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Community Vulnerability to Health Impacts of Wildland Fire Smoke Exposure

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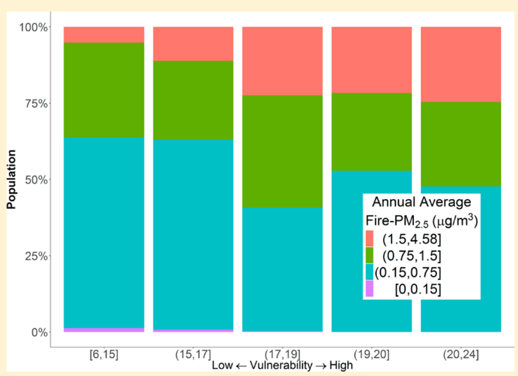
Supporting Information

ABSTRACT: Identifying communities vulnerable to adverse health effects from exposure to wildfire smoke may help prepare responses, increase the resilience to smoke and improve public health outcomes during smoke days. We developed a Community Health-Vulnerability Index (CHVI) based on factors known to increase the risks of health effects from air pollution and wildfire smoke exposures. These factors included county prevalence rates for asthma in children and adults, chronic obstructive pulmonary disease, hypertension, diabetes, obesity, percent of population 65 years of age and older, and indicators of socioeconomic status including poverty, education, income and unemployment. Using air quality simulated for the period between 2008 and 2012 over the continental U.S. we also characterized the population size at risk with respect to the level and duration of exposure to fire-originated fine particulate matter (fire-$PM_{2.5}$) and CHVI. We estimate that 10% of the population (30.5 million) lived in the areas where the contribution of fire-$PM_{2.5}$ to annual average ambient $PM_{2.5}$ was high (>1.5 $\mu g/m^3$) and that 10.3 million individuals experienced unhealthy air quality levels for more than 10 days due to smoke. Using CHVI we identified the most vulnerable counties and determined that these communities experience more smoke exposures in comparison to less vulnerable communities.



INTRODUCTION

Exposure to wildfire smoke is a serious health risk which can disproportionally impact sensitive groups. A number of studies have shown an association between smoke exposure and worsening of respiratory symptoms, increased rates of cardiorespiratory emergency visits, hospitalizations, and even

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death.[1−12] Identifying communities vulnerable to adverse health outcomes during smoke days can provide valuable information for local, state, and federal governments and nongovernmental organizations to prioritize public health actions and improve public health outcomes on fire-smoke days.

Among the pollutants found in smoke, fine particulate matter ($PM_{2.5}$) is of the highest concern to health. In the most recent synthesis and evaluation of scientific literature on the health effects of air pollution, the Integrated Science Assessment (ISA), the U.S. Environmental Protection Agency[13] concluded that the weight of scientific evidence suggests a causal relationship between short- and long-term exposures and cardiovascular effects and mortality, and a likely causal relationship with respiratory effects. ISA is a comprehensive review of the health and ecological effects caused by air pollutants, mandated by the Clean Air Act, and provides the scientific basis for review of the National Ambient Air Quality Standards (NAAQS). Multiple studies demonstrate that the health impacts from $PM_{2.5}$ exposures are disproportionately shared by individuals in the sensitive groups.[14,15] The most sensitive groups include children, the aged, and pregnant women, as well as those with a pre-existing cardiopulmonary disease. Individuals and communities of lower socioeconomic status, and those with other pre-existing chronic inflammatory conditions are also considered at higher risk. Distribution of sensitive populations defines the vulnerability to adverse health effects across communities and reducing impacts among these populations is likely to bring the greatest public health burden benefit on smoke days.

Population vulnerability to various natural hazards has been studied for decades, however population vulnerability to smoke has not been well documented. Various aspects of population vulnerability have been examined in the context of heat waves,[16] famine, seismic events, coastal and inland floods, sea level rise, and drought.[17−20] Recent assessments have also focused on identifying communities vulnerable to environmental hazards exacerbated by climate change.[19,21,22] The purpose of assessing population vulnerability is to determine the population at greatest risk to environmental hazards, understand how communities respond and adapt and inform ways to mitigate the risk and negative impacts.[23] The communities that adapt to and recover after a disaster are those that can better plan, prepare and respond to environmental hazards. The alarming trends in the severity of wildland fires and growth of populations in the communities adjacent to wildlands call for an improved understanding of which communities are the most vulnerable to health impacts in order to improve public health response.

Here, we index community vulnerability to health effects of air pollution and wildfire smoke, based on previously studied clinical and social risk-factors that were found to modify the association between air pollution and adverse health outcomes. We then quantify population size at risk with respect to the levels of the index and the level and duration of smoke exposure in the recent past. To characterize smoke exposure in the recent past we simulated fire-originating fine particulate matter ($PM_{2.5}$) over a five-year period (2008−2012) using a chemical transport modeling system. The objective of this work is to demonstrate that community health vulnerability can be readily assessed using existing data and to provide motivation as to why it may be necessary. Understanding where the most vulnerable communities are found can be useful in developing outreach and education material.

■ MATERIALS AND METHODS

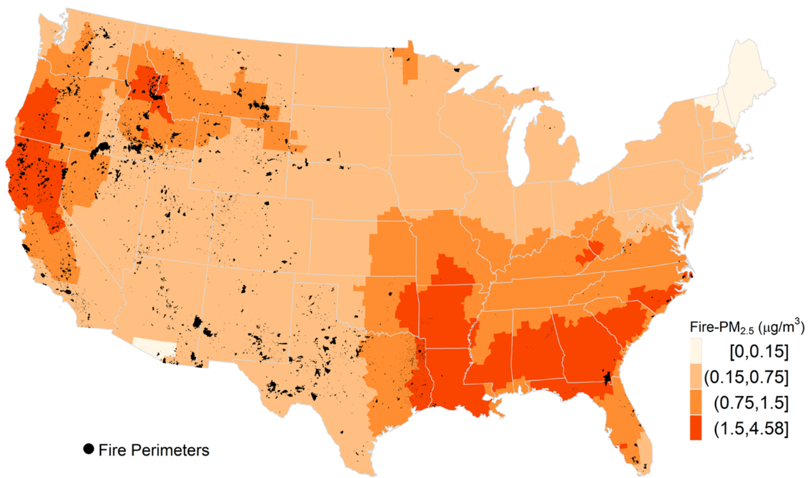
Development of Community Health-Vulnerability Index. To develop an index of community health-vulnerability to the adverse health effects of smoke exposures, we obtained specific socio-economic, demographic, and health outcome measures previously determined in the literature to modify the risk of air pollution related health outcomes.[13,24,25] More specifically, we obtained county prevalence for diabetes, hypertension, adult and pediatric asthma, chronic obstructive pulmonary disease (COPD); percent of population over 65 years of age, household income, education, rates of poverty, and unemployment. In the $PM_{2.5}$- Integrated Science Assessment,[13] both intrinsic (disease status) and extrinsic factors (poverty) are referred to as factors of susceptibility and vulnerability, respectively. However, because all of the factors are aggregated and not individual data, we use the term "vulnerability" throughout to define increased risk of adverse health outcomes related to exposure. In all cases we used county level indicators available across the continental U.S. because mitigation and adaptation plans are often planned and executed at the county level. The list of variables used to profile vulnerability is not intended to be exhaustive, but rather representative of the key clinical and social conditions known to or suspected to increase the risk of adverse health outcomes associated with fire- $PM_{2.5}$. Data sources and summary statistics are available in Supporting Information (SI) Table S1.

Prevalence and incidence estimates of pediatric asthma (in children <18 years of age), adult asthma (18+ years of age), and adult COPD (30+) which includes chronic bronchitis and emphysema, were obtained from the American Lung Association.[26] American Lung Association projected national and state prevalence of chronic lung disease to county levels using the Behavioral Risk Factor Surveillance System (BRFSS)[27] a phone based survey system that has been collecting data continuously since 2004, and statistical methods developed by the U.S. Census Bureau.

We used county level prevalence of hypertension to approximate prevalence of cardiovascular disease. We used sex specific and age adjusted hypertension prevalence data in adults over 30 years of age reported in Olives et al.[28] The study characterized the relationship between self-reported and physical measurements of hypertension reported in the National Health Examination and Nutrition Survey and used the relationship to adjust BRFSS 2009 self-reported responses on hypertension prevalence (among all respondents, percentage of those who reported systolic BP of at least 140 mmHg and/or self-reported taking medication) for self-reporting bias. Prevalence for county-level age, race, and sex adjusted estimates of diagnosed diabetes and obesity in adults (20 years of age and older) were obtained from BRFSS 2012 from http://www.cdc.gov/diabetes/atlas/countyrank/County_ListofIndicators.html.

Older adults and individuals of lower socio-economic status have been shown to be of increased risk of cardiovascular and respiratory effects in both short-term exposure studies and long-term exposure studies of air pollution.[13] Similarly, several studies found that socio-economic factors also modified health responses during the exposures to wildfire smoke.[29,30] Socio-economic and demographic profiles used in this study were taken from 2010 U.S. Census including population size by age group and gender, percent of individuals living in poverty, percent of families living in poverty, medium household income, and percent of unemployment.[31]

a



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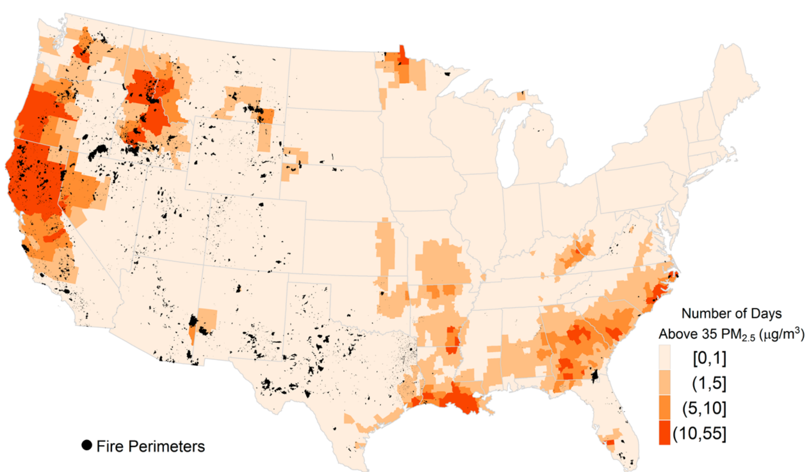

Figure 1. (a) Annual average daily fire-$PM_{2.5}$ footprint by counties of continental US and perimeters of area burned by large fires in black (GeoMAC) between 2008 and 2012. (b) Number of days with fire-$PM_{2.5}$ above 35 $\mu g/m^3$ by counties of continental US and perimeters of area burned by large fires in black (GeoMAC) between 2008 and 2012.

We used principal components analysis and varimax rotation to reduce the number of measures of vulnerability into a smaller number of independent components. All measures of vulnerability were standardized prior to analysis. The first five components explained 84% of variance and were highly loaded on (1) economic deprivation, (2) population of 65 years and older, (3) chronic adult respiratory conditions (COPD and asthma), (4) pre-existing conditions linked to hypertension, obesity and diabetes, and (5) pediatric asthma (SI Table S2). All five components were positively associated with primary measures, with the exception of median household income that was negatively loaded on the first component measuring economic deprivation (SI Figure S11). The higher scores of all five components described the more vulnerable state (more poverty, more individuals 65 years and older, more chronic respiratory and other conditions). The five components were individually assigned quintile scores (1 (the least vulnerable) to 5 (the most vulnerable)). Quintile ranks for each component were added together to create overall Community Health-Vulnerability Index (CHVI) with higher values defining more vulnerable states.

Air Quality Simulations. We simulated daily air quality from 2008 to 2012 using the Community Multiscale Air Quality (CMAQ) model with and without wildland and prescribed fires. The calculated difference between the two model runs represents the contribution of fire emissions to the ambient $PM_{2.5}$ levels (fire-$PM_{2.5}$). Inputs to the model included gridded meteorological fields, emissions data, and boundary conditions. For a regional or continental CMAQ model simulation, the meteorological fields were provided by annual CONUS Weather Research and Forecasting model (WRF) simulation that utilized 12 km horizontal grid spacing and 35 vertical layers of variable thickness extending up to 50 hPa, with the top of the lowest model layer at approximately 20 m above ground level. Initial and boundary conditions for WRF were provided by the North American Mesoscale Model available from the National Centers for Environmental Prediction. The input emissions were based on a 12 km national U.S. domain with speciation for the Carbon-Bond 05 chemical mechanism.[32]

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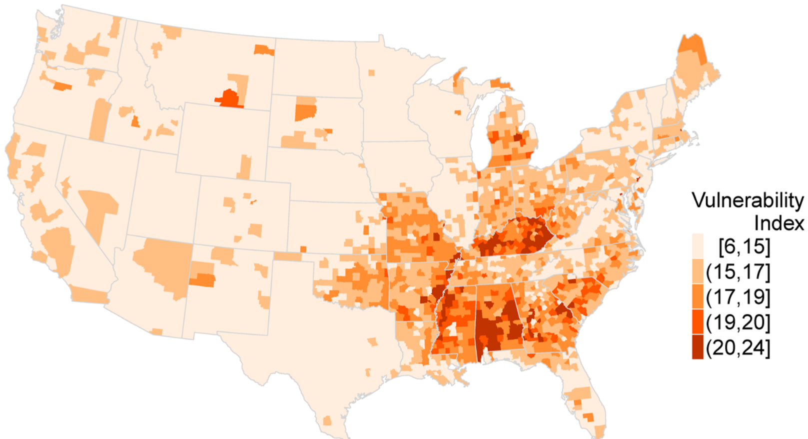

Figure 2. National map of the Community health-vulnerability Index (CHVI). The break points 15, 17, 19, and 20 correspond to the 50th, 75th, 90th, and 95th percentile of CHVI scores, respectively.

The emission inventory and ancillary files were based on the 2008 emissions modeling platform for 2008, 2009, and 2010 and on the 2011 emission modeling platform for 2011 and 2012. The fire emissions were based on year-specific daily fire estimates using the Hazard Mapping System fire detections and Sonoma Technology SMARTFIRE system (version 2) (http://www.getbluesky.org/smartfire/docs/Raffuse 2007.pdf). Plume rise was calculated within the CMAQ model (in-line). Biogenic emissions were processed in-line in CMAQ and are based on the Biogenic Emissions Inventory System v3.14 (http://www.cmascenter.org).

CMAQ hourly output was averaged to daily averages (midnight to midnight and adjusted for time zone) for each grid point. From the gridded output we calculated area weighted averages for daily and annual fire-$PM_{2.5}$ daily averages for each county. We characterize smoke exposure impacts with respect to the magnitude of exposure, frequency of days with moderate air quality (15−35 $\mu g/m^3$) and frequency of days with unhealthy levels of fire-$PM_{2.5}$ (>35 $\mu g/m^3$) according to 2006 $PM_{2.5}$ NAAQS. In terms of health risks, moderate air quality days are interpreted as "Unhealthy for Unusually Sensitive Groups"; while concentrations above 35.4 are interpreted as unhealthy for a broader population. More specifically, 35.5−55.4 $\mu g/m^3$ is considered "Unhealthy for Sensitive Individuals", 55.5−150.4 $\mu g/m^3$ is considered "Unhealthy" for all individuals, 150.5−250.4 is "Very Unhealthy", and ≥250.5 is "Hazardous".[33] The two concentrations used in this analysis also correspond to the annual (15 $\mu g/m^3$) and daily (35 $\mu g/m^3$) 2006 $PM_{2.5}$ NAAQS. Here we used the 2006 standard because it was the standard of the time period 2008 to 2012. In December, 2012 the NAAQS for $PM_{2.5}$ was revised, and the annual standard was reduced to 12 $\mu g/m^3$ while the daily standard 35 $\mu g/m^3$ was retained. We note that we use these thresholds to define moderate and unhealthy smoke days and not to define compliance to air quality regulations. Finally, to calculate population size at risk we used age and gender specific population size from 2010 U.S. Census.

Wildfire perimeters for each year in this five-year period used in the study were obtained from USGS Geospatial Multi-Agency Coordination Group (GeoMAC) Wildland Fire Support archives. The GeoMAC is an interactive mapping application that displays maps of current fire locations and perimeters in the 48 contiguous states plus Alaska. This tool gathers fire data from daily incidence reports and defines wildland fire perimeters based on incident intelligence sources, GPS data, fixed wing aircraft sources, and satellite data. Fires not reported to the incidence intelligence such as prescribed and agricultural fires are not represented in the GeoMAC. The shape files and metadata are available at http://rmgsc.cr.usgs.gov/outgoing/GeoMAC/historic_fire_data/.

■ RESULTS

Fire-$PM_{2.5}$ Patterns over the Continental U.S., 2008–2012. In Figure 1, we mapped a geographic distribution of the estimated fire-$PM_{2.5}$ daily average with respect to (a) the magnitude and (b) frequency of unhealthy smoke days. The maps of fire-$PM_{2.5}$ were also overlaid with the geocoded perimeters of large wildfires from GeoMAC archives. In combination with large fire parameters and with respect to the magnitude of impact, two distinct and large spatial footprints are observed for fire-$PM_{2.5}$. The first footprint was observed over the heavily forested, cold and temperate climates of Northern California and Pacific Northwest, where high concentrations were colocated with a dense distribution of fire perimeters. The second fire-$PM_{2.5}$ footprint was observed across the Southeast where vegetation includes hardwood, pine and southern mixed forests, and wetlands. According to the National Emissions Inventory used in our CMAQ simulations, a majority of the emissions in this region are attributed to smaller and more localized wildland fires, which include agricultural burning and prescribed burning, and a large number of smaller fires. Prescribed burning is done on an annual basis in early months of the year and with the exception of drought years, the smoke footprint is consistently present from year to year. Daily average fire-$PM_{2.5}$ on smoke days was substantially lower in the Southeast than in the Northwestern states with the exception of days when large wildfires occurred (wildfire impacts can be observed from hourly concentrations which are not shown here). Maps for individual years are given in the SI Figures S1−S10.

Figure 1 demonstrates a notable difference between the Northwest and Southeast regions in frequency by which estimated county-averaged fire-$PM_{2.5}$ was above the level considered "Unhealthy for Sensitive Individuals" (>35 $\mu g/m^3$). The largest impact was in the Northwest region where a number of communities experienced 10 or more days of high fire-$PM_{2.5}$ levels. With the exception of Louisiana during winter 2008, the Southeast region had a significantly lower number of

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Table 1. Population Size at Risk Summarized by Annual Average Fire-$PM_{2.5}$ (2008−2012)[a]

$PM_{2.5}$ (μg/m3)	adult asthma	pediatric asthma	COPD	hyper- tensive	diabetes	obesity	poverty	under 18	65 and over	total population
	20.8	6.4	11.8	68.8	20.3	60.9	42.5	73.7	40.0	306.7
(0,0.15]	0.2	0.1	0.1	0.6	0.2	0.5	0.4	0.6	0.4	2.8
(0.15,0.75]	12.7	3.8	6.6	40.0	11.3	34.4	23.6	43.5	23.7	182.2
(0.75,1.5]	5.9	1.9	3.8	20.8	6.4	19.0	13.2	22.2	11.9	91.1
(1.5,4.58]	2.0	0.7	1.3	7.4	2.4	7.0	5.3	7.4	4.0	30.5

[a]We used outcome specific prevalence by county. Population size is given in millions.

Table 2. Population Size at Risk by Community Health-Vulnerability Index, Annual Average Fire-$PM_{2.5}$, and Frequency of Unhealthy Fire-$PM_{2.5}$ Days Between 2008 and 2012[a]

	CHVI bins	[6,15]	(15,17]	(17,19]	(19,20]	(20,24]	total
annual mean (μg/m^3)	[0,0.15]	2 (72.3%)[#]	0.7 (25.2%)	0.1 (2.6%)	0 (0%)	0 (0%)	2.8 (0.9%)*
	(0.15,0.75]	98.6 (54.1%)	61.4 (33.7%)	13.5 (7.4%)	5.6 (3.1%)	3.1 (1.7%)	182.2 (59.4%)
	(0.75,1.5]	49 (53.8%)	25.4 (27.8%)	12.3 (13.5%)	2.7 (3%)	1.8 (2%)	91.2 (29.7%)
	(1.5,4.58]	8.1 (26.6%)	11 (36.1%)	7.5 (24.6%)	2.3 (7.4%)	1.6 (5.3%)	30.5 (9.9%)
num. days with 15−35 μg/m^3	[1,5)	69.6 (63.1%)	29.9 (27.1%)	8 (7.3%)	2.1 (1.9%)	0.7 (0.6%)	110.4 (36%)
	[5,10)	16.6 (31.2%)	23.5 (44.2%)	8.8 (16.6%)	2.1 (4%)	2.1 (4%)	53.1 (17.3%)
	[10,76]	39.5 (47.9%)	22.9 (27.8%)	13.6 (16.4%)	3.8 (4.6%)	2.7 (3.3%)	82.4 (26.9%)
num. days with >35 μg/m^3	[1,5)	28.5 (49%)	14.4 (24.7%)	11 (18.9%)	2.8 (4.9%)	1.4 (2.5%)	58.2 (19%)
	[5,10)	9.9 (51.6%)	5.4 (28.2%)	2.2 (11.7%)	0.8 (4%)	0.9 (4.5%)	19.1 (6.2%)
	[10,55]	6.9 (67%)	2.8 (27.1%)	0.3 (2.9%)	0.2 (1.6%)	0.1 (1.3%)	10.3 (3.4%)
	Total	157.7 (51.4%)	98.5 (32.1%)	33.4 (10.9%)	10.6 (3.5%)	6.5 (2.1%)	306.7 (100%)

[a]Population size is given in millions ([#] % expressed conditional on the population in the right margin, * expressed as % of the total population).

unhealthy fire-$PM_{2.5}$ days. In summary, both footprints had a large number of moderate air quality days due to fire-$PM_{2.5}$, while days with fire-$PM_{2.5}$ exceeding the level considered unhealthy for wider population were mostly in the Northwest region.

Health-Vulnerability and Smoke Impacts. The CHVI score ranged from 6 to 25, with a median score of 15, and 75th, 90th, and 95th percentile of 17, 19, and 20, respectively. The highest vulnerability is observed in the counties along the western slope of the Appalachian Mountains, parts of the Midwest (Kentucky, Missouri, Oklahoma, and Kansas) and parts of the South (Arkansas, Mississippi, Alabama, and Georgia) (Figure 2). Although none of the five indices dominated CHVI overall, the regions of the highest vulnerability tend to have high index values on multiple factors, particularly the prevalence of preexisting cardiovascular, metabolic diseases, and childhood asthma as well as economic deprivation.

Table 1 shows the estimated population size at risk by factors of vulnerability. We estimate that 30.5 million (13%) individuals, including 7.4 million children under 18, and 4 million persons over 65 years of age lived in communities where the annual average of fire-$PM_{2.5}$ was estimated to be above 1.5 μg/m^3 (annual average). Among these communities, there were 7.4 million individuals over 30 years of age with known hypertension, 2 million adults with asthma and 0.7 million children with asthma, 1.3 million people with COPD, 7.0 million obese individuals, and 2.4 million individuals with diabetes. We note that population size at risk was calculated separately for each county level factor of vulnerability; thus individuals with comorbidities are counted for each health outcome.

Table 2 shows the population size at risk by CHVI, annual mean fire-$PM_{2.5}$ levels, and frequency of moderate and unhealthy fire-$PM_{2.5}$ days. We estimate that 82.4 million individuals lived in counties with moderate air quality due to fire-$PM_{2.5}$ (15−35 μg/m^3) and 10.3 million individuals lived in the counties with unhealthy air quality levels (>35 μg/m^3) for more than 10 days between 2008 and 2012. Among the communities with the highest annual fire-$PM_{2.5}$ means (>1.5 μg/m^3), 8.1 million (26.6%) lived in counties with vulnerability index below the median (CHVI 6−15) while 22.4 million lived in the counties with vulnerability above the median (73.4%, 36.1 + 24.6 + 7.4 + 5.3; CHVI (15−24] combined) and 12.7% lived in the counties with high vulnerability (7.4%+5.3%; CHVI > 19). In contrast, across the nation approximately half of population (51.4%) lived in counties where CHVI is below the median and half (49.6%) lived in the counties where CHVI was above the median.

Over the time period considered, areas with the highest vulnerability were more likely to experience unhealthy levels of fire-$PM_{2.5}$ annual average ([1.5,4.58]) than less vulnerable populations (1.6/6.5×100 = 25% for CVHI (20,24] compared to 8.1/157.7×100 = 5% for CVHI [6,15]). Similar was true for number of days with moderate fire-$PM_{2.5}$ (15−35 μg/m^3) for 10+ days and for number of days with fire-$PM_{2.5}$ above 35 μg/m^3 for 5+ days (Table 2). More specifically, among the counties with vulnerability index below the median, 25% (39.5/157.5×100%) lived in places that experienced an excess of 10 days of moderate air quality due to fire while among the counties with the highest vulnerability (CHVI 21−24), 41.5% (2.7/6.5*100%) of population experienced an excess of 10 days of moderate air quality due to fire. A substantially smaller population size was impacted by a large number of days with unhealthy air quality (>35 μg/m^3); 10.7% of the population in the counties with CHVI below the median and 15.2% of the population in the most vulnerable counties experienced more than 5 days of unhealthy air quality (>35 μg/m^3). However,

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4.4% of the least vulnerable communities and only 2.1% of the most vulnerable communities were impacted by 10 or more days of fire-$PM_{2.5}$ above 35 $\mu g/m^3$.

■ DISCUSSION

In this study we constructed an index of population vulnerability to health impacts from smoke exposure based on clinical and social factors known to modify the risk of adverse health effects and estimated population size at risk with respect to the frequency and magnitude of smoke exposure in a recent period. The modeling methods used in the study estimate that between 2008 and 2012 population exposure to smoke in the continental U.S. was extensive; 29.7% of the population lived in areas with moderate exposure (annual average fire-$PM_{2.5}$ between 0.75 and 1.5 $\mu g/m^3$) and another 10% lived in areas where the contribution to annual ambient $PM_{2.5}$ was high (>1.5 $\mu g/m^3$). We identified the most vulnerable U.S. counties and determined that vulnerable communities were more likely to experience high and frequent smoke exposure in comparison to less vulnerable populations. The findings described in the study have potential implications for efficient and effective allocation of limited resources for dissemination of public health messaging, and land and fuel management to prevent large wildfires.

The constructed Community Health-Vulnerability Index incorporates disease prevalence, age and socio-economic status of individuals in the community. The specific factors were chosen based on published literature that demonstrates their role as risk factors for cardio-respiratory effects of particles or wildfire smoke. Published research describes multiple biological mechanisms by which air pollution causes cardio-respiratory effects including oxidative stress, pulmonary and systemic inflammation, activation of pulmonary nocioceptive receptors, and modulation of the autonomic nervous system (Brook et al. 2010). Therefore, individuals having chronic health conditions characterized in part by pro-inflammatory states (e.g., asthma, COPD, diabetes, cardiovascular disease) are considered at higher risk.[34] Among the risk factors, preexisting cardiovascular disease is one of the leading factors of increased health risks to air pollution effects.[35] We used hypertension to approximate prevalence of cardiovascular disease because it is well documented, the most prevalent cardiovascular condition, and is responsible for one in six deaths among adults. Chronic metabolic and inflammatory health conditions such as diabetes and obesity have been shown to increase the risk to air pollution impacts.[36−38] Children are considered more sensitive to impacts of air pollution because their lungs are smaller, and their dose per body weight and lung surface areas exceed those of the adult population.

The majority of evidence for wildfire smoke effects are based on studies of exposure to ambient air pollution[13] but there is also a growing number of fire-$PM_{2.5}$ studies that suggest consistency between respiratory effects within fire specific studies and in comparison to studies of urban air pollution.[9,39] The effects of air pollution and wildfire smoke exposure on adults with preexisting respiratory conditions such as asthma and COPD are extensively documented in literature. These effects have also been noted in both children with asthma and children without asthma[5,40] and have been noted to be stronger than in adults.[41] Additionally, older adults have been shown to have an increased risk of cardiovascular and respiratory effects in fire-$PM_{2.5}$ exposure studies.[3,7,42,43] Apart from the clinical characteristics discussed, low socioeconomic status has also been reported to modify the risk of respiratory outcomes in response to large wildland fire smoke events.[30] We have previously shown that when considering external factors influencing health (health behaviors, access and quality of clinical care, social and economic factors, and the physical environments) socio-economic factors are strong contributors of differences in risk for asthma and congestive heart failure resulting from exposure to wildfire smoke.[29]

In the development of the health-vulnerability index we restrict our attention to the key clinical and social conditions that have been identified by the Integrated Science Assessment as populations sensitive to adverse health effects following air pollution exposure. It is clear, however, that these are not the only risk factors involved at the individual level. Evidence for a role for genetics, epigenetics, diet, availability of green space and behavior is emerging and it is likely that some of these will ultimately prove to be strong predictors of $PM_{2.5}$ associated health outcomes. As new risk factors are identified the CHVI can be adapted to incorporate the new information. Additionally, a number of other extrinsic factors have been shown to identify social vulnerability to environmental hazards such as heat waves, including occupation, employment, housing, built environment, neighborhood deprivation, poor English skills and are likely to apply in wildfire smoke situations.[44−47] When constructing indicators at the regional, state or local levels, and particularly when considering decision making, it may be helpful and advantageous to incorporate determinants of social vulnerability along with the indicators of health vulnerability (e.g., built environment, landscape, social and physical connectivity, existing air quality, etc.) and examine sensitivity of the indicators.

Implications for Public Health Actions. Interventions and health-promoting behaviors can improve public health outcomes.[48,49] Many of the recommended measures including staying indoors during very unhealthy air quality days, running air conditioning on recirculation mode, creating a clean room, ensuring a supply of regular medication, etc. can reduce personal exposure and decrease the health risks. However, during wildfire episodes, individuals do not perceive risks to their health and become aware of them once smoke exposure is already occurring, when it may be too late to take many of the recommended preventative measures. Smoke impacts in the areas where wildfires are less common (e.g., Southeast) can be a special concern exactly because they are less frequent and the health risk awareness is not established at the individual or community level. Prior knowledge about community health vulnerability can help guide deliberate awareness building and outreach among the most sensitive populations. However, identifying communities at the greatest risk from wildfire smoke is currently based solely on the predicted risk of fire and we do not consider the composition of the communities. As such public health messaging and actions may not be appropriately scaled to communities with high numbers of sensitive individuals.

Increased frequency of large wildland fires is anticipated to continue and have effects on human health and environment.[50−52] Fuel management activities, such as prescribed burning, are a critically important component of the national strategy to improve ecological diversity and decrease wildfires harmful to human health and have been examined with respect to changes in frequency and area burned.[53−56] While such information provides important insights for a broad risk-based management system for wildfire, the framework does not

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consider the potential public health burden of smoke emissions or disparities in sensitivity of the populations affected. Projecting community health-vulnerability under different fire mitigation strategies, climate change scenarios, and population growth projections may offer further refinement of such risk-based management approaches. In projecting community health-vulnerability for a specific future scenario we recommend using population-weighted exposures.

Limitations of the Study. We note some limitations to our analysis. To estimate smoke exposure at the national level we use CMAQ model simulated with and without fires and attribute the difference in estimated ambient $PM_{2.5}$ concentrations to large fires (mostly wild and prescribed). To assess model performance, we matched CMAQ grid locations to the locations of environmental monitors and compare predicted and observed values. We found the model has a high bias at low $PM_{2.5}$ concentrations suggesting that (1) plumes are too dispersive, and/or (2) small fires have too high emissions in the simulation. The model also over predicts $PM_{2.5}$ (mainly organic and elemental carbon) during all seasons for fire events. Another limitation is that only fire events that are part of the emission inventory have been evaluated. Any misspecification of emissions in the inventory is not included in our analysis. An important limitation to our simulation of fire-$PM_{2.5}$ that affects air quality is that our modeling system does not simulate the smoldering aspects of peat fires well which are common in the Southeast and emit large quantities of particles and gases. We note that as with all models CMAQ results should be interpreted with caution because any combination of these factors could lead to uncertainty and over or under prediction of estimated exposures. While various aspects of CMAQ performance have been published in the literature,[57] additional factors could play a role in the uncertainty specific to fire-$PM_{2.5}$.

Another limitation is the assumption that $PM_{2.5}$ from all sources is equally harmful to health. The composition and toxicity of these particles varies with respect to the type of fuel burned, conditions of burning and the age of the particles. Lower combustion efficiency yields more volatile and organic compounds in both particles and gases (polynuclear aromatic hydrocarbons, oxygenated organics, and various gases) which are harmful to human health. Toxicological studies also indicate that relative toxicity of particles varies when examined per unit mass or total mass, and by chemical composition of the particles. Fire-$PM_{2.5}$ and fire-PM_{10} collected during a peat fire in eastern North Carolina in 2008 had very different targets of cellular toxicity that depended on the particle mass of the smoke particles and the phase of the fire.[58] Cardiovascular toxicity was the dominant effect caused by ultrafine PM fraction collected during the active smoldering phase of the fire while in vitro pulmonary inflammatory responses were the dominant effects of coarse fraction of PM. Smoldering fires, as seen in the peat fires across Southeast U.S., Indonesia, and Boreal forest have also been hypothesized to carry higher risk for cardiovascular Emergency Department visits as well.[11,43] This could be due to lower combustion efficiency and vegetation type that define chemical composition of particles, such as the abundance polynuclear aromatic hydrocarbons which are carcinogenic and particularly harmful to health.[59] However, a systematic review of published literature suggests that there is no consistent relationship that identifies specific $PM_{2.5}$ components that may be unequivocally related to health outcomes.[60]

The most significant limitation to this assessment of human vulnerability to health impacts of smoke is the lack of a good measure of a community's ability to adapt. While the factors that define the vulnerability status certainly play a role, other less quantifiable measures including awareness, previous experience, outreach programs, engagement of public health, and proximity to health care providers or facilities can define human responses. Gaither et al. 2011 examined spatial association between fire prone areas in the Southeast and socially vulnerable "hot spots" using proximity to wildland fire mitigation programs as a measure of community's ability to adopt. However, we did not find equivalent measures of community responses specific to health responses.

Wildland fires have been an integral part of human history with clear benefit to the management of fire hazards and to the ecologic diversity of ecosystems. However, recent trends in very large wildfires, termed mega fires, have brought attention to the adverse health effects of smoke exposure, the high cost of wildfire suppression and management, and the need to establish community-based adaptation plans. Employing the same methodology used to determine social vulnerability to environmental hazards,[23] we provide a concept of mapping the vulnerability to health outcomes specific to smoke exposure. Such maps can be helpful tools for public officials in preparation of smoke adaptation plans for their communities and prioritization of communities for allocation of resources by the local, state and federal governments. In the U.S. there are over 70 000 wildfires annually, impacting communities and regional air quality with varying frequency and intensity and thus representing a challenge to building community resilience with respect to fire smoke and public health guidance. Therefore, as a proof of concept, the Community Health-Vulnerability Index offers a tool to help identify communities that have the potential to benefit the most from mitigation strategies to minimize smoke exposure for sensitive populations and to decrease the health and economic burden imposed on the population by fire-$PM_{2.5}$ The next step could include tailoring messages to community needs and development of exposure mitigation strategies.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.6b06200.

> List of data sources (Table S1), figures of the annual average daily fire-PM2.5 footprint by year (Figures S1−S5), figures of number of days with fire-PM2.5 above 35 $\mu g/m^3$(Figures S6−S10) and details of principal components analysis output (Table S2, Figure S11) (PDF).

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