

Disruptions from Wildfire Smoke: Vulnerabilities in Local Economies and Disadvantaged Communities in the U.S.

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Disclaimer

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Executive Summary

Wildfires, which are increasing in frequency, duration, and intensity, are measurably affecting vulnerable populations, labor, housing, and education. This report describes how wildfire smoke disrupts various sectors of the economy across the United States. Wildfire smoke is a growing problem for groups that face greater economic barriers than the general population, such as low-income families, housing-vulnerable communities, and frontline workers.

Key Takeaways

- In the past decade, most Americans have experienced statistically significant increases in days of light, medium, and heavy wildfire smoke and decreases in smoke-free days.
- Increases in the number of days of smoke were greatest for the most dense, dangerous, and disruptive category of smoke.
- Avoiding wildfire smoke exposures is likely worth hundreds of billions of dollars per year to Americans.
- Increases in wildfire smoke are occurring in the nation's most vulnerable communities, with disproportionate increases for minority populations and those with limited English proficiency.
- Frontline workers (here referring to those workers in outdoor occupations and often without indoor air filtration) are increasingly experiencing exposure to wildfire smoke. Smoke will continue to increase the risk of occupational hazards, decrease productivity, and cause worker disruptions in industries that depend on these workers. Adapting to these changing conditions will result in additional costs for businesses, consumers, and governments.
- Wildfires have increased heavy smoke exposures for young children and students in poverty. This could have impacts on early childhood and K–12 education, such as disruptions in learning, poor academic outcomes, and increased food insecurity.
- Housing-vulnerable communities are experiencing an increase in heavy smoke days, especially in the high-cost regions of the West (The Federal Reserve's Twelfth District). Wildfires are likely to pressure the housing sector by increasing housing costs and disproportionately impacting housing for vulnerable communities who live in housing types (older units, rental units, etc.) that are less likely to access protective adaptations.
- Dramatic increases in disruptive smoke overlap with eligibility for existing financing programs that could help build resilience to smoke-related damages. Programs that target low- and moderate-income communities may have outsized importance in building broad economic resilience.



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Introduction

Wildfires are an increasingly inescapable challenge in the United States that cause significant economic and social disruptions (Burchfield et al. 2007; Paveglio et al. 2015). Wildfires in the United States have increased the acreage burned per year since 1990 (Hoover 2022), leading to over \$20 billion worth of damages and \$3 billion in response costs in 2018 alone (Bayham et al. 2022). In addition to causing physical damage, wildfires release smoke that compromises air quality by increasing concentrations of particulate matter (PM), ozone, polycyclic aromatic hydrocarbons, volatile organic compounds, and other harmful air pollutants that have well-documented impacts on respiratory and cardiovascular health, as well as overall mortality (Cascio 2018; Rappold et al. 2017; Childs et al. 2022).

Wildfire smoke can lead to economic and labor market changes, resulting in decreased earnings and employment outcomes (Borgschulte, Molitor, and Zou 2022), decreased recreational opportunities (Hesseln, Loomis, and González-Cabán 2004), and decreased property values (McCoy and Walsh 2018). The total costs of wildfire, including social, economic, and health costs of smoke, far exceed physical damage and fire suppression/management costs. One estimate for a single year (2018) of fires in California came to \$148.5 billion, approximately 1.5% of the state's gross domestic product that year (Wang et al. 2021). Wildfire smoke causes social and behavioral changes, prompting households to take costly avoidance or defensive actions. Behavioral changes, such as spending more time indoors, reducing time away from home, or missing work, are associated with increasing wildfire smoke (Burke et al. 2022; Jones et al. 2018).

Smoke from large, uncontrolled fires, also referred to as wildland or wildfire smoke, can travel thousands of miles, potentially exposing distant populations, including communities less prepared for smoke and more susceptible to adverse impacts from air pollution (Afrin and Garcia-Menendez 2021; Palaiologou et al. 2019). Although the risk of wildfire—for example, the probability of property burning in any given year—can be clearly defined and used in planning, the movement of wildfire smoke over large areas means that unexpected exposures can occur. As with other ambient climate hazards, such as extreme heat, the characteristics of the local economy and residents play an important role in determining capacity to adapt and in explaining destabilizing impacts of wildfire smoke (Eisenman et al. 2016; Basu and Ostro 2008).

Wildfire smoke impacts cut across different sectors, affecting public health and safety, the labor force, housing, property and infrastructure, and education. An individual's socioeconomic status, housing situation, employment status, and job type can impact his or her adaptive capacity—the relative ability to prepare for, respond to, and recover from wildfire smoke exposures. For example, lower socioeconomic status is associated with a greater likelihood of preexisting health conditions, such as respiratory or cardiovascular disease, and thus may result in greater susceptibility to adverse health outcomes when exposed to wildfire smoke. Lower-income households may also have fewer resources for or access to emergency protective equipment, such as indoor air filters.



This brief aims to fill existing gaps in our understanding of wildfire smoke exposures across different sectors and populations in the United States and to document changes in those exposures in recent years. The following report enumerates smoke exposures for general and sub-populations of concern and discusses the impacts of wildfire smoke on communities of concern, including frontline workers, school-aged children, housing-vulnerable households and people experiencing homelessness, and communities eligible for federal investments.


Research Motivations and Methodology

Wildfire Smoke Health Effects

The health impacts of wildfire smoke exposure are not uniformly distributed across regions and populations. Certain populations, such as lower-income, children or older adults, medically compromised individuals or those who cannot avoid exposure, are especially vulnerable to smoke-induced health effects. Wildfire smoke exposure is associated with asthma exacerbations, chronic obstructive pulmonary disease, respiratory infections, myocardial infarction, ischemic heart disease, heart failure, dysrhythmia, pulmonary embolism, ischemic stroke, transient ischemic attack, out-of-hospital cardiac arrests, and all-cause mortality (Reid et al. 2016; Heaney et al. 2022; Wettstein et al. 2018). Such health outcomes as cardiovascular disease and cerebrovascular emergency department visits have been linked specifically to heavy-density smoke exposure, which has increased the most in the past decade (Wettstein et al. 2018). Previous research has shown that the negative health effects of prescribed fire smoke are more pronounced in children born to black and Hispanic mothers, as well as children of low-income mothers (Jones and Berrens 2021). Our findings suggest that individuals who are experiencing increased exposures might also live in communities with limited resources to reduce the impacts of the exposures.

Descriptive analyses were conducted on the presence of wildfire smoke plumes and their overlap with population centers to describe the magnitude of and trends in wildfire smoke affecting communities across the United States in 2011–2021. These data on census tract--level wildfire smoke exposures were combined with information on specific populations to characterize wildfire smoke exposures across different socioeconomic groups.

To describe recent trends in wildfire smoke, a comparison of estimates in the earliest five years (2011–2015) to those of the latest five years (2017–2021) of the 11-year study period was conducted. Using census tract aggregations of the daily smoke data, the mean annual days of smoke were calculated and then used to statistically test changes in frequency of wildfire smoke plumes across the study



period. In each analysis, census tract estimates of person-days or number of smoke-days are used as the basis for central tendency estimates within the county or SVI (Social Vulnerability Index) tertile. All analyses were performed using R Statistical Software (R Core Team 2021).

Wildfire Smoke Exposures

To obtain community-level exposure to wildfire smoke, data from the National Oceanic and Atmospheric Administration (NOAA) Hazard Mapping System (HMS) smoke dataset were combined with population data from the 2010 U.S. Census. HMS data use satellite-detected fires with multiple daily satellite images and a combination of analyst examination and automated processing to record smoke plumes of categorical densities across North America. Satellite imagery that detects smoke plumes can reliably identify periods of wildland fire influence on ground-level measurements of air quality from validated monitors. Plume densities reported in HMS data correlate with $PM_{2.5}$ concentrations, with concentrations $<10 \mu g/m^3$ categorized as *light*, $10-21 \mu g/m^3$ as *medium*, and $>21 \mu g/m^3$ as *heavy*.¹

To estimate the sizes of populations potentially impacted by light, medium, and heavy wildfire smoke plumes between January 1, 2011, and December 31, 2021, smoke plume data and 2010 census block group centers of population were linked. Daily smoke density categories were assigned to populations in each block group if a smoke plume from any time in the day contained the block group population center. The spatial intersection of HMS plumes and population centers is detailed in Vargo 2020. Block group populations were held constant at 2010 levels to quantify the impact of changes in wildfire smoke regimes and disentangle them from population shifts over the course of the decade. Populations under each smoke category were considered for each day. The resulting quantity, person-days (see box), is the product of the number of people in a census block group or tract and the number of days that block group experiences smoke. Person-days by smoke density and smoke-free person-days were then aggregated across geographies and time periods for our analyses.

¹ Particulate matter (PM) is a measure of air pollution that refers to inhalable particles made up of various chemicals. $PM_{2.5}$ refers to particles that are generally 2.5 micrometers and smaller (Source: EPA Particulate Matter [PM] Basics).

What is a person-day?

Throughout the report, **person-days** are used to capture, together, the number of people and the amount of time spent under smoke plumes. When a smoke plume is observed over a population center, each person who lives there is considered to have experienced one smoke day. Suppose 500 people live in a population center; each time a plume is over it, 500 person-days of smoke would be tallied. This measure can be adapted to consider communities of concern—for example, to count frontline worker-days, student-days, or household-days of smoke.

A person-day is a useful metric specifically because it incorporates people into descriptions of air quality. It helps to give an accounting of the potential impact of smoke by capturing the number of people and the amount of time people may have been exposed. Person-days assign exposures at fine scale but allow for versatile aggregation and comparison of exposures for different geographies and time periods.




After quantifying and describing general trends in wildfire smoke since 2011, the same data are combined with information on specific populations of interest to better understand who is most affected by wildfire exposures and how those communities might be prioritized for community development.

Populations of Concern

There are several community dimensions of interest relevant to understanding wildfire smoke exposure and the resulting economic impacts. The characteristics of people or a community (e.g., age, race, health status, income, occupation), social inequalities (e.g., social capital, political power, lack of access to information), place-based inequalities (e.g., rural versus urban, elevation), and adaptation inequalities all impact a population's susceptibility to disaster events and their resulting exposures (Cutter, Boruff, and Shirley 2003). Although wildfire smoke events affect entire populations together, their impacts are shaped by the population's susceptibility and its adaptive capacity. This report's findings suggest that increases in smoke are occurring in communities with high vulnerability in the labor, housing, and education sectors. Communities with fewer economic resources may face more barriers in avoiding exposures during a wildfire smoke event (Murphy et al. 2015). However, this overlap of vulnerability and growing exposure suggests that interventions that target at-risk communities may more efficiently reduce smoke exposure, potential health impacts, and social and economic losses associated with wildfires. This report is not exhaustive in its description of populations of concern. Considering other marginalized populations, such as indigenous communities, is important for improving understanding of the impacts of wildfire smoke.

The Centers for Disease Control and Prevention (CDC)'s SVI data were used to investigate populations of concern for wildfire smoke and evaluate characteristics that might affect the health risks of wildfire smoke exposures. All analyses were performed using the 2018 version² of the SVI data at the census tract scale. Daily person-days of wildfire smoke at the block group level were aggregated to annual census tract aggregates and linked with 2018 SVI percentile rankings of four themes: (1) socioeconomic status, (2) race/ethnicity/language, (3) household composition and disability, and (4) housing/transportation. Estimates of person-days and number of smoke-days for each smoke density were calculated using national tertiles of the overall SVI theme and the four component themes. The tertile with the lowest SVI scores is referred to as having the greatest health/social "advantage," and the tertile with the highest SVI scores is referred to as having the greatest health/social "disadvantage." The assignment of tertiles using the census tract file (rather than other aggregations of SVI data) ensures that each tertile has roughly the same number of people. Additionally, specific

² The 2018 version of the CDC's Social Vulnerability Index is the most recent release at the time of the analysis. It is the case that neighborhood/population characteristics shift over time, such that a neighborhood's SVI score in 2010 may be different than in 2018. By using the 2018 designations, the analysis highlights where smoke exposure changes over the last decade in neighborhoods that recently rank among the nation's most vulnerable.



components of the SVI (e.g., the number of persons without a high school diploma) were considered to examine changes in wildfire smoke among specific populations over the study period.

Frontline Workers

Wildfires have uneven impacts across the labor force and especially affect those who work outdoors or in indoor situations lacking adequate air conditioning or ventilation. Wildfire smoke impacts among these workers, referred to here as frontline workers, are expected to be greater than for other workers. Frontline workers are often paid lower wages, especially workers involved in food production and preparation or the movement and distribution of goods. These workers are also disproportionately racial and ethnic minorities. Migrant workers are also overrepresented in many of these frontline occupations, especially farmworkers and construction workers (Thomason and Bernhardt 2020). As a result of structural inequities, frontline workers have underlying health risks, low socioeconomic status, and reduced health-care access, which increases their overall vulnerability to wildfire smoke (Schenker et al. 2015). Frontline workers face increased occupational hazards, such as smoke-related health effects and exacerbated health vulnerabilities (Zhou et al. 2021), decreased productivity, and a greater likelihood of work disruptions and instability. As wildfire smoke increases hazards for these workers and disrupts productivity, the national economy suffers.

The contribution of industries to state labor forces and GDPs (gross domestic product), the percentage of workers considered frontline, and how frontline workers' exposure to smoke changed from 2011–2015 to 2017–2021 were used to quantify smoke exposures in the labor force. The American Community Survey (ACS) five-year data from 2019 were used to enumerate frontline workers or those more likely to work outdoors and less likely to be able to mitigate their smoke exposures. Using estimates for variables included within the group C24050: Industry by Occupation for the Civilian Employed Population 16 Years and Over, the contribution of frontline industries to local labor forces and exposures among frontline workers were assessed. Among the 13 industries captured within the ACS group, frontline workers included in two occupations (“Natural resources, construction, and maintenance” and “Production, transportation, and material moving”) were counted as frontline workers and used with smoke days to arrive at frontline worker-days of smoke exposure. Four industries in the ACS variable with a majority of workers in frontline occupations were given special consideration: “Agriculture, forestry, fishing and hunting, and mining”, “Construction”, “Manufacturing”, and “Transportation and warehousing, and utilities”. State-specific GDP information was collected from the Bureau of Economic Analysis Table (SAGDP2N Gross domestic product by state) for year 2020.³

³ Industry codes "11, 21", "31-33", and "22, 48-49" from the SAGDP2N data are used to capture industries with majority frontline workers.



School-Aged Children

The negative impacts on air quality make children a population of concern for wildfire smoke exposures. The development of the brain and organs throughout childhood and adolescence makes pollution potentially more damaging to children's health, with much more long-lasting permanent effects, compared to adults (WHO 2005). Air pollution can decrease cognition and lead to poorer educational outcomes in the long term (Shier et al. 2019; Miller and Hui 2022). The economic impacts of childhood air pollution exposures can also impact near- and long-term school facilities and district budgets (Li and Jimenez 2022). A study of California schools from 2002–2003 through 2018–2019 found that wildfires related to nearly two-thirds of the school closure days and more than 70% of missed student-days over the 17 years (Miller and Hui 2022). Moreover, the study found significant negative impacts on academic performance among younger students. Another recent study found that the presence of wildfire smoke decreased students' test scores, particularly for younger grades and disadvantaged districts. The impacts of one year, 2016, were projected to result in lost future earnings of more than \$1.5 billion (Wen and Burke 2022).

Outside the classroom, school closures disrupt resources and services, such as meals and child care, and, as a result, students face increased risk of food insecurity and poor academic outcomes. Child-care providers and school districts with smaller budgets that serve disadvantaged communities could be particularly vulnerable to the impacts of wildfires because they often have greater needs and fewer resources available to address such issues. Parents are more likely to miss work to meet unexpected child-care needs, and households in low- and middle-income communities are less likely to have reliable and affordable child-care options available to them (Harknett, Schneider, and Luhr 2022; Shrimali 2020). Additionally, child care disproportionately falls on low- and middle-income women and women of color, widening existing inequities (Shrimali 2020).

To estimate the impact of wildfire smoke on economically disadvantaged students, we used the ACS 2019 five-year estimates for the number of K–4 students enrolled in school and below the poverty line (variable group B14006) to calculate student-days of heavy smoke.

Housing-Vulnerable People and People Experiencing Homelessness

Affordable and safe housing is an important factor in dealing with many natural hazards, as well as a commodity that is also threatened by disasters. Homes are places of refuge from outdoor elements, such as wildfire smoke, and at the same time, fires pressure housing markets through loss of housing stock, limiting where new housing should be built, requiring retrofits, and increasing risks to existing properties. Guidance for coping with wildfire smoke advises individuals to keep indoor air as clean as possible, often by closing windows and doors and running an air conditioner with a clean filter (CDC 2022). Lower-income households are more likely than higher-income households to live in housing that needs repair (Divringi et al. 2019), less likely to buy air filters, less likely to live in homes with air conditioning, and more likely to avoid running air conditioning due to the cost of energy (Hansen et al. 2011; English et al. 2007). Similarly, renters are more likely to be low-income and thus more likely to rely on landlords to modify their homes to mitigate the effects of natural disasters.



Housing tenure is particularly important as a proxy for improvements and retrofits being installed, such as HVAC or window/door upgrades to control indoor environments. Few renters are in the position to invest in such improvements, and landlords are reluctant to pursue such investments (Melvin 2018). To consider the smoke exposures among housing-vulnerable households, estimates of renter-occupied households—along with cost-burdened (spending more than 30% of the household’s income on housing), owner-occupied households built prior to 1980—were counted for all U.S. census tracts.

The Comprehensive Housing Affordability Strategy (CHAS) data from the U.S. Department of Housing and Urban Development (HUD) were used to describe the overlap of smoke exposures with housing conditions that make it more difficult for residents to protect themselves (CHAS Database 2019). CHAS data are generated by HUD from custom tabulations of ACS data and provide estimates at the census tract scale within the range of the smoke record, specifically 2014–2018. CHAS Table 12 was used to obtain detailed estimates of housing tenure (renter vs. owner-occupied), cost burden, year the structure was built, and household income. The estimates were combined with tract information about wildfire smoke exposure to describe household-days of smoke and changes across the study period.

People experiencing homelessness face a lack of regular shelter, as well as access to information and resources to prepare for and respond to wildfires, which amplify their wildfire smoke and health risk (Every et al. 2014; Gin et al. 2021; Gin et al. 2022). Additionally, many people experiencing homelessness are also working in low-wage, frontline jobs and thus represent a portion of the labor force especially vulnerable to disruptions from smoke exposures. A 2020 survey of people experiencing homelessness in Portland, Oregon, found that 75% did not receive any information during wildfires and 69% received no type of help during wildfire and smoke events (Hines, Petteni, and Knowlton 2021). Information on unhoused populations was obtained from HUD’s inventory of Point-in-Time (PiT) Counts assembled as part of the Annual Homeless Assessment Report to Congress (HUD 2021). Information about boundaries of Continuum of Care (CoC) were overlaid with census tracts to calculate the average number of days of smoke experienced by a CoC each year and to arrive at homeless-days of exposure. Although limited in their coverage, the PiT numbers give an idea of where the confluence of people experiencing homelessness and dangerous smoke resides.



Community Investment Opportunities

Several programs exist to direct investment to the communities where there are concentrations of disadvantaged populations discussed in this report. Given the intersectional nature of many of the factors⁴ used to describe those disadvantages, programs targeting low- and moderate-income communities can be important for fostering resilience to many risks from extreme weather and other social determinants of economic, physical, and mental health. The Community Reinvestment Act (CRA) is one example of legislation intended to ensure regulated banks help meet the credit needs of the local communities in which they operate. Specifically, banks are assessed on their record of meeting the credit needs of the entire community they serve, including low- and moderate-income neighborhoods. The U.S. Department of Housing and Urban Development (HUD) also identifies tracts for its Low-Income Housing Tax Credit (LIHTC) and those that are in Difficult Development Areas (DDAs) (CHAS Database 2019)—areas with high land, construction, and utility costs relative to the area median income and based on Fair Market Rents (FMRs) and income limits.

The Federal Financial Institutions Examination Council (FFIEC) identifies tracts for the Community Reinvestment Act (CRA). To be considered CRA-eligible, metropolitan tracts must be identified as low - tract median family income less than 50% of area median family income – or moderate - tract median family income greater than or equal to 50% and less than 80% of area median family income – income, or be identified as nonmetropolitan, middle - tract median family income greater than or equal to 80% and less than 120% of area family median income – income tracts designated by the FFIEC as distressed or underserved. Using CRA-eligible tract designations from 2020, changes in smoke exposures in qualified tracts were assessed.

Results

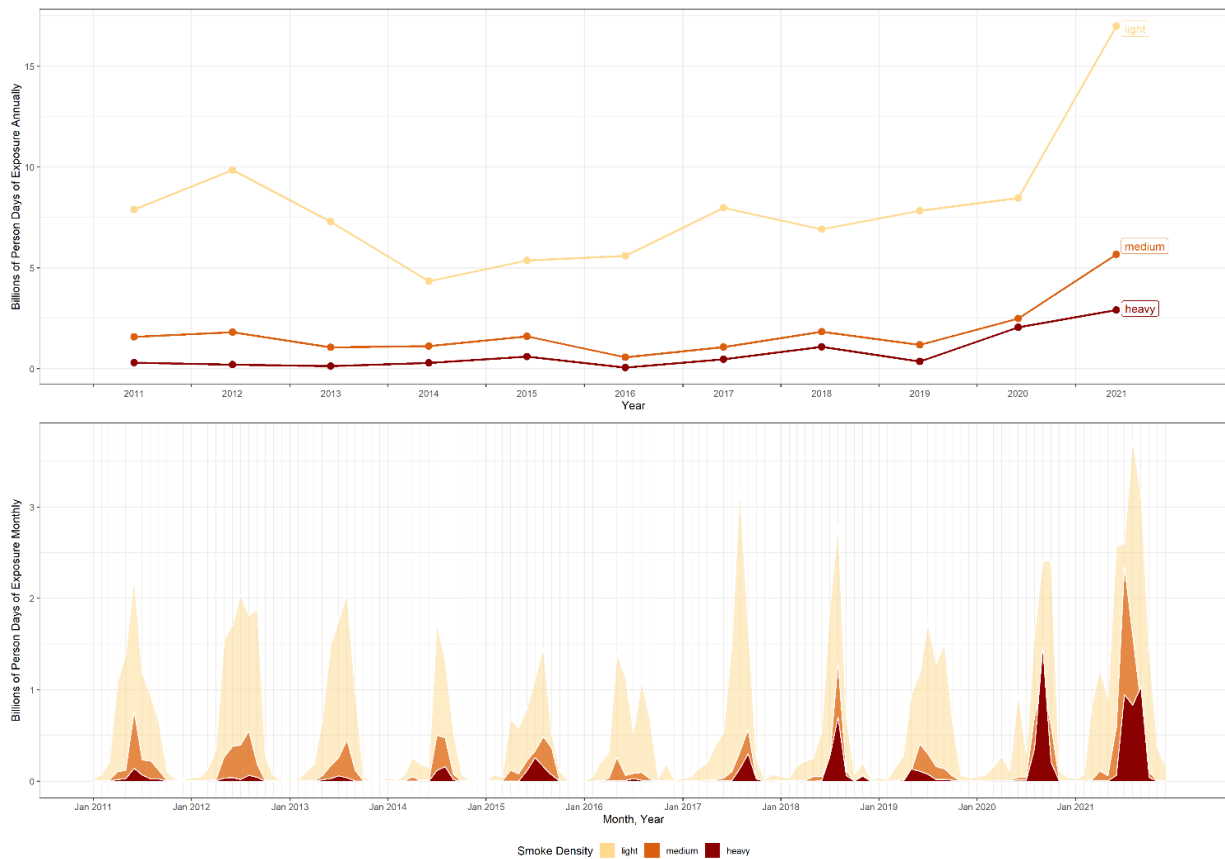
National Trends in Wildfire Smoke, 2011–2021

Exposure to wildfire smoke increased in the United States from 2011 to 2021 (Figure 1). The total numbers of person-days of all categories of wildfire smoke in the last five years of the study (2017–2021) increased relative to those in the first five years (2011–2015). For person-days of heavy-density smoke, the five-year annual average increased 350%, from 307,106,829 to 1,381,038,566 person-days. The increases for light- and medium-density smoke person-days were 39% and 71%, respectively. The number of smoke-free person-days decreased 4.6% between the two periods.

⁴ For examples of some of these “social determinants of health,” see the individual indicators of the CDC’s Social Vulnerability Index.

Figure 1. Wildfire smoke exposures of all smoke densities have increased in recent years, with the largest increases in the most dangerous and disruptive category of smoke.

Annual (upper panel) and monthly (lower panel) person-days of smoke exposure, 2011–2021 (billions)



Source: Hazard Mapping System Smoke Product from National Oceanic and Atmospheric Administration (NOAA).

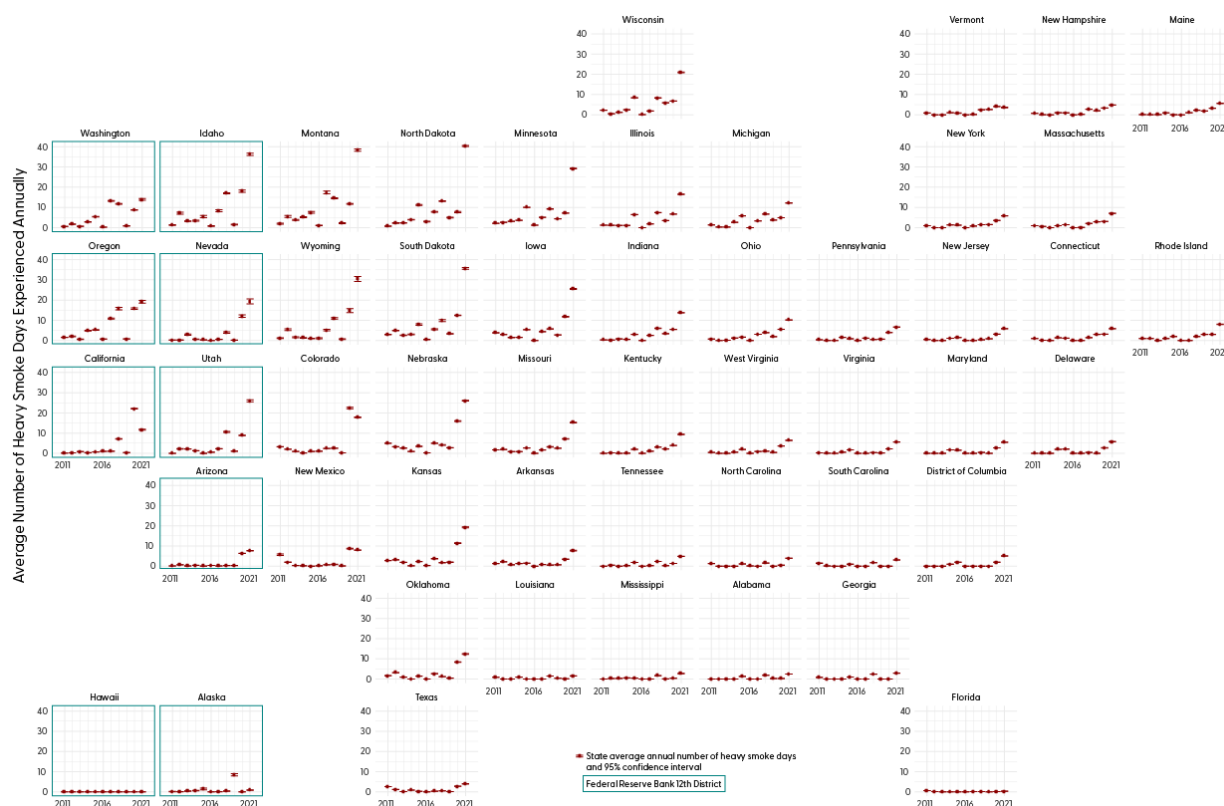
Increases in the annual number of days of heavy smoke are evident and significant⁵ for most states (Figure 2) but are largest in the western United States.⁶ States in the West, such as Idaho, Oregon, and Washington, experienced 339%, 340%, and 297% increases in heavy smoke days per year, respectively. Smoke is not confined to one geographic region of the United States, may originate outside of the U.S., and can travel across long distances. States in the East, such as Maryland, South Carolina, and Virginia, experienced increases of 166%, 88%, and 233%, respectively.

⁵ Mean number of days for each state are calculated using census tracts in the state; 95% confidence intervals around each mean are used to perform tests of significance.

⁶ The states of the western United States comprise the Federal Reserve 12th District: Alaska, Arizona, California, Hawaii, Idaho, Nevada, Oregon, Utah, and Washington.

Figure 2. The number of days of heavy smoke experienced annually have increased in most places; increases in the western and northern states were the largest.

Mean number of days of heavy smoke for residents of each state from 2011 to 2021



Source: Hazard Mapping System Smoke Product from National Oceanic and Atmospheric Administration (NOAA).

Most counties in the United States experienced statistically significant⁷ decreases in smoke-free days and statistically significant increases in days of all smoke densities. When comparing the first and last five years of the study period, 1,517 counties—representing 78.6% of the U.S. population—experienced significant decreases in the number of smoke-free days. Similarly, 72.3%, 75.2%, and 87.3% of the population of the United States experienced increases in the number of days of light, medium, and heavy smoke, respectively.

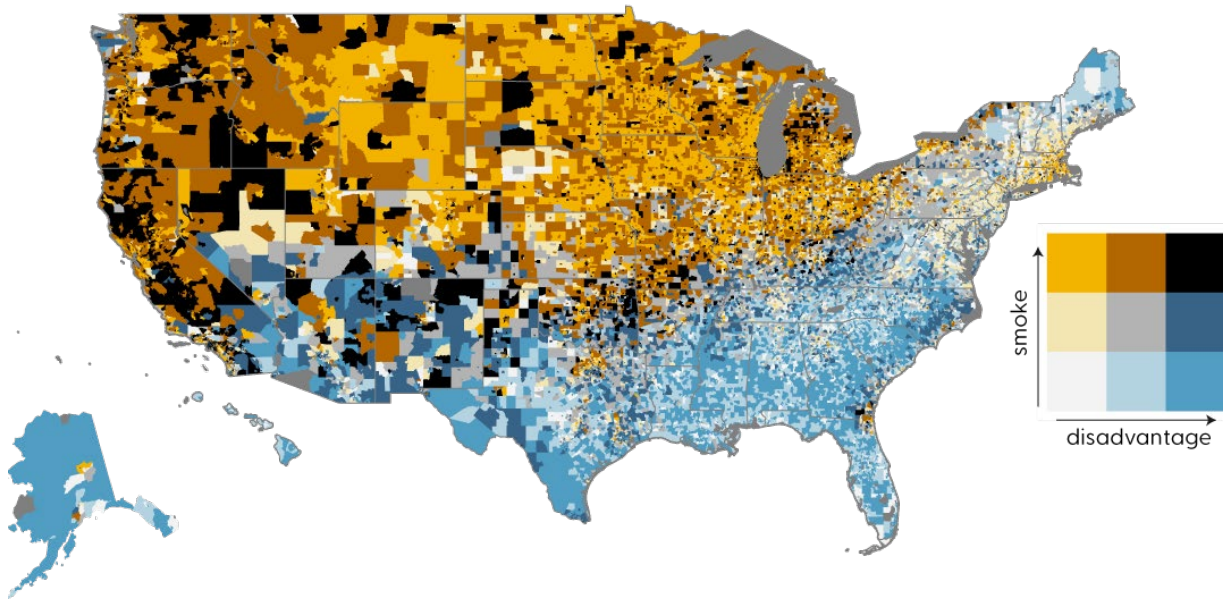
⁷ The mean number of days for each county is calculated using census tracts in the county; 95% confidence intervals around each mean are used to perform tests of significance.

Communities of Concern for Wildfire Smoke

Communities with fewer opportunities for healthy lives and fewer economic resources are experiencing dramatic increases in wildfire smoke. Census tracts in the highest SVI tertile, according to the overall SVI score (i.e., tracts at the greatest health disadvantage for living healthy lives), experienced an increase in the average annual number of heavy smoke days when comparing the first five years to the last five years, from 0.92 (95% CI: 0.91–0.93) to 4.21 (95% CI: 4.18–4.25), a 358% increase. Similar increases in heavy smoke were observed when exploring those with the greatest disadvantage in the SVI's four component themes: (1) socioeconomic status: 346%, (2) race/ethnicity/language: 449%, (3) household composition and disability: 309%, and (4) housing and transportation: 357%. Exposures to heavy smoke were observed for all tertiles of the SVI; however, the impacts of these common exposures are expected to be greatest among those communities with fewer resources, which is why results focus on the highest tertile.

Figure 3. The largest need for assistance and mitigation occurs where heavy smoke exposures and social vulnerabilities coincide—in the West and Upper Midwest.

Need-based map using heavy smoke exposure and Social Vulnerability Index (SVI)



Source: Hazard Mapping System Smoke Product from National Oceanic and Atmospheric Administration (NOAA); Social Vulnerability Index (SVI) Estimates from Centers for Disease Control and Prevention (CDC)

The coincidence of heavy smoke person-days with the highest overall SVI percentile is located primarily in the American West and Upper Midwest along the Canadian border. California, Oregon, and Washington account for 39% of the heavy smoke person-days in the highest SVI tertile; California accounts for almost a third (33%) alone.



Wildfire smoke, its impacts, and the magnitude of its effect vary by location and population. Results show that person-days of smoke were unequal for specific SVI indicators. Indicators included in the SVI's race/ethnicity/language theme—minority populations and individuals with limited English proficiency—exhibited some of the largest increases. Notable increases were also seen for household and transportation indicators, such as crowded households and multifamily housing. Tracts with the highest number of persons in these indicators and themes tend to be more concentrated in the West (Figure 3), relative to the rest of the United States, and thus overlap with the largest smoke exposure increases in the study (Vargo et al. 2022).

Wildfire Smoke Impacts on the Labor Force

Each industry's share of the state labor force, the percentage of workers considered frontline, and how frontline workers' exposure to smoke changed from 2011–2015 to 2017–2021 are presented (Table 1) to describe smoke exposures in the labor force.


More than 34 million Americans are frontline workers, representing 23% of the nation's workforce. Frontline workers comprise a substantial percentage of specific labor industries, including agriculture, fishing, mining, construction, manufacturing, warehousing, and transportation. Nationally, 62% of these industries are frontline workers—working in occupations where they are exposed to outdoor air-quality hazards—while only 10% of other industries are (Table 1).

The total number of heavy smoke frontline worker-days from 2011 to 2021 was 990,319,321. Frontline workers' exposure to wildfire smoke increased in nearly all states from 2011–2015 to 2017–2021. The change in frontline workers' heavy smoke days by state is shown in Figure 4. Although California unsurprisingly experiences the largest increase in heavy smoke days (33,522,008 person-days in 2017–2021), Upper Midwest states that are not typically associated with wildfires, such as Illinois (10,083,191 person-days in 2017–2021) and Michigan (7,385,187 person-days in 2017–2021), experienced some of the largest absolute increases in frontline worker smoke days.

In certain states, employees are disproportionately working outdoors or without sufficient indoor air filtration. As such, with increasing wildfires, workers in these conditions are more frequently exposed to wildfire smoke, and these industries are more frequently interrupted. This is of particular concern in California, which saw some of the largest increases in smoke and has more than two million frontline workers who play an essential role in the economy (Table 1). For example, California is home to the Port of Los Angeles, one of the busiest seaports for international trade, and the Central Valley, which produces 8% of the national agricultural output by value, both of which are part of industries that predominantly employ frontline workers. Many frontline workers in California are not aware of the health hazards of wildfire smoke or the protective measures that can be taken (Riden et al. 2020).

Table 1. The total labor force, frontline workers, industry-specific workers, and frontline workers for each state are shown below.

	All workers	Frontline workers	% GDP in frontline-majority industries	% Increase in frontline worker-days heavy smoke
United States	154,842,185	34,213,775	16.8	336
Alabama	2,097,384	567,873	22	243
Alaska	347,774	84,622	29	277
Arizona	3,130,658	627,959	15.5	1121
Arkansas	1,303,490	363,291	22.8	102
California	18,591,241	3,912,179	17	2132
Colorado	2,904,589	554,940	13.4	534
Connecticut	1,815,636	316,882	15.3	266
Delaware	455,620	92,340	10.6	130
District of Columbia	376,871	25,382	1.6	125
Florida	9,495,353	1,885,667	10.1	-16
Georgia	4,834,622	1,152,807	15	199
Hawaii	680,258	128,731	7.7	0
Idaho	792,237	200,808	19.6	301
Illinois	6,250,862	1,389,558	18.2	232
Indiana	3,202,509	912,684	31.4	571
Iowa	1,613,902	432,703	26.5	230
Kansas	1,440,453	347,352	23.3	269
Kentucky	1,978,477	546,020	25.7	806
Louisiana	2,033,758	502,014	23.7	80
Maine	670,417	150,812	14.4	1021
Maryland	3,073,886	513,234	9.9	164
Massachusetts	3,612,375	579,690	12.2	276
Michigan	4,654,930	1,155,157	22.9	197
Minnesota	2,958,615	643,996	18.5	156
Mississippi	1,235,224	353,552	23.4	189
Missouri	2,916,000	687,662	17.5	271
Montana	512,329	117,394	17.1	259
Nebraska	999,212	243,424	24.7	254
Nevada	1,406,568	296,853	12.4	745
New Hampshire	729,701	152,236	13.9	393
New Jersey	4,422,491	823,212	13.7	227
New Mexico	888,646	184,770	15.4	143
New York	9,498,320	1,628,158	7.3	281
North Carolina	4,764,135	1,137,887	20.4	162
North Dakota	402,322	102,235	30.1	265
Ohio	5,595,444	1,367,433	21	581

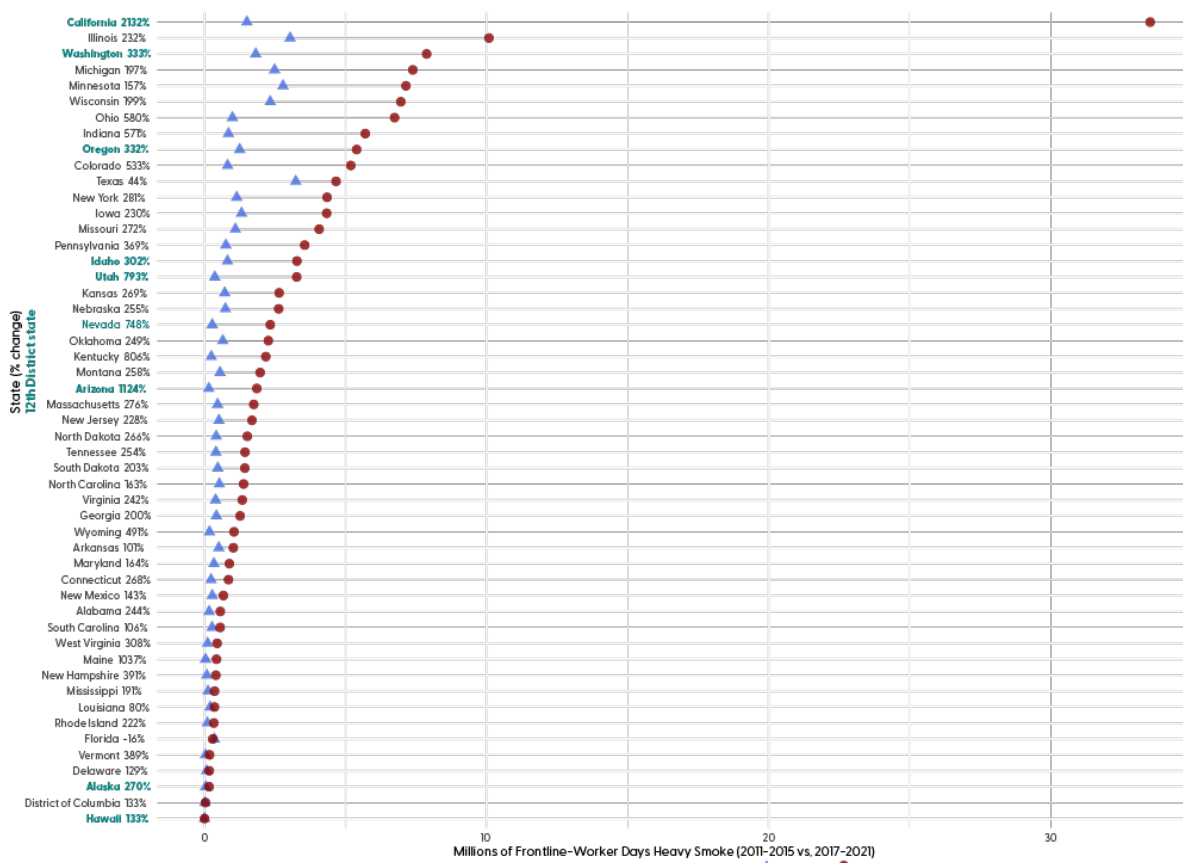


	All workers	Frontline workers	% GDP in frontline-majority industries	% Increase in frontline worker-days heavy smoke
United States	154,842,185	34,213,775	16.8	336
Oklahoma	1,772,123	453,140	24.9	249
Oregon	1,979,043	427,407	19.5	332
Pennsylvania	6,199,456	1,400,992	18.4	369
Rhode Island	533,878	103,147	11.1	224
South Carolina	2,275,531	571,737	19.6	107
South Dakota	443,891	109,379	18.7	203
Tennessee	3,109,872	795,940	20.4	254
Texas	13,253,631	3,159,925	21.3	44
Utah	1,497,354	329,886	17	793
Vermont	329,028	68,847	14.6	400
Virginia	4,156,018	783,271	12.3	242
Washington	3,594,279	778,734	14	334
West Virginia	740,910	184,617	25	307
Wisconsin	2,982,359	782,642	23.5	199
Wyoming	288,503	82,594	32.2	489

Source: American Community Survey (ACS) 2019, Industry by Occupation for the Civilian Employed Population 16 Years and Over; Bureau of Economic Analysis (SAGDP2N); Hazard Mapping System Smoke Product from National Oceanic and Atmospheric Administration (NOAA)

Figure 4. The largest percentage increases in frontline worker heavy smoke days occurred in California (2132%) and Arizona (1124%).

Average annual frontline worker person-days of heavy smoke by state from 2011–2015 to 2017–2021



Source: American Community Survey (ACS) 2019, Industry by Occupation for the Civilian Employed Population 16 Years and Over; Hazard Mapping System Smoke Product from National Oceanic and Atmospheric Administration (NOAA).

These results reiterate that the economic impacts of wildfires extend far beyond their geographic range, making work less stable and predictable for many industries. As the COVID-19 pandemic showed, economic changes in one sector have cascading effects on other sectors as a result of the interconnectivity of the American and global economy. Industries and workers will likely have to adjust to changing wildfire conditions, which may mean shifting seasons, relocating, or changing jobs altogether. These adaptations may be costly for businesses, consumers, and workers, as well as governments. Adaptation will be more difficult for workers who are vulnerable in other aspects of their lives, such as health and housing. Smoke from wildfires is estimated to reduce labor market earnings by \$93 billion per year (Borgschulte, Molitor, and Zou 2022). When industries must invest in defensive measures to mitigate their exposure to wildfire smoke and forgo other economic activities, these costs also impact society. The importance of regional industries most affected by wildfire smoke, such as warehousing and agriculture, to the national economy emphasizes how the impacts of wildfires on

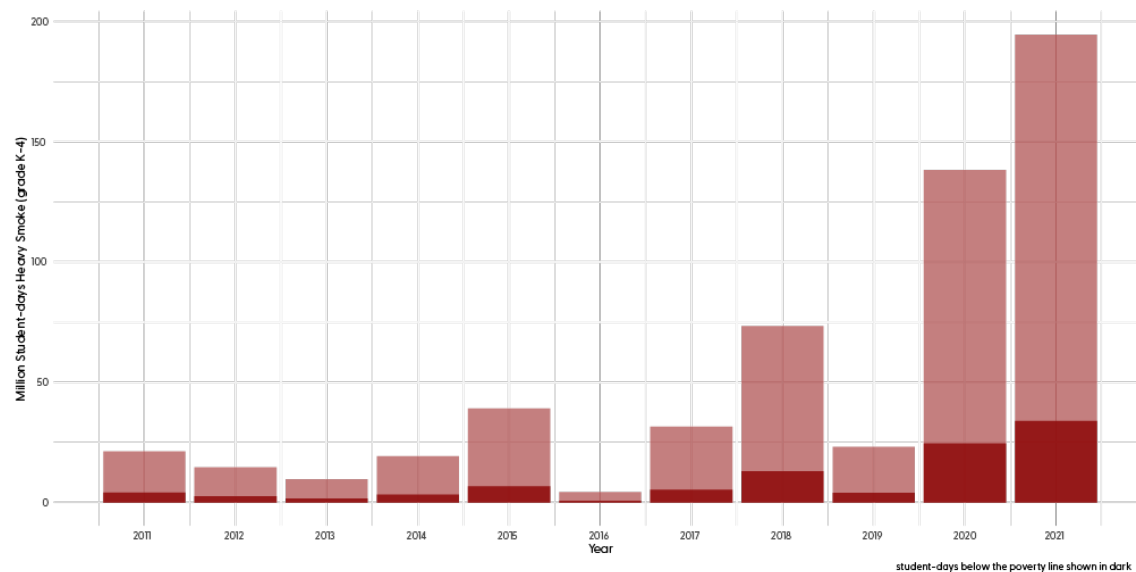
these industries may ripple beyond their localities. Policies that include guidance on smoke exposure assessment, respiratory protection measures, and communication training requirements and prioritize the protection of frontline workers, and the industries most dependent on their occupations, may improve economic resilience to wildfire smoke.

Wildfire Smoke Impacts on Children and Schools

Nationally, there were 569 million heavy smoke student-days (grades K–4), with 100 million among students below the poverty line (Figure 5). Between 2011–2015 and 2017–2021, heavy smoke days increased 300%. The largest absolute number of student person-days of heavy smoke occurred in California, Illinois, and Michigan (Figure 6). Given the increases in disruptive smoke exposures among young students, programs to improve indoor air quality at schools, particularly in low-income communities, may be important for making economies more resilient to climate risks.

Figure 5. Heavy smoke exposures among vulnerable students have increased dramatically in recent years. Younger students (grades K–4), particularly those in poverty, are most affected academically by school closures.

Student-days of heavy smoke for students above the poverty line (light) and below the poverty line (dark) from 2011 to 2021⁸

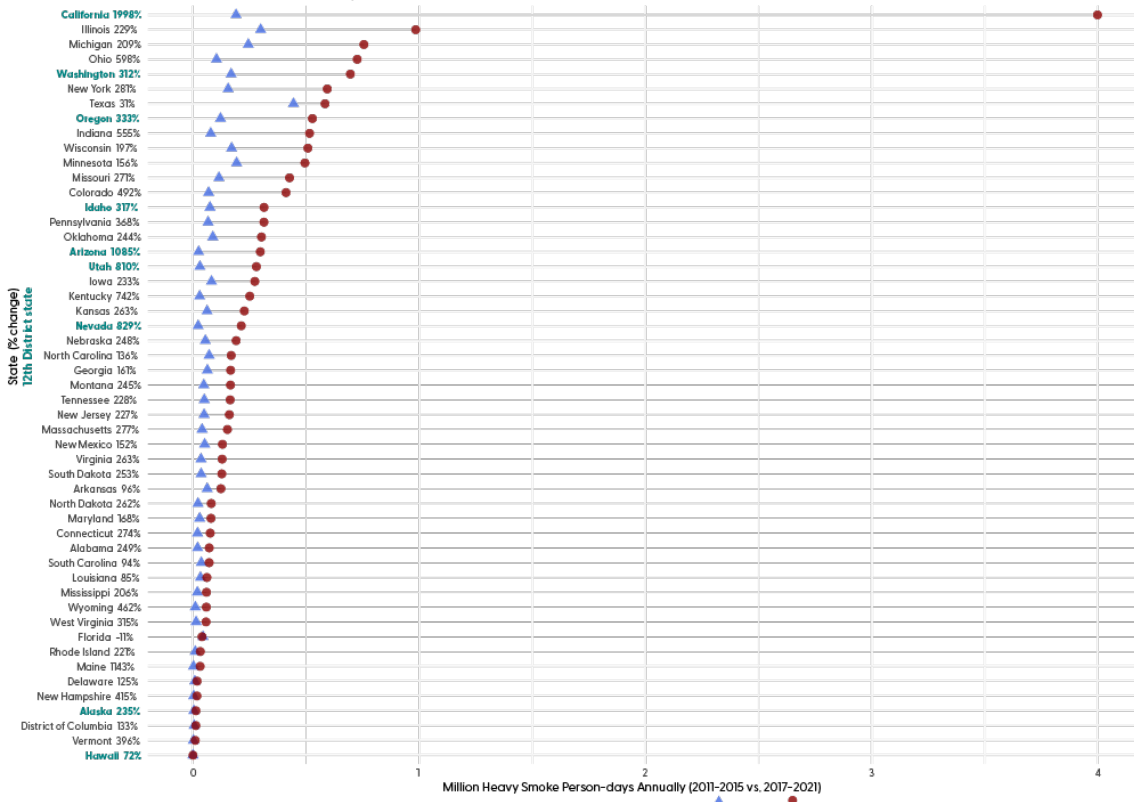


Source: American Community Survey (ACS) Five-Year Estimates 2019; Poverty Status in the Past 12 Months by School Enrollment by Level of School for the Population Three Years and Over (B14006); Hazard Mapping System Smoke Product from National Oceanic and Atmospheric Administration (NOAA).

⁸ Reflects only changes in smoke over the study period and not changes to the number of students or students in poverty.

Figure 6. Heavy smoke exposure among students has increased dramatically in recent years across the United States.

Annual average student-days of heavy smoke by state from 2011–2015 to 2017–2021



Source: American Community Survey (ACS) Five-Year Estimates 2019; Poverty Status in the Past 12 Months by School Enrollment by Level of School for the Population Three Years and Over (B14006); Vargo 2020.

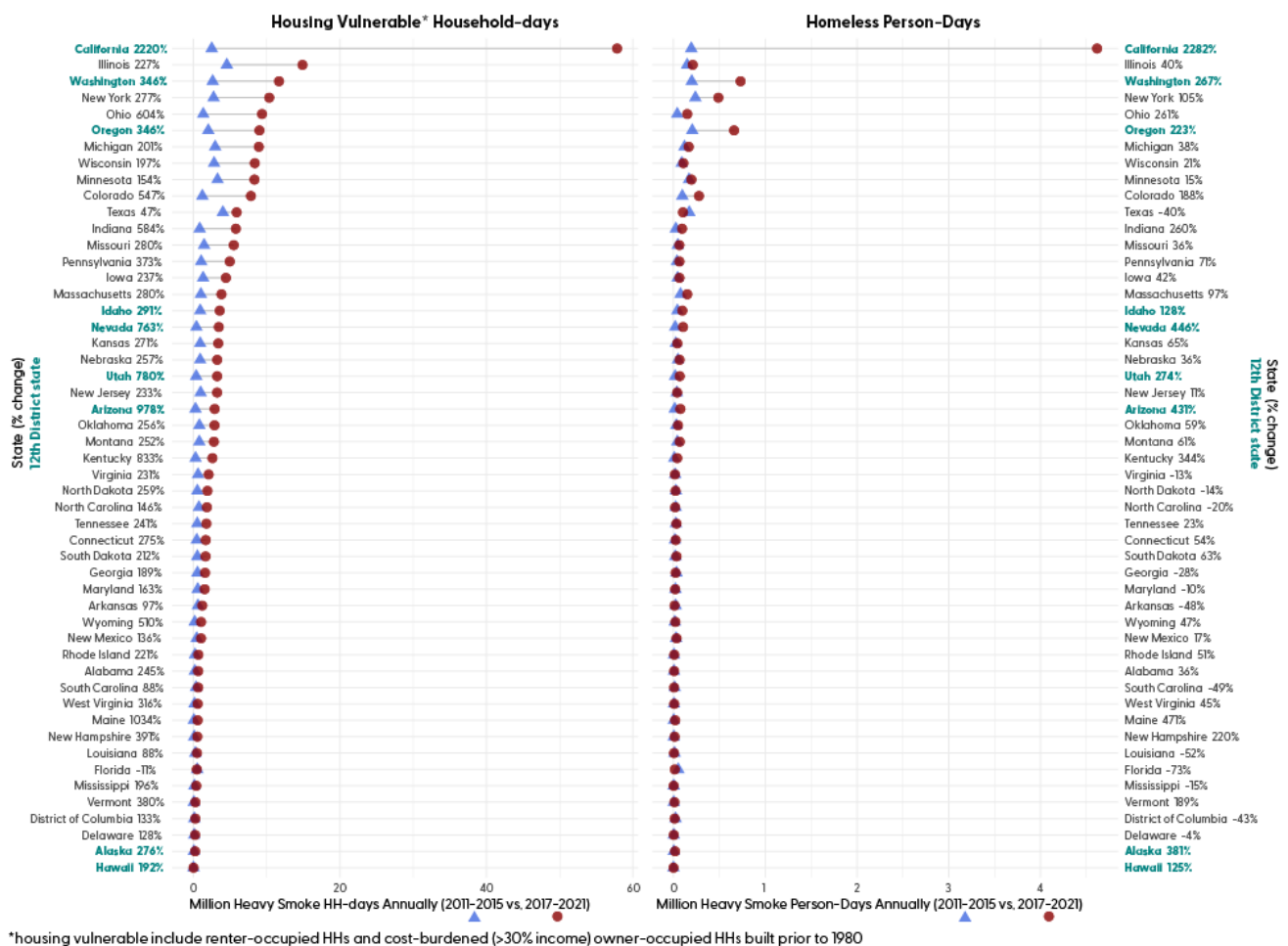
Housing Vulnerability and Resilience

Housing-vulnerable household-days of heavy smoke were largest in California, Illinois, Washington, and New York. Wildfires and wildfire smoke present difficult recovery trajectories for housing-vulnerable communities because of the enormous destruction of housing supply, which increases housing costs and exacerbates the nation's housing affordability crisis, especially in the high-demand regions of the West (Kearns 2022; Ibarra and Ruth 2009). Nearly 72 million properties face some risk of wildfires over the next 30 years, representing an immense challenge to future housing security (First Street Foundation 2022). Many older homes were built with features—such as single-pane windows or wood roofing or siding—that make them more vulnerable to igniting during wildfires and lack features—such as air conditioning and filtration—needed to adapt to increased risks and mitigate the effects of wildfire smoke. Housing-vulnerable communities have fewer resources to manage the increased costs of homeownership or to build and rebuild in high wildfire risk areas, such as the


wildland urban interface (Davies et al. 2018). Repeated shocks and stresses of wildfires can push housing-vulnerable individuals into a permanent state of poverty (Ibarraran and Ruth 2009) and perpetuate a cycle of disparities. Additionally, those who live in rental housing largely depend on landlords to modify their homes for wildfires. Given the significant increases in renter-occupied heavy smoke household-days (Figure 7), programs to incentivize landlords to retrofit homes for energy efficiency and indoor air quality may boost the resilience of the broader economy.

Figure 7. Increases in heavy smoke exposures were observed for housing-vulnerable people (left, including renters and cost-burdened owners in older homes) and for those experiencing homelessness (right) and were largest in western states frequently exposed to wildfires.

Average annual housing-vulnerable household-days (left) and homeless person-days (right) of heavy smoke by state from 2011–2015 to 2017–2021



Source: Comprehensive Housing Affordability Strategy Survey; Annual Homeless Assessment Report to Congress; Hazard Mapping System Smoke Product from National Oceanic and Atmospheric Administration (NOAA).



Person-days for those experiencing homelessness are concentrated in the smoke-dense areas of the West, including California, Washington, and Oregon. The states in which wildfire smoke exposure is the highest are the same states in which the population of persons experiencing homelessness is growing the fastest (Henry et al. 2021). Many states in the Fed’s 12th District saw increases in homeless person-days from 2011–2015 to 2017–2021 of over 200%: California, Washington, Oregon, Nevada, Utah, Arizona, and Alaska (Figure 7).

Existing homes and communities will need to adapt to ensure they are adequately protected from growing wildfire hazards. However, even if individual homeowners take steps to protect their properties from wildfires, they still will face risks if community-level mitigations—such as open spaces that serve as fuel breaks and help safeguard fire-prone communities—are not adequate to protect against growing wildfires. Community-level mitigation measures are essential to counter growing wildfire risk.

The Value of Avoiding Wildfire Smoke

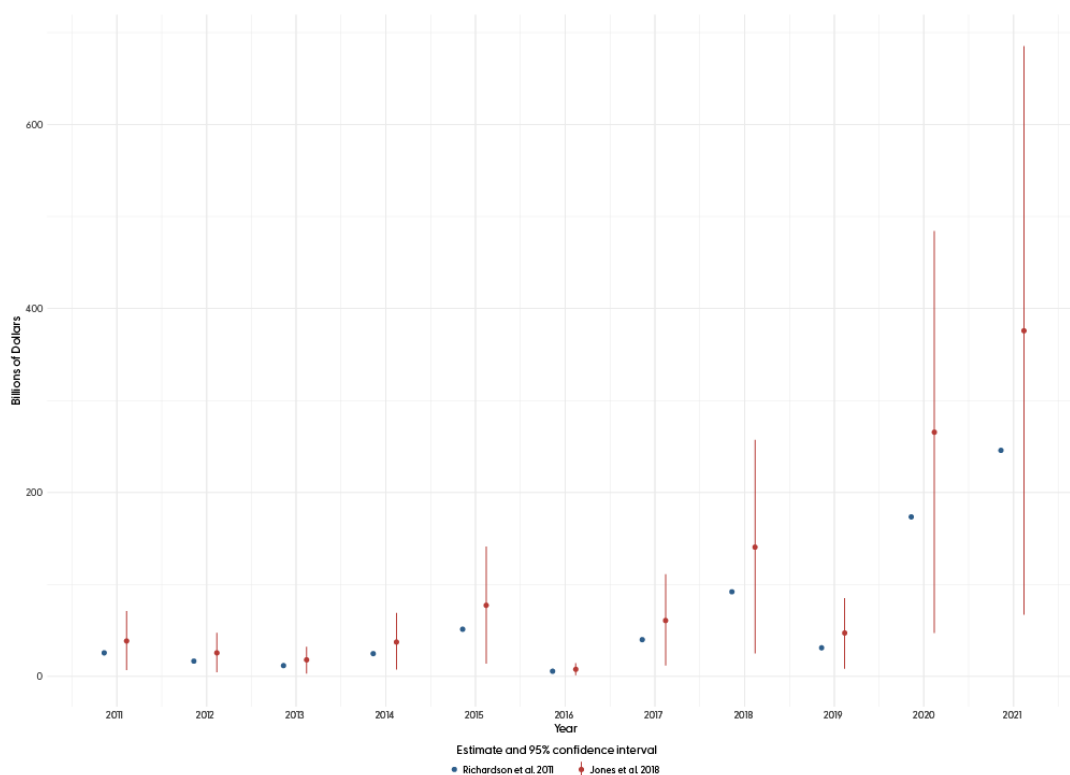
There is a growing realization among Americans that the health effects of wildfire smoke are costly and should be avoided (Bowman and Johnston 2014). One way in which Americans’ interest in avoiding the health effects of wildfire smoke has been quantified is through applying the life satisfaction approach to willingness to pay (WTP) to avoid the health effects of wildfire smoke (Jones 2018; Richardson, Champ, and Loomis 2012). Jones (2018) estimated that U.S. adults have a WTP of \$129⁹ to avoid one day of wildfire smoke health effects. Applying this estimate to the person-days of heavy smoke results in a valuation of \$376 billion in 2021 alone (Figure 8). Other WTP estimates show similar results. Given that this estimate includes only WTP to avoid smoke health effects and no other effects of smoke, such as recreational or labor costs, and does not consider light or medium smoke,¹⁰ it is likely conservative. Nonetheless, it demonstrates the significant and increasing costs that wildfire smoke imposes on society.

⁹ Jones (2018) estimated willingness-to-pay (WTP) estimates of \$129 a day, with a 95% confidence interval of \$23 to \$235. Applying this confidence interval to our estimate, we find Americans’ WTP is \$376 billion, with a 95% confidence interval of \$67 billion to \$685 billion in 2021 (Figure 8).

¹⁰ Smoke in the “heavy” category is expected to cause more severe and common adverse health impacts and societal disruptions.

Figure 8. As heavy smoke becomes more frequent and widespread, so does the value of avoiding wildfire smoke.

Estimates of Americans’ willingness to pay to avoid health effects of heavy smoke from 2011 to 2021. The lines represent the 95% confidence interval of the estimate (where available).



Source: Richardson, Champ, and Loomis 2011, Jones et al. 2018; Hazard Mapping System Smoke Product from National Oceanic and Atmospheric Administration (NOAA).

Community Reinvestment Act

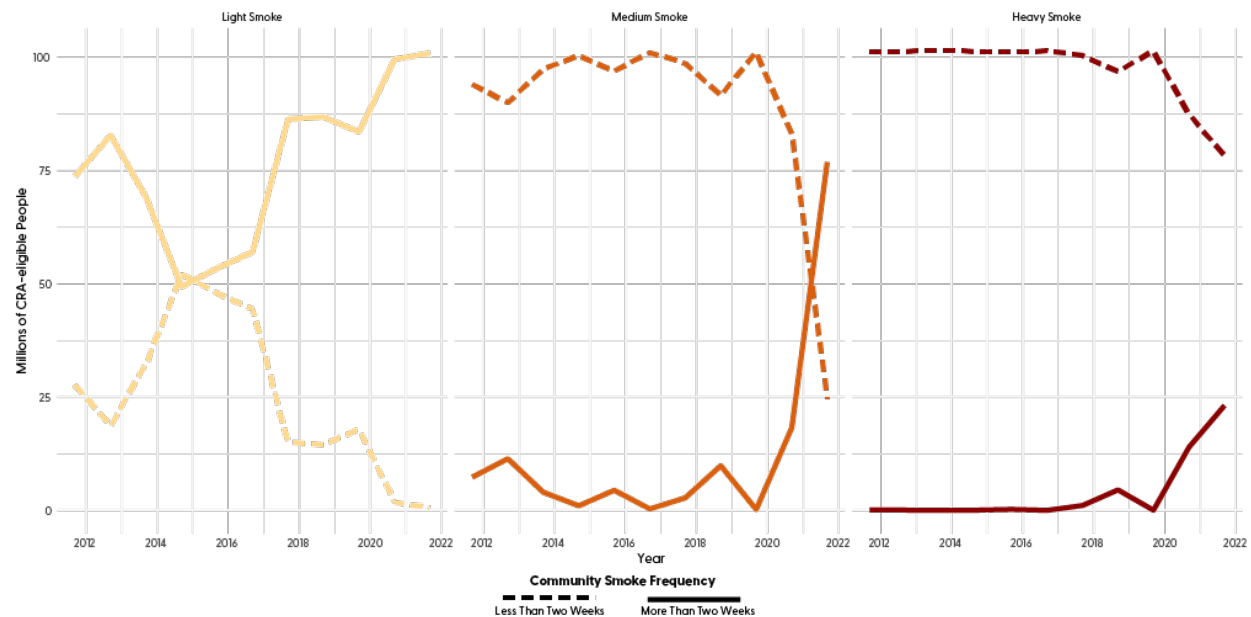
In 2021, a majority of the population living in CRA-eligible tracts experienced more than two weeks of light and medium smoke. Given the dramatic increases in disruptive smoke among many susceptible portions of the economy, existing programs that target low- and moderate-income communities and communities of color may have outsized importance in building broad economic resilience to climate risks. According to Mattiuzzi and McElvain (2022):

Existing CRA guidance includes activities that benefit both LMI [low- and moderate-income] areas in general and specific disaster recovery efforts (Keenan and Mattiuzzi 2019). Proposed rule changes to the CRA would additionally define “disaster preparedness and climate resiliency activities as activities that assist individuals and communities to prepare for, adapt to, and withstand natural disasters, weather-related disasters, or climate-related risks,” including “activities that help low- or moderate-

income individuals and communities proactively prepare for or mitigate the effect of disasters and climate-related risks—for example, earthquakes, severe storms, droughts, flooding, and forest fires (Regulatory Agencies 2022, p. 82).” Examples of proactive disaster preparation include, but are not limited to, “retrofitting affordable housing to withstand future disasters” (Regulatory Agencies 2022, p. 83).

Figure 9. Trends in smoke frequency among low- and moderate-income communities show that they increasingly experienced more frequent smoke. In recent years, nearly all CRA-eligible communities annually experienced more than two weeks of light smoke, and a majority of CRA-eligible communities annually experienced more than two weeks of medium smoke.

Millions of CRA-eligible people in communities experiencing fewer and greater than two weeks of smoke each year



Source: Hazard Mapping System Smoke Product from National Oceanic and Atmospheric Administration (NOAA); CRA-Eligible Census Tracts; Vargo 2020.

Such future financing opportunities may be facilitated and expedited by local and regional plans that specifically recognize the unique climate risks LMI communities and communities of color face. If adopted, the proposed CRA rulemaking would require “these activities to be conducted in conjunction with a government plan, program, or initiative that is focused on disaster preparedness or climate resiliency that includes an explicit focus on benefiting a geographic area that includes the targeted census tracts” (Mattiuzzi and McElvain 2022; Regulatory Agencies 2022, p. 80). Community-level mitigation measures are essential to counter growing wildfire risk, particularly in LMI communities and communities of color.



Conclusion

This report illustrates that although wildfire smoke has generally increased across the United States, it has not done so equally for all states or regions. Certain groups of people and communities are more vulnerable to experiencing the negative impacts of wildfires, based on where they live, work, and go to school, as well as the level of their economic resources and adaptive capacity to cope with hazardous and disruptive environmental conditions, such as heavy wildfire smoke. Many communities face a multitude of threat multipliers for wildfire smoke exposure that have been outlined in this report.

Several populations of concern have experienced large increases in their exposures to dangerous and disruptive wildfire smoke. These populations of concern are more likely to experience disruptions from smoke for reasons that include legacies of racial discrimination and economic exclusion. Thus, prioritizing these groups in policy and for climate resilience activities may more effectively help prepare local economies for the economically destabilizing effects of climate risks, such as wildfire smoke. Importantly, as this report has shown, smoke exposures are increasing far from fire burn sites and are likely to require planning and response from localities not typically accustomed to considering these issues.

Summary of Results

- The five-year annual average of person-days of heavy smoke increased 350% between 2011–2015 and 2017–2021. The increases for person-days of light and medium smoke were 39% and 71%, respectively.
- Over 78% (1,517) of U.S. counties experienced significant decreases in the number of smoke-free days. Similarly, 72%, 75%, and 87% of U.S. counties saw increases in the number of days of light, medium, and heavy smoke, respectively.
- In 2021, Americans valued avoiding the most dangerous wildfire smoke at roughly \$376 billion.
- Locations with the greatest health disadvantages (greatest barriers to living healthy lives) experienced a 358% increase in the average annual number of heavy smoke days. Similar increases in heavy smoke were observed when exploring those with the greatest disadvantage specific to socioeconomic status (346%), race/ethnicity/language (449%), household composition and disability (309%), and housing and transportation (357%).
- Frontline worker–days of heavy smoke increased for 49 states. The largest absolute frontline worker–days of heavy smoke were seen in California (33,522,008), Illinois (10,083,191), and Washington (787,526). The largest percentage increase in heavy smoke days for frontline workers occurred in California (2132%) and Arizona (1124%).
- Nationally, there were 569 million heavy smoke student–days (grades K–4), with 100 million (18%) among students in poverty. Heavy smoke days for students increased 300% from 2011–2015 to 2017–2021.



- Many states in the Fed's 12th District saw increases of over 200% in homeless person–days of heavy smoke from 2011–2015 to 2017–2021: California, Washington, Oregon, Nevada, Utah, Arizona, and Alaska (Figure 7).
- California, Illinois, Washington, and New York experienced the largest number of housing-vulnerable person–days of heavy smoke.
- A majority of CRA-eligible communities annually experienced more than two weeks of medium smoke in recent years.



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