Social Vulnerability in US Communities Affected by Wildfire Smoke, 2011 to 2021

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See also Eisenman, p. 724.

Objectives. To describe demographic and social characteristics of US communities exposed to wildfire smoke.

Methods. Using satellite-collected data on wildfire smoke with the locations of population centers in the coterminous United States, we identified communities potentially exposed to light-, medium-, and heavy-density smoke plumes for each day from 2011 to 2021. We linked days of exposure to smoke in each category of smoke plume density with 2010 US Census data and community characteristics from the Centers for Disease Control and Prevention's Social Vulnerability Index to describe the co-occurrence of smoke exposure and social disadvantage.

Results. During the 2011-to-2021 study period, increases in the number of days of heavy smoke were observed in communities representing 87.3% of the US population, with notably large increases in communities characterized by racial or ethnic minority status, limited English proficiency, lower educational attainment, and crowded housing conditions.

Conclusions. From 2011 to 2021, wildfire smoke exposures in the United States increased. As smoke exposure becomes more frequent and intense, interventions that address communities with social disadvantages might maximize their public health impact. (*Am J Public Health*. 2023;113(7):759–767. https://doi.org/10.2105/AJPH.2023.307286)

In recent years, wildfires have, on average, burned more than double the acreage per year compared with earlier decades. In the 1990s, 3.3 million acres were burned per year, while in 2021, 7.1 million acres were burned.[1] Smoke from wildfires compromises air quality by increasing concentrations of particulate matter (PM), ozone, polycyclic aromatic hydrocarbons, volatile organic compounds, and other harmful air pollutants[2–4] that have well-described impacts on respiratory disease and all-cause mortality.[5,6] Projected wildfire trends in the United States predict increasing risk of exposure to wildfire smoke[7] because of increases in weather- and climate-related factors associated with wildfire risk, including heat, drought, and wind speed.[8]

Smoke, also referred to as wildland or wildfire smoke, can travel thousands of miles, potentially exposing distant populations, including communities less prepared for smoke.[9,10] The movement and coverage of wildfire smoke over large areas may result in similar exposures for neighboring communities; however, wildfire risk can vary spatially by population susceptibility and adaptive capacity, or the ability to absorb, recover, and modify exposure to wildfires.[10–15] As with other ambient climate hazards, such as extreme heat, the social and community characteristics that determine adaptive capacity may play an important role in explaining health disparities related to wildfire smoke.[16,17]

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 and transient ischemic attack, out-of-hospital cardiac arrests, and all-cause mortality.[18–20] Public health

recommendations to reduce exposure to wildfire smoke currently include recommendations to stay indoors in places with adequate air filtration, reduce activity during smoke events, reduce other sources of indoor air pollution, use air filters, and, for those who cannot stay indoors (e.g., agricultural and outdoor workers),[21] wear suitable respiratory protection when outdoors.[22]

Making these types of changes can be especially difficult for people with limited resources.[11,15,23,24] For example, people without high-quality indoor air filtration at home, those without access to clean air spaces, and people experiencing homelessness might be particularly challenged to make these changes to reduce their personal exposure to wildfire smoke. Recent work shows that wealthier households are more aware of wildfire smoke, allowing them to take protective actions such as closing windows and doors or wearing respirators, seeking out protective devices such as air filters, adjusting their lifestyles to avoid exposures, or more easily temporarily evacuating.[25] Many of the self-protective actions are costly and, therefore, unlikely to benefit some populations.

Demographic, economic, institutional, and sociocultural characteristics such as socioeconomic status, household composition, racial or ethnic minority status, language, and housing type may affect an individual's ability to prepare for, respond to, and recover from wildfire smoke. If these characteristics are associated with an unequal risk of exposure, then these individuals face greater risk of respiratory, cardiovascular, and other adverse health outcomes. We conducted this study to describe wildfire smoke exposure from January 2011 to December 2021 across the United States and to assess the extent to which wildfire smoke exposures overlap with social and community characteristics that might affect adaptive capacity and, as a result, health.

METHODS

We conducted descriptive analyses of 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 from 2011 to 2021. We combined data on census tract–level wildfire smoke exposures with information about social and community factors, including demographic and socioeconomic components, to characterize wildfire smoke exposures and particularly vulnerable populations.

Wildfire Smoke Exposures

To estimate community-level exposure to wildfire smoke, we combined data from the National Oceanic and Atmospheric Administration Hazard Mapping System (HMS) smoke product[26,27] with population data from the 2010 US Census and American Community Survey.[28] 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.[29] Satellite imagery that detects smoke plumes can reliably identify periods of wildland fire influence on ground-level measurements of air quality from validated monitors.[30–32] Plume densities reported in HMS data correlate with $PM_{2.5}$ (particulate matter of ≤ 2.5 microns in diameter) concentrations, with concentrations less than 10 micrograms per cubic meter ($\mu g/m^3$) categorized as light, 10 to 21 $\mu g/m^3$ as medium, and greater than 21 $\mu g/m^3$ as heavy.[27,33]

We assigned daily smoke density categories to each block group center of population and its 2010 population using methods adapted from Vargo.[34] In that work, a block group could be simultaneously assigned plumes of progressively less dense smoke; here, we limited the exposure assignment of each block group on each study day to the densest smoke plume of that day. The resulting quantity, person-days, was the product of the number of people in a census block group and the number of days that block group experiences smoke. We then aggregated person-days by smoke density to the geography and time period of interest for analyses. If any block group in a tract experienced smoke on a given day, we counted that day as a smoke day for the tract. We used census tract person-days in analyses with the other community characteristics.

Social Vulnerability Index

We used the Centers for Disease Control and Prevention's (CDC's) Social Vulnerability Index (SVI) to investigate characteristics that might affect the health risks of wildfire smoke exposures.[35] We conducted all analyses using the 2018 version of the SVI data at the census tract scale. The SVI is a composite index comprising census-derived data on sociodemographic, economic, and cultural characteristics.[35] Flanagan et al.[36] details the methods and data inclusion for the creation of the SVI and SVI components.

Daily person-days of wildfire smoke at the block group level were aggregated to annual census tracts and linked with 2018 SVI percentile rankings of 4 themes: (1) socioeconomic status,

(2) race/ethnicity and language, (3) household composition and disability, and (4) housing and transportation. We estimated person-days and number of smoke-days for each smoke density within tertiles of the distribution of the overall SVI and the 4 component themes. For the housing and transportation theme, which is a household-level index, the resulting quantity was household-days rather than person-days. Hereafter, we refer to the tertiles with the lowest SVI scores as the tertiles with the greatest health and social "advantage" and the tertiles with the highest SVI scores as having the greatest health and social "disadvantage." We assigned tertiles using the census tract file, rather than county-level SVI, to ensure that each of the tertiles represents approximately the same number of people. In addition, we used specific components of the SVI (e.g., the number of persons without a high school diploma) to examine changes in wildfire smoke among specific populations over the study period.

Analytic Methods

We conducted descriptive analyses to describe characteristics of communities in the United States potentially affected by wildfire smoke. For most of these analyses, we compared wildfire smoke estimates in the first 5 years (2011–2015) to those of the last 5 years (2017–2021) of the 11-year study period. Using census tract aggregations of the daily smoke data, we calculated annual numbers of days of each smoke level and used the *t* test to assess changes in the mean frequency of wildfire smoke plumes from the first and last 5 years of the study period; we considered *t* tests with *P* values less than .05 to be statistically significant. In each analysis, we used census tract estimates of person-days as the basis for central tendency estimates within the county or SVI tertile. We performed all analyses with R statistical software.[37]

RESULTS

During the 2011-to-2021 study period, exposure to wildfire smoke increased in the coterminous United States (Figure 1). The total person-days of all categories of wildfire smoke in the last 5 years of the study (2017–2021) increased relative to those in the first 5 years (2011–2015). For heavy-density smoke, the 5-year annual average increased 350%, from 307 million person-days during 2011 to 2015 to 1.381 billion person-days during 2017 to 2021. The increases for light- and medium-density smoke person-days were 39% and 71%, respectively. Counts of person-days by state and smoke density are shown in Tables A1 through A3 (available as supplements to the online version of this article at https://ajph.org).

Most counties in the United States experienced decreases in smoke-free days and increases in days of all smoke densities, with the most pronounced changes for heavy smoke (Figure 2). When we compared the first and last 5 years of the study period, 1517 counties experienced significant decreases in the number of smoke-free days (78.6% of the US population). 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. The magnitude of the increase in heavy smoke was largest in the western United States (Figure A, available as a supplement to the online version of this article at https://ajph.org). While western states of Idaho, Oregon, and Washington experienced 339%, 340%, and 297% increases in heavy smoke days per year, respectively, the eastern states of Maryland, South Carolina, and Virginia also experienced substantial increases (166%, 88%, and 233%, respectively).

Census tracts in the highest SVI tertile (i.e., tracts at the greatest overall disadvantage for living healthy lives) experienced a 358% increase in the average annual number of heavy smoke days, from 0.92 (95% confidence interval [CI] = 0.91, 0.93) days in 2011 to 2015 to 4.21 (95% CI = 4.18, 4.25) days in 2017 to 2021. We observed similar increases for the SVI's 4 themes: (1) socioeconomic status: 346%; (2) race/ethnicity and language: 449%; (3) household composition and disability: 309%; and (4) housing and transportation: 357%.

Table B (available as a supplement to the online version of this article at https://ajph.org) shows the average annual number of days in each of the SVI themes and tertiles. The coincidence of heavy smoke person-days with highest overall SVI percentile occurred primarily in the American West and north along the Canadian border (Figure B, available as a supplement to the online version of this article at https://ajph.org). Notably, 3 states—California, Oregon, and Washington—accounted for 39% of the heavy smoke person-days in the highest SVI tertile. The average number of days of all smoke densities in tracts at the highest SVI tertile increased significantly between the start and end of the study period. However, tracts with the highest SVI tertile did not account for a disproportionate amount of all heavy smoke person-days. Rather, each tertile of SVI tracts was evenly distributed.

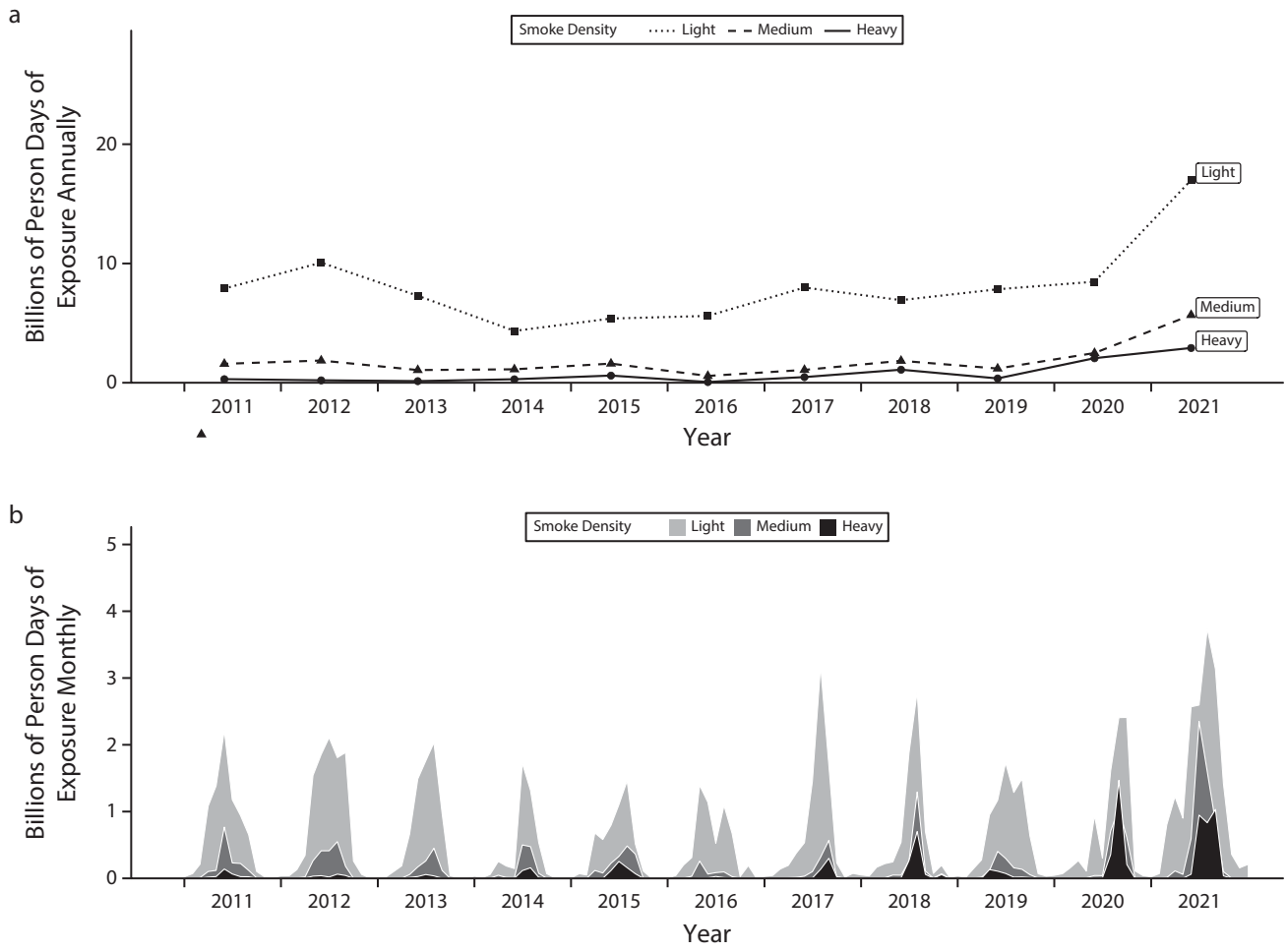

FIGURE 1— Potential Wildfire Smoke Exposure in the United States by Smoke Density and (a) Year and (b) Month: 2011–2021

Person-days of smoke varied across specific SVI components. When we compared the first and last 5 years of the study period, the percentage increases in person- (or household-) days differed by SVI component (Figure 3). Increases were observed among all components, with the largest increases seen for heavy-density plumes. Components of the SVI's race/ethnicity/language theme, including minority populations and individuals with limited English proficiency, exhibited some of the largest increases; for example, the minority component in the race/ethnicity/language theme had the largest increase in number of person-days for any SVI component across all smoke densities (Figure C, available as a supplement to the online version of this article at https://ajph.org). Notable increases were also seen for components such as crowded households and multifamily housing from the housing and transportation theme. Tracts with the highest number of persons in these components and themes tend to be more concentrated in the western United States,[35] relative to the rest of the United States and, thus, overlap with the largest smoke exposure increases in the study (Figure A).

DISCUSSION

Person-days of exposure to light, medium, and heavy wildfire smoke in the United States increased significantly from 2011 to 2021, but the most pronounced change was seen for heavy smoke (Figure 1). Exposures to smoke were not distributed equally, and the increases in smoke were largest in the most disadvantaged communities. This is especially concerning given that wildfire smoke exposure is associated with a number of negative respiratory and cardiovascular health effects.[18–20] Health outcomes such as cardiovascular disease and cerebrovascular emergency department visits have been linked specifically to heavy-density smoke exposure.[20] Our findings suggest that individuals living in communities with limited resources to reduce

FIGURE 2— **Counties With Significant Changes in the Number of Days (a) Without Wildfire Smoke, (b) With Light Wildfire Smoke, (c) With Medium Wildfire Smoke, and (d) With Heavy Wildfire Smoke: United States, 2011–2015 vs 2017–2021**

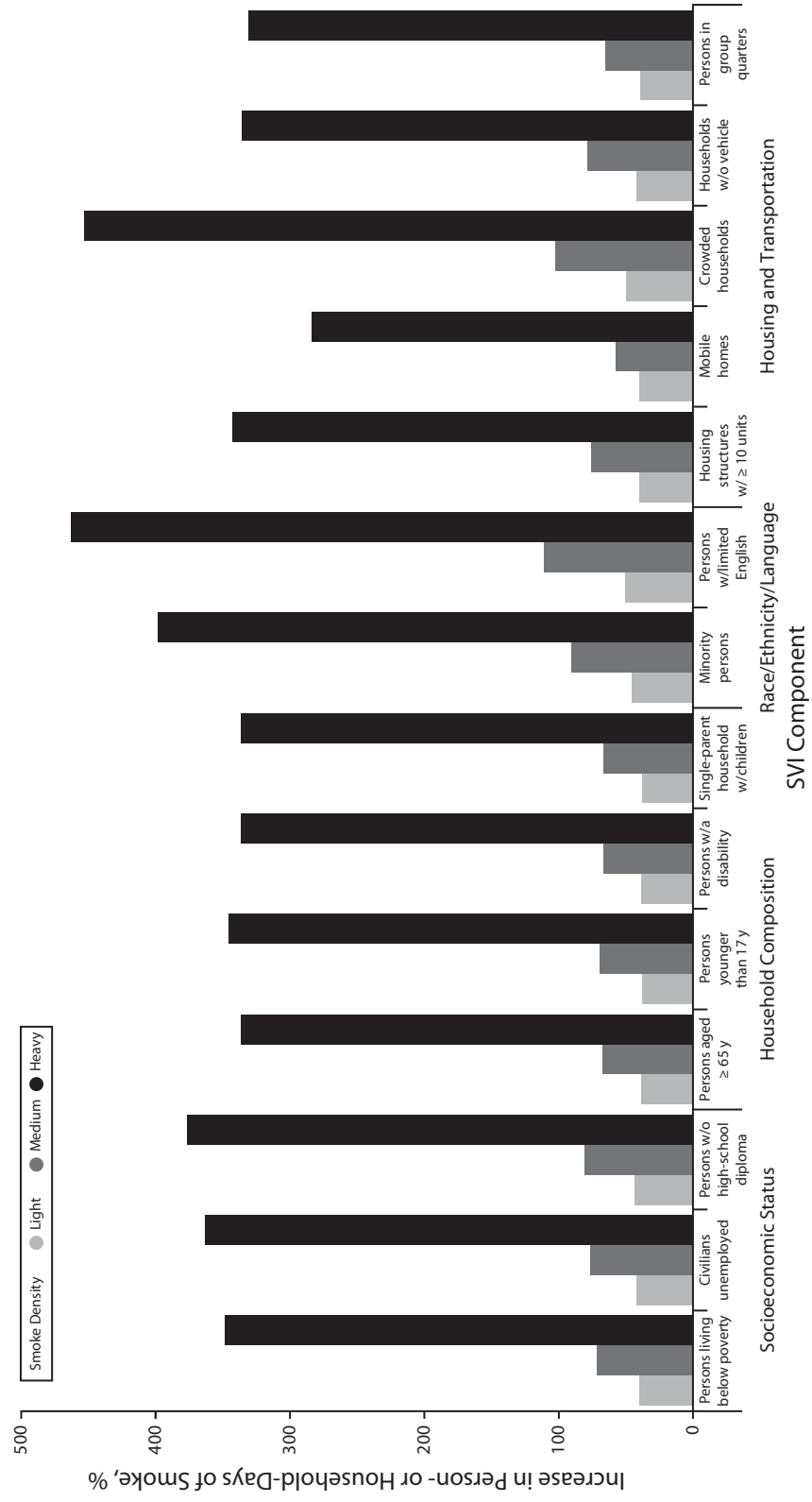

FIGURE 3— Percentage Change in Person- or Household-Days of Wildfire Smoke Exposure by Social Vulnerability Index (SVI) Theme: United States, 2011–2015 to 2017–2021

the health impacts of the smoke exposures have seen the frequency of such exposures increase dramatically across this study's time period.

We estimated an annual average increase of approximately 1 billion person-days of heavy smoke and medium smoke, and more than 2.5 billion person-days for light smoke. These estimates might represent an upper bound for potential wildfire smoke–exposed populations, in part because populations move between census tracts over time. Also, HMS data are derived from satellite plume data rather than ground-level measurements of air quality. A recent analysis of the air quality monitor record covering a much longer study period estimated that wildfires and meteorology led to increased harmful air pollution exposures by 25 million person-days annually over the last 20 years.[7] Nonetheless, the trends observed here are important for public health planning because even more conservative estimates of wildfire smoke exposures than those presented here would produce significant health impacts and costs to individuals and health care systems. A national study estimated that Americans are willing to pay $129 per day to avoid the health impacts of being exposed to heavy smoke, indicating the social and economic costs of wildfires.[38]

Broadly speaking, the characteristics of people or a community (e.g., age, race, health status, income), social inequalities (e.g., social capital, political power, lack of access to information), place-based inequalities (e.g., rural vs urban, elevation), and adaptation inequalities[39] combine to affect a population's susceptibility to disaster events and their resulting impacts. Our findings suggest that increases in smoke are occurring in communities with the highest disadvantage. Individual components of the SVI may be associated with both increased susceptibility to wildfire and decreased adaptive capacity.[40] The SVI does not include every indicator that may be desired to capture susceptibility to wildfire smoke; however, as a composite of several social determinants of health, it may serve as a sufficient proxy in the absence of better, more specific data.

If the adaptive capacity is hindered by factors such as the language in which wildfire warning systems deliver messages, then those with the highest disadvantage in the race/ethnicity and language theme may be the most impacted. Similarly, opportunities to reduce exposures are affected by existing housing not being fitted with proper air filtration or other smoke prevention measures, which may be more common in older multiunit houses, mobile homes, or crowded housing considered under the highest housing and transportation disadvantage. Communities with fewer economic resources as indicated by highest SVI may face more barriers in avoiding outdoor exposures following a wildfire smoke event.[40]

While we assessed social disadvantage and wildfire smoke, vulnerability as captured by the SVI is relevant to a wider range of climate-related disasters including more proximate exposure to wildfire and its effects.[10,41–43] Social vulnerability and adaptive capacity affect the ability to prepare for and recover from the fire, evacuation, or clean up. Wildfires present difficult recovery trajectories for communities with housing and transportation disadvantage because of the enormous destruction of housing supply, which makes it more difficult to find adequate housing, especially in the high-cost regions of the West.[44,45]

More than 71.8 million properties face some risk of wildfires over the next 30 years, representing an immense challenge to future housing security.[46] Communities with low SVI have more resources to build and rebuild at high wildfire-risk areas such as the wildland urban interface,[11] whereas communities with high SVI often have less. Repeated shocks and stresses of wildfires can push individuals living in communities with high SVI into a permanent state of poverty[47] and perpetuate a cycle of disparities. However, this overlap of social vulnerability and growing exposure suggests that interventions that consider housing modifications, such as retrofits and air purification, particularly in communities with high SVI, may more effectively reduce the potential health impacts and social and economic losses associated with wildfire smoke.

While we did find that the highest SVI tertile in the housing and transportation theme had one of the highest increases in smoke exposure days, this theme falls short of including the people especially susceptible to smoke exposure: people experiencing homelessness. People experiencing homelessness face a lack of regular shelter, access to information, and resources to prepare and respond to wildfires, which amplify their wildfire smoke and health risk.[48–50] 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.[51] Spare and less-reliable data on persons experiencing homelessness prevent a detailed accounting of smoke exposures among such persons; however, 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.[52] As areas at the wildland–urban interface

continue to be occupied by people with differing susceptibility, intensifying wildfires are likely to prompt discussions on who will be most affected by wildfires and how to address related injustices and social equity concerns.

In this study, we used the CDC's SVI to provide information about the demographic, economic, institutional, and sociocultural characteristics of census tracts in the coterminous United States. The SVI is based on publicly available data and does not explicitly account for numerous factors affecting exposure to wildfire smoke or the burden of its associated health effects, but has been correlated with increased prevalence of several pre-existing conditions that exacerbate adverse health outcomes associated with smoke exposures.[53,54] Because the SVI values are representative of a community, rather than any one individual in that community, it may misclassify individuals who are represented by an SVI ranking that is not indicative of their personal social advantages.

HMS data cannot differentiate plumes of differing heights in the atmosphere; thus, a plume may be over a census tract with minimal impact on ground-level air quality. Studies examining the correlation between plume presence and monitored air quality have shown significant increases in $PM_{2.5}$, particularly in the presence of medium and heavy smoke plume.[32] The HMS data do not differentiate sources of fire smoke; smoke from prescribed fires are included in smoke estimations. However, fires of the size and intensity typical of prescribed burns are less likely to result in heavy smoke plumes. Our analysis focuses mostly on heavy smoke because it is expected to be the most detrimental for health and is increasing most for most of the population.

Our data show that wildfire smoke exposure coincides with demographic, economic, institutional, and sociocultural characteristics. Our results suggest that there are inequalities in wildfire smoke exposures by SVI and highlight opportunities to identify geographic areas in need of increased emergency preparedness messages, supplies, shelters, and recovery support. These findings can be used by emergency planners and others to better understand and address the contribution of wildfire smoke to poor health. Designing and implementing specific interventions for communities experiencing economic and social disadvantage may improve health in communities and for individuals exposed to wildfire smoke in a changing climate. AJPH

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CONTRIBUTORS

J. Vargo contributed to conceptualizing the study, conducted data management and processing of wildfire smoke information and the Social Vulnerability Index, and contributed to the methods, analysis, interpretation of results, and writing of the article. B. Lappe led the writing and revising of the article and contributed to interpretation of results. M. C. Mirabelli conceptualized the study and contributed to interpretation of results and writing and revision of the article. K. C. Conlon contributed to conceptualizing the study, method selection, interpretation of results, and revision of the article. All authors approved submission of the article to be published.

CONFLICTS OF INTEREST

All authors have no conflicts of interest to declare.

HUMAN PARTICIPANT PROTECTION

No protocol approval was needed for this study because the data used were publicly available, deidentified, and obtained from secondary sources.

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