WY); Midwest (IA, IL, IN, KS, MI, MN, MO, ND, NE, OH, SD, WI); Northeast (CT, DC, DE, MA, MD, ME, NH, NJ, NY, PA, RI, VT); California (CA); Southwest (AZ, CO, NM, NV, UT); South (OK, TX); and Southeast (AL, AR, FL, GA, KY, LA, MS, NC, SC, TN, VA, WV).

on a projected rise in vapor pressure deficit, a measure of moisture in the air that is highly correlated with wildfire activity.

Policy Responses

The two primary strategies available to policy makers and managers to reduce smoke impacts are to reduce wildfire hazard and to encourage people to avoid exposure. Whereas air quality regulation is generally the 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, McCaffrey, and Huber-Stearns 2019). Prescribed burning is seen as a particularly effective and cost-efficient way to reduce fuels in fire-adapted ecosystems in the United States (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 of public and private land in the western United States—approximately the area of Nebraska—needed to be restored over the next 10 years to reduce wildfire hazard in the highest-risk areas.

Although 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, McCaffrey, and Huber-Stearns 2019). In 2021, Clavet et al. estimated that, over the next 10 years, five to six billion dollars 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 2022–2026, 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.[3] 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). Finally, 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, McCaffrey, and Huber-Stearns 2019). Combined, these factors incentivize land managers to rely on 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.

[3]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.

The fact that prescribed fires, which are intended to reduce fire hazard, can affect air quality is known as the "smoke paradox" (Schweizer and Cisneros 2017; Jones et al. 2022). 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, the EPA treats wildfire smoke as an uncontrollable "exceptional event" and exempts smoke events from determinations of air quality attainment; a similar framework is used in Canada and Australia (Hyde et al. 2017). However, exempting smoke from prescribed burns is more difficult (Williams 2021). These rules implicitly wager that the benefits of reduced smoke from future wildfires 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).

Given the current regulatory framework, though, the 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, the 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. Although 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, as well as 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.

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.

Both economics and social sciences literature have documented numerous impacts of wildfire smoke on human health and economic activity. These impacts are borne unequally. They include increases in mortality and severe illness, declines in maternal and infant health, and reductions in labor productivity and perceived well-being. Although 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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