EPA Public Access
Author manuscript
Environ Sci Technol. Author manuscript; available in PMC 2019 February 13.

Published in final edited form as:
Environ Sci Technol. 2017 June 20; 51(12): 6674–6682. doi:10.1021/acs.est.6b06200.

Community vulnerability to health impacts from wildland fire smoke exposure

Ana G. Rappold, PhD,
United States Environmental Protection Agency / National Health and Environmental Effects Research Laboratory / Environmental Public Health Division, NC

Jeanette Reyes, PhD,
United States Environmental Protection Agency / National Health and Environmental Effects Research Laboratory / Environmental Public Health Division, NC

George Pouliot,
United States Environmental Protection Agency / National Exposure Research Laboratory / Computational Exposure Division, NC

Wayne E. Cascio, MD, and
United States Environmental Protection Agency / National Health and Environmental Effects Research Laboratory / Environmental Public Health Division, NC

David Diaz-Sanchez, PhD
United States Environmental Protection Agency / National Health and Environmental Effects Research Laboratory / Environmental Public Health Division, NC

Abstract

Background: Identifying communities vulnerable to adverse health outcomes from wildfire smoke exposure can help prepare community-level responses, increase the community resilience to wildfire smoke and improve public health outcomes when smoke episodes arise.

Methods: We developed an index of community vulnerability to the health effects from smoke exposure based on factors known to define susceptibility to the adverse health effects of air pollution. 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, income and unemployment. Using air quality simulated for the period between 2008 and 2012 over the continental U.S. we characterized the population size at risk with respect to the level and duration of smoke exposure and vulnerability to health effects.

Corresponding author: Ana G. Rappold, 109 T.W. Alexander Drive, US EPA, Research Triangle Park, NC 27709, 919 843 9504, rappold.ana@epa.gov.

Results: We estimate that 29.7% of the population (91.1 million) lived in areas with annual average fire-$PM_{2.5}$ between 0.75 and 1.5μg/m^3 while and nearly 10% of the population (30.5 million) lived in the areas where annual average ambient $PM_{2.5}$ was above 1.5 μg/m^3. Additionally, 82.4 and 10.3 million individuals experienced moderate air quality due to fire-$PM_{2.5}$ (daily $PM_{2.5}$ between 15 and 35 μg/m^3) and 10.3 million individuals experienced unhealthy air quality levels (daily fire-$PM_{2.5}$ > 35 μg/m^3) for more than 10 days between 2008 and 2012. Using the index of vulnerability to health effects we identified the most vulnerable U.S. counties and determined that higher percent of vulnerable communities experience frequent smoke exposures in comparison to less vulnerable communities.

Conclusion: Wildfire smoke impacts local and regional air quality and presents a challenge to protecting public health. Knowledge of the location of those communities at the highest risk of smoke exposure (i.e., most vulnerable) and subsequently smoke-related health effects can inform development of smoke adaptation plans for these communities and increase their resilience to the effects of wildfire smoke.

INTRODUCTION

Exposure to wildfire smoke is a serious health risk which can disproportionally impact sensitive groups. In order to reduce the public health impacts identification of those communities at greatest risk of both exposure and health effects is of paramount importance. 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 death (Delfino et al. 2008; Dennekamp and Abramson 2011; Dennekamp et al. 2015; Haikerwal et al. 2015; Haikerwal et al. 2016; Jalaludin et al. 2000; Johnston et al. 2012; Johnston et al. 2014; Nino Kunzli et al. 2006; Liu et al. 2015; Morgan et al. 2010; Rappold et al. 2011). Identifying communities vulnerable to adverse health outcomes during smoke days can provide valuable information for local, State and Federal Governments as well as non-governmental organizations to prioritize public health actions to minimize adverse health outcomes attributed to wildfire smoke exposures.

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 particulate matter, the U.S. Environmental Protection Agency (EPA 2009) concluded there is a causal relationship between short- and long-term exposures and cardiovascular effects and mortality, and a likely to be causal relationship with respiratory effects. Multiple studies demonstrate that the risk from $PM_{2.5}$ is not equally shared and that particular groups of people within the population are more sensitive to the adverse health impacts from particulate matter than others (Bell et al. 2013; Sacks et al. 2011). These sensitive groups include children, the aged, as well as those with a pre-existing cardio-pulmonary disease. Individuals and communities of lower socioeconomic status, and those with other pre-existing chronic inflammatory conditions may also be at higher risk . Reducing impacts among the sensitive groups during smoke events is of paramount importance.

EPA Author Manuscript

EPA Author Manuscript

Population vulnerability to 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 (Reid et al. 2009), famine, seismic events, coastal and inland floods, sea level rise, and drought (Blaikie et al. 2014; Cutter et al. 2000; Morrow 1999; Wu et al. 2002). Recent assessments have also focused on identifying communities vulnerable to environmental hazards exacerbated by climate change. The purpose of assessing population vulnerability is to determine the population at greatest risk to an environmental insult, understand how communities respond and adapt as well as to inform ways to mitigate the risk and negative impacts of environmental hazards (Cutter et al. 2003). The term vulnerability, therefore, may encompass both the risks of physical hazard (exposure) and societal responses (economic and health impacts) and is used throughout in this context. 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 within the wildland urban interface call for an improved understanding of which communities are the most vulnerable.

Here we describe the development of an index of community vulnerability for the health effects of smoke based on factors known to define susceptibility to air pollution in general as well as wildfire smoke in particular. We simulated air quality over a recent 5 year period to map population vulnerability to smoke with respect to the level and duration of smoke exposure. Using this approach we characterized the population size at risk and, therefore, the magnitude of the public health impact with respect to moderate and high level of exposures as well as with respect to short and intermediate duration of exposure.

METHODS AND DATA

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-PM emissions to 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 (WRF) model 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 (Yarwood G. 2005). 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/Raffuse2007.pdf). Year specific continuous emission monitoring system data was used for the electric generating units

EPA Author Manuscript

EPA Author Manuscript

sector. 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 24 hours (midnight to midnight and adjusted for time zone) and annually for each grid point. Area weighted averages were made to obtain daily and annual fire-$PM_{2.5}$ averages for each county. We characterize impacts with respect to the magnitude and frequency of smoke days and use two concentrations to identify days with moderate air quality (15 -35 μg/m^3) and days with high levels of fire-$PM_{2.5}$ (>35 μg/m^3) according to 2006 $PM_{2.5}$ National Ambient Air Quality Standards (NAAQS). In terms of health risks, moderate air quality days are defined as “Unhealthy for Unusually Sensitive Groups”; while concentrations above 35.4 are defined as unhealthy for a broader population. More specifically, U.S. EPA Air Quality Index defines $PM_{2.5}$ concentrations between 35.5-55.4 μg/m^3 as “Unhealthy for Sensitive Individuals”; between 55.5-150.4 μg/m^3 as “Unhealthy” for all individuals; between 150.5-250.4 as “Very Unhealthy”; and ≥250.5 as “Hazardous”(EPA 2013). The two concentrations used in this analysis also correspond to the annual (15 μg/m^3) and daily (35 μg/m^3) 2006 $PM_{2.5}$ National Ambient Air Quality Standards (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, with the annual standard being reduced to 12 μg/m^3 while the daily standard of 35 μg/m^3 was retained.

Wildfire perimeters for each year in this 5 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/.

Development of Community Vulnerability Index

To develop an index of community vulnerability to the adverse health effects of exposure to fire-$PM_{2.5}$ 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 (Bateson and Schwartz 2004; EPA 2009). More specifically, we obtained county prevalence rates 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. 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 Supplemental Material Table 1.

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 (2014). ALA projected national and state prevalence rates of chronic lung disease to county levels using Behavioral Risk Factor Surveillance System (BRFSS 2012). BRFSS is a phone based survey system that has been collecting data continuously since 2004, and statistical methods developed by US Census Bureau.

As a proxy measure of prevalence in cardiovascular disease we used county level prevalence of hypertension as detailed in Olives et al. (2013), which provided sex specific and age adjusted hypertension prevalence data in adults over 30 years of age . The study characterized the relationship between self-reported and physical measurements of hypertension reported in 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 140mm Hg 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 wildfire exposure studies (Haikerwal et al. 2015; Rappold et al. 2012; Reid et al. 2016b). Socioeconomic and demographic profiles used in this study were taken from the 2010 US 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.

We used principal components analysis and varimax rotation to reduce the number of measures of vulnerability into a smaller number of independent components. The first five components explained 84% of variance and were highly loaded on: 1) pre-existing conditions linked to hypertension, obesity and diabetes, 2) chronic adult respiratory conditions (COPD and asthma), 3) population of 65 years and older and housing value, 4) economic deprivation, and 5) pediatric asthma. All five components were positively associated with primary measures, with the exception of unemployment that was negatively loaded on the third component (lower housing value) and positively on the fourth (higher economic deprivation). The five components were individually assigned quintile scores (1-5). Quintile ranks for each component were added together to create the overall Community Vulnerability Index (CVI).

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 high smoke days (“Unhealthy for Sensitive Individuals”). The maps of fire-$PM_{2.5}$ were also overlaid with the geocoded perimeters of the large wildfires from GeoMAC archives. With respect to the magnitude of impact, two distinct and large spatial footprints are observed for fire-$PM_{2.5}$ in combination with large fire parameters. The first footprint was observed over the heavily forested, cold and temperate climates of Northern California and Pacific Northwest, where high concentrations were co-located 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. Maps for individual years are given in the Supplemental Materials.

Figure 1b 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" (>35μg/m^3). The largest impact was in the Northwest region where a number of communities experienced 10 or more days of high fire-$PM_{2.5}$. With the exception of Louisiana during winter 2008, the Southeast region had a significantly lower number of high 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.

County Scale Vulnerability and Smoke Impacts

The CVI 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 Appalachian Mountains, parts of Midwest (Kentucky, Missouri, Oklahoma and Kansas) and South (Arkansas, Mississippi, Alabama, and Georgia). Although none of the five indices dominated CVI 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. We estimate that 30.5 million (13%) individuals, including 7.4 million children under 18, and 4 million persons over 65 years of age live in communities where the annual average contribution of fire-$PM_{2.5}$ to total $PM_{2.5}$ was estimated to be above 1.5 μg/m^3. 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 as well as 7.0 million obese individuals, and 2.4 million individuals with diabetes.

Table 2 shows the population size at risk when considering the number of days with fire-$PM_{2.5}$ at levels "Unhealthy for unusually sensitive groups" (15 - 35 μg/$m^{3)}$ and unhealthy for a broader population (>35 μg/m^3). We estimate that 82.4 million individuals lived in counties with moderate air quality due to fire-$PM_{2.5}$ and 10.3 million individuals lived in the counties with unhealthy air quality levels for more than 10 days between 2008 and 2012.

Out of 306.7 million people in 3009 counties in the lower US, it was estimated that 51.5% (157.7 million) lived in counties with CVI bellow the median (CVI<15), while only 2.1% (6.5 million) individuals live in the counties with the highest vulnerability (CVI >20, 95th percentile) (Table 2). The distribution of population across CVI categories living in areas with high number of days in the "Unhealthy for Unusually Sensitive Groups" category (15-35 μg/m^3) was not consistent with the nationwide distribution (Table 2). More specifically, among the counties with CVI below the median (6-15) 25% of population lived in places that experienced an excess of 10 days of moderate air quality due to fire while among the counties with the highest CVI (21-24), 42.3% 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 CVI below the median and 15.2% of the population in the most vulnerable counties experienced 5 to 10 days of unhealthy air quality (>35 μg/m^3). However, 4.4% of the least vulnerable communities and only) 0.1% the most vulnerable communities were impacted by 10 or more days of fire-$PM_{2.5}$ above 35 μg/m^3.

DISCUSSION

In this study we approach the assessment of community vulnerability to the adverse health effects of wildfire smoke, particularly $PM_{2.5}$ exposure, at the county scale considering both the physical risk of hazard (smoke) and population response (the potential for health impacts) (Cutter et al. 2003). More specifically we characterize population vulnerability to health impacts with respect to frequency and magnitude of smoke exposure and the measures of clinical and social factors that increase susceptibility to the adverse health effects of smoke exposure. The modeling methods used in the study estimate that between 2008 and 2012 population exposure to smoke in the U.S. was extensive with 29.7% of population living in areas with moderate exposure (annual average fire-$PM_{2.5}$ between 0.75 and 1.5μg/m^3). Nearly 10% of the continental U.S. population lives in areas where the contribution of fires to annual ambient $PM_{2.5}$ was high (>1.5 μg/m^3). Using previously published determinants of susceptibility to health effects of air pollution we identified the most vulnerable U.S. counties and determined that vulnerable communities within these counties were more likely to experience high and frequent smoke exposure. 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.

Wildfires and prescribed burning define two distinct geographic footprints of smoke impacts as shown in Figure 1. In the Northwest, wildfires were the dominant source of fire-$PM_{2.}$ and in the Southeast it was the prescribed burning. While both sources of smoke had a negative impact on overall air quality, they diverged with respect to the frequency of high exposure days which were mainly associated with wildfires. The high levels of fire-$PM_{2.5}$ were most common and frequent in the Northwest. However, although less frequent, as evident by GeoMAC fire perimeters, the wildfires in Southeast also had a significant impact on daily air quality. Days with high exposure are particularly relevant to the risk of triggering clinical events and contributing to the public health burden of fire-$PM_{2.5}$.

The constructed Community Vulnerability Index (CVI) 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 risks for cardio-respiratory effects of particles or wildfire smoke. Preexisting cardiovascular disease is among the leading factors of increased susceptibility to air pollution effects on health (Brook et al. 2010). In the absence of county level national prevalence rates for CVD we used hypertension as a proxy measure. Hypertension is 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 susceptibility to air pollution impacts (Devlin et al. 2014; Ruckerl et al. 2014; Schneider et al. 2008).

Children are considered more susceptible 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 particulate matter (EPA 2009) because of the relative sparseness of studies examining the relationship between fire-$PM_{2.5}$ exposure and health effects, but there is a growing number of fire-$PM_{2.5}$ studies. Two new reviews suggest consistency between respiratory effects and smoke exposure and consistency with health effects observed in studies of urban air pollution (Liu et al. 2015; Reid et al. 2016a). Additionally, the impacts of wildfire exposures has also documented in asthmatic and non-asthmatic children. Several studies reported higher rates of symptoms in non-asthmatic children (Jalaludin et al. 2000; N. Kunzli et al. 2006) who were less likely to take preventive actions(Nino Kunzli et al. 2006; N. Kunzli et al. 2006). Ignotti et al. (2010) reported higher rates of respiratory related hospital admissions for children and elderly in comparison to intermediate age groups. The effects of air pollution and wildfire smoke exposure on adults with preexisting respiratory conditions such as asthma and COPD is extensively documented in the literature as well. Older adults have been shown to be at increased risk of cardiovascular and respiratory effects in studies of wildfire smoke exposure (Haikerwal et al. 2015).

It is clear that the risk factors used in current study are not the only risk factors that may increase the risk of health effects attributed to wildland fire smoke exposure. 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 prove ultimately to be strong predictors of $PM_{2.5}$ associated health outcomes. As new risk factors are identified the CVI can be adapted to incorporate new information. Additionally, at the local and state levels additional or different factors may be incorporated.

Implications for Public Health Actions

Acute exposures to wildfire smoke are a concern among the vulnerable populations because of the higher likelihood of adverse health outcomes in comparison to the less vulnerable populations. 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 RD, et al. Circulation 2009). Therefore individuals

EPA Author Manuscript

EPA Author Manuscript

having chronic health conditions characterized in part by pro-inflammatory states (e.g.. asthma, COPD, diabetes, cardiovascular disease) are considered more susceptible. Apart from the clinical characteristics discussed, low socioeconomic status has been shown to increase the risk for adverse health effects for some respiratory outcomes in response to large wildland fire smoke events (Reid et al. 2016b). 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 (Rappold et al. 2012).

Adopting health promoting behaviors can improve health outcomes (Neidell 2010), however communicating the risks and changing behaviors during hazardous conditions such as wildfires is challenging. Individuals may not perceive risks to their health and may become aware of them once smoke exposure is already occurring, when it may be too late to take many of the recommended preventative measures. Although less common, wildfires in the 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. In contrast, planned burning activities provide more opportunities for public health interventions. Burning authorities are required to minimize impacts on public health by notifying individuals and agencies of the intent to burn, by avoiding impacts within sensitive communities, and by minimizing impacts from smoldering smoke among others (SERPAS). However, because of the concentrated vulnerability in the Southeast even the low daily fire-PM2.5 can cumulatively increase the overall burden, particularly within the sensitive populations. Mapping of the vulnerabilities can help ensure that communities are adequately served during the burning season or when the wildfires occur.

Currently, identification of communities at the greatest risk from wildfire smoke is based solely on the level of exposure and does not consider the composition of the communities and the number of sensitive individuals residing within those communities. This presents a challenge because public health messaging and actions may not be appropriately scaled to communities with high numbers of sensitive individuals but where smoke levels are not at their highest. Identifying the most vulnerable communities in smoke-prone areas prior to these events can help guide deliberate awareness building, e.g. the U.S. Forest Services and Department of Interior supported Fire Adapted Communities Learning Network (http://fireadaptednetwork.org/about/), educational materials and programs to facilitate preparedness of public health officials, emergency medical services, healthcare providers and local decision makers, thus increasing the community's resilience to wildfire and decreasing the public health burden of smoke exposures.

Implications for Wildfire Mitigations Strategies

Large western wildland fires release massive amounts of particulate emissions into the atmosphere that impact human and environmental health(Liu et al. 2015; Reid et al. 2016a). By contrast, prescribed burning limits such large wildland fires but at the cost of low, frequent daily contributions, which amount to the largest single source of $PM_{2.5}$ in some regions. 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 (Ager et al. 2014). While such information can provide important insights for a broad risk-based management system for wildfire, the framework does not consider the potential public health burden of smoke emissions or disparities in sensitivity of the populations affected. Such an additional factor as shown in this paper might offer further refinement of such risk-based management approaches.

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 (wild, prescribed and agricultural). To assess model performance, we matched CMAQ grid locations to the locations of environmental monitors and compare predicted and observed values. We found that 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 OC, EC) 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 for fires is not included in our analysis. There are currently intense research efforts being conducted to improve the inventories of fires, improve emissions characterization, and measure the differential toxicity of smoke emitted from different fuel types.

Another limitation is the assumption that all $PM_{2.5}$ is equally harmful to health. The composition 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 compound in both particles and gases (hydrocarbons, oxygenated organics, and various gases). Toxicological studies also indicate that relative toxicity of particles varies when examined per unit mass or total mass. 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 (Kim YH, et al. PFT 2014). Cardiovascular toxicity was the dominant effect caused by ultrafine PM fraction collected during the active smoldering phase of the fire. By contrast in vitro pulmonary inflammatory responses were the dominant effects of coarse PM (Kim YH, et al. PFT 2014). 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 (EPA 2009; Stanek 2011).

The most significant limitation to our 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 role, other less quantifiable measures including the awareness, previous experience and outreach programs, engagement of public health, 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. (Mott et al. 2002) examined the effectiveness of interventions to reduce adverse health effects of smoke exposure was conducted in Hoopa Indian community during 1999 fire season. The results of that study suggested that public service announcements were effective in reducing adverse health effects. Additionally, it has also been shown that air quality health risk communication tools can help protect public health from high levels of air pollution (Neidell 2010) but the effectiveness has not been examined for wildfire events.

Conclusion

Wildland fires have been integral part of human history with clear benefit to the management of fire hazards and to the ecologic diversity of forests. 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 (Cutter et al. 2003), 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. Smoke impacts community and regional air quality with varying frequency and intensity thus representing a challenge to increasing community resilience to wildfire smoke and public health guidance. Therefore, as a proof of concept, the Community Vulnerability Index (CVI) offers a tool to identify communities that have the potential to benefit the most from mitigation strategies to minimize smoke exposure to sensitive populations and to decrease the health and economic burden imposed on the population by fire-$PM_{2.5}$.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

ACKNOWLEDGEMENTS

Enter any acknowledgements here.

REFERENCES

American Lung Ager AA, Day MA, McHugh CW, Short K, Gilbertson-Day J, Finney MA, et al. 2014 Wildfire exposure and fuel management on western us national forests. J Environ Manage 145:54–70. [PubMed: 24997402]

Association AL. 2014 Estimated prevalence and incidence of lung disease.

Bateson TF, Schwartz J. 2004 Who is sensitive to the effects of particulate air pollution on mortality?: A case-crossover analysis of effect modifiers. Epidemiology 15:143–149. [PubMed: 15127905]

Bell ML, Zanobetti A, Dominici F. 2013 Evidence on vulnerability and susceptibility to health risks associated with short-term exposure to particulate matter: A systematic review and meta-analysis. Am J Epidemiol 178:865–876. [PubMed: 23887042]

Blaikie P, Cannon T, Davis I, Wisner B. 2014 At risk: Natural hazards, people's vulnerability and disasters:Routledge.

BRFSS. 2012 Behavioral risk factor surveillance system Available: ftp://ftp.cdc.gov/pub/Data/Brfss/userguide.pdf. [accessed 2015.

Brook RD, Rajagopalan S, Pope CA, Brook JR, Bhatnagar A, Diez-Roux AV, et al. 2010 Particulate matter air pollution and cardiovascular disease an update to the scientific statement from the american heart association. Circulation 121:2331–2378. [PubMed: 20458016]

Census. 2010 Us census bureau Available: Https://www2.Census.Gov/geo/tiger/tiger2010dp1/county_2010census_dp1.Zip.

Cutter SL, Mitchell JT, Scott MS. 2000 Revealing the vulnerability of people and places: A case study of georgetown county, south carolina. Annals of the association of American Geographers 90:713–737.

Cutter SL, Boruff BJ, Shirley WL. 2003 Social vulnerability to environmental hazards. Social science quarterly 84:242–261.

Delfino RJ, Brummel S, Wu J, Stern H, Ostro B, Lipsett M, et al. 2008 The relationship of respiratory and cardiovascular hospital admissions to the southern california wildfires of 2003. Occupational and environmental medicine.

Dennekamp M, Abramson MJ. 2011 The effects of bushfire smoke on respiratory health. Respirology 16:198–209. [PubMed: 20920143]

Dennekamp M, Straney LD, Erbas B, Abramson MJ, Keywood M, Smith K, et al. 2015 Forest fire smoke exposures and out-of-hospital cardiac arrests in melbourne, australia: A case-crossover study. Environ Health Perspect 123:959–964. [PubMed: 25794411]

Devlin RB, Smith CB, Schmitt MT, Rappold AG, Hinderliter A, Graff D, et al. 2014 Controlled exposure of humans with metabolic syndrome to concentrated ultrafine ambient particulate matter causes cardiovascular effects. Toxicol Sci 140:61–72. [PubMed: 24718702]

EPA. 2009 Integrated science assessment (isa) for particulate matter (final). EPA/600/R-08/139F Washington, D.C.

EPA. 2013 Technical assistance document for the reporting of daily air quality-the air quality index (aqi). Research Triangle Park, NC.

Haikerwal A, Akram M, Del Monaco A, Smith K, Sim MR, Meyer M, et al. 2015 Impact of fine particulate matter (pm2.5) exposure during wildfires on cardiovascular health outcomes. Journal of the American Heart Association 4.

Haikerwal A, Akram M, Sim MR, Meyer M, Abramson MJ, Dennekamp M. 2016 Fine particulate matter (pm2.5) exposure during a prolonged wildfire period and emergency department visits for asthma. Respirology 21:88–94. [PubMed: 26346113]

Ignotti E, Valente JG, Longo KM, Freitas SR, Hacon SdS, Artaxo Netto P. 2010 Impact on human health of particulate matter emitted from burnings in the brazilian amazon region. Revista de saude publica 44:121–130. [PubMed: 20140336]

Jalaludin B, Smith M, O’Toole B, Leeder S. 2000 Acute effects of bushfires on peak expiratory flow rates in children with wheeze: A time series analysis. Aust N Z J Public Health 24:174–177. [PubMed: 10790937]

Johnston FH, Henderson SB, Chen Y, Randerson JT, Marlier M, Defries RS, et al. 2012 Estimated global mortality attributable to smoke from landscape fires. Environ Health Perspect 120:695–701. [PubMed: 22456494]

Johnston FH, Purdie S, Jalaludin B, Martin KL, Henderson SB, Morgan GG. 2014 Air pollution events from forest fires and emergency department attendances in sydney, australia 1996-2007: A case-crossover analysis. Environ Health 13:105. [PubMed: 25491235]

Kunzli N, Avol E, Wu J, Gauderman WJ, Rappaport E, Millstein J, et al. 2006 Health effects of the 2003 southern california wildfires on children. American journal of respiratory and critical care medicine 174:1221–1228. [PubMed: 16946126]

Kunzli N, Avol E, Wu J, Gauderman WJ, Rappaport E, Millstein J, et al. 2006 Health effects of the 2003 southern california wildfires on children. Am J Respir Crit Care Med 174:1221–1228. [PubMed: 16946126]

Liu JC, Pereira G, Uhl SA, Bravo MA, Bell ML. 2015 A systematic review of the physical health impacts from non-occupational exposure to wildfire smoke. Environmental research 136:120–132. [PubMed: 25460628]

Morgan G, Sheppeard V, Khalaj B, Ayyar A, Lincoln D, Jalaludin B, et al. 2010 Effects of bushfire smoke on daily mortality and hospital admissions in sydney, australia. Epidemiology 21:47–55. [PubMed: 19907335]

Morrow BH. 1999 Identifying and mapping community vulnerability. Disasters 23:1–18. [PubMed: 10204285]

Mott JA, Meyer P, Mannino D, Redd SC, Smith EM, Gotway-Crawford C, et al. 2002 Wildland forest fire smoke: Health effects and intervention evaluation, hoopa, california, 1999. West J Med 176:157–162. [PubMed: 12016236]

Neidell M 2010 Air quality warnings and outdoor activities: Evidence from southern california using a regression discontinuity design. J Epidemiol Community Health 64:921–926. [PubMed: 19822555]

Olives C, Myerson R, Mokdad AH, Murray CJ, Lim SS. 2013 Prevalence, awareness, treatment, and control of hypertension in united states counties, 2001-2009. PLoS One 8:e60308. [PubMed: 23577099]

Rappold AG, Stone SL, Cascio WE, Neas LM, Kilaru VJ, Carraway MS, et al. 2011 Peat bog wildfire smoke exposure in rural north carolina is associated with cardiopulmonary emergency department visits assessed through syndromic surveillance. Environ Health Perspect 119:1415–1420. [PubMed: 21705297]

Rappold AG, Cascio WE, Kilaru VJ, Stone SL, Neas LM, Devlin RB, et al. 2012 Cardio-respiratory outcomes associated with exposure to wildfire smoke are modified by measures of community health. Environmental Health 11:1. [PubMed: 22236490]

Reid CE, O'Neill MS, Gronlund CJ, Brines SJ, Brown DG, Diez-Roux AV, et al. 2009 Mapping community determinants of heat vulnerability. Environmental health perspectives 117:1730. [PubMed: 20049125]

Reid CE, Brauer M, Johnston F, Jerrett M, Balmes JR, Elliott CT. 2016a Critical review of health impacts of wildfire smoke exposure. Environmental health perspectives.

Reid CE, Jerrett M, Tager IB, Petersen ML, Mann JK, Balmes JR. 2016b Differential respiratory health effects from the 2008 northern california wildfires: A spatiotemporal approach. Environmental Research 150:227–235. [PubMed: 27318255]

Ruckerl R, Hampel R, Breitner S, Cyrys J, Kraus U, Carter J, et al. 2014 Associations between ambient air pollution and blood markers of inflammation and coagulation/fibrinolysis in susceptible populations. Environ Int 70:32–49. [PubMed: 24907704]

Sacks JD, Stanek LW, Luben TJ, Johns DO, Buckley BJ, Brown JS, et al. 2011 Particulate matter-induced health effects: Who is susceptible? Environ Health Perspect 119:446–454. [PubMed: 20961824]

Schneider A, Neas L, Herbst MC, Case M, Williams RW, Cascio W, et al. 2008 Endothelial dysfunction: Associations with exposure to ambient fine particles in diabetic individuals. Environmental health perspectives 116:1666. [PubMed: 19079718]

SERPAS. Prescribed fire smoke management pocket guide. Coalition of Prescribed Fire Councils, Inc

Smoke W 2016 Wildfire smoke a guide for public health officials. (US Environmental Protection Agency; US Forest Service; US Centers for Disease Control and Prevetnion, California Air Resources Board).

Stanek LWS, Jason D ; Dutton Steven J.; Dubois Jean-Jacques B.. 2011 Attributing health effects to apportioned components and sources of particulate matter: An evaluation of collective results. Atmospheric Environment 45:5655–5663.

Wu S-Y, Yarnal B, Fisher A. 2002 Vulnerability of coastal communities to sea-level rise: A case study of cape may county, new jersey, USA. Climate Research 22:255–270.

Yarwood G. RST Yocke M, Whitten GZ 2005 Updates to the carbon bond mechanism: Cb05. US EPA Final Report.

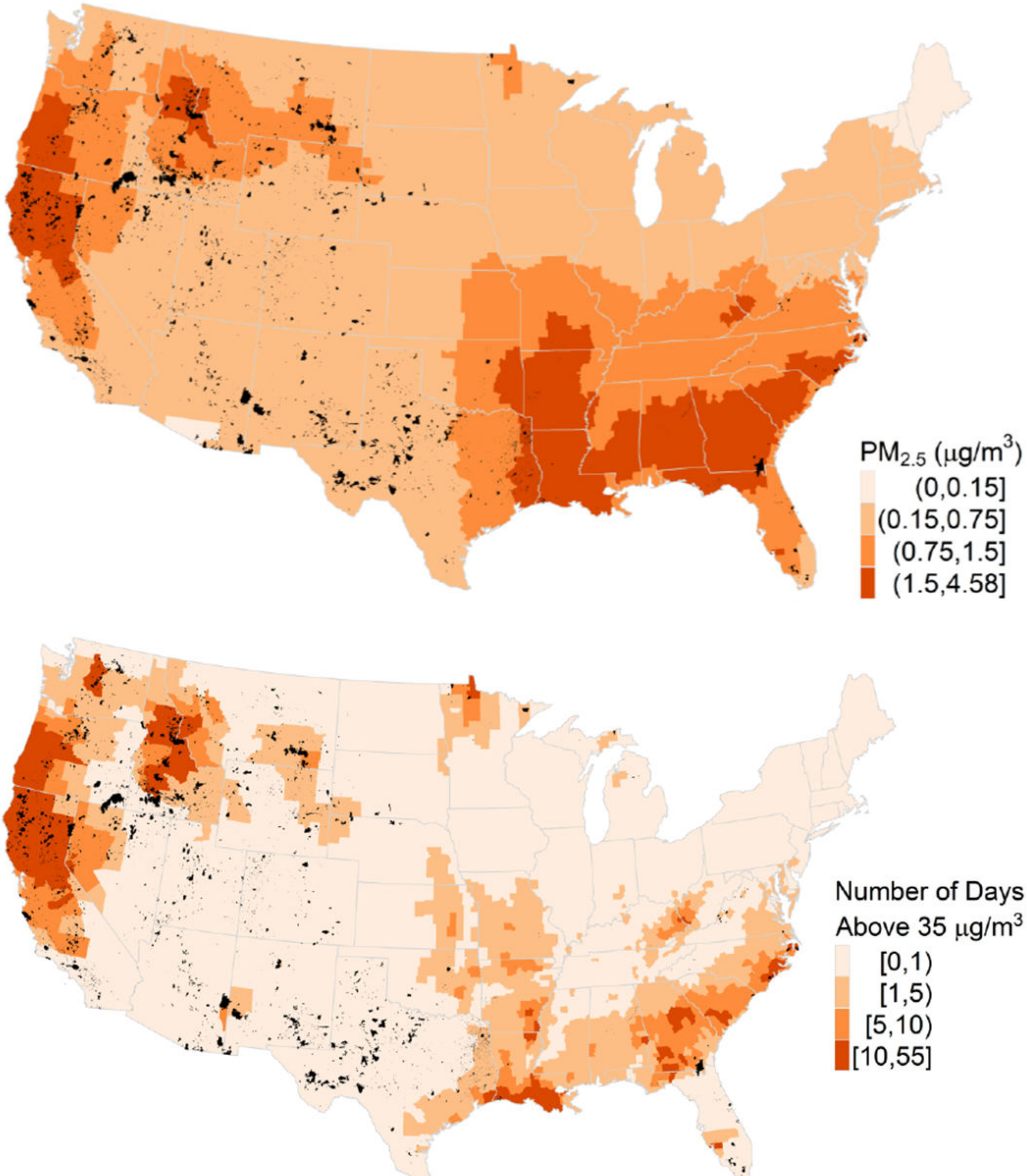
$PM_{2.5}$ (μg/m^3)
(0,0.15]
(0.15,0.75]
(0.75,1.5]
(1.5,4.58]
Number of Days
Above 35 μg/m^3
[0,1)
[1,5)
[5,10)
[10,55]

Figure 1a.

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

EPA Author Manuscript
EPA Author Manuscript

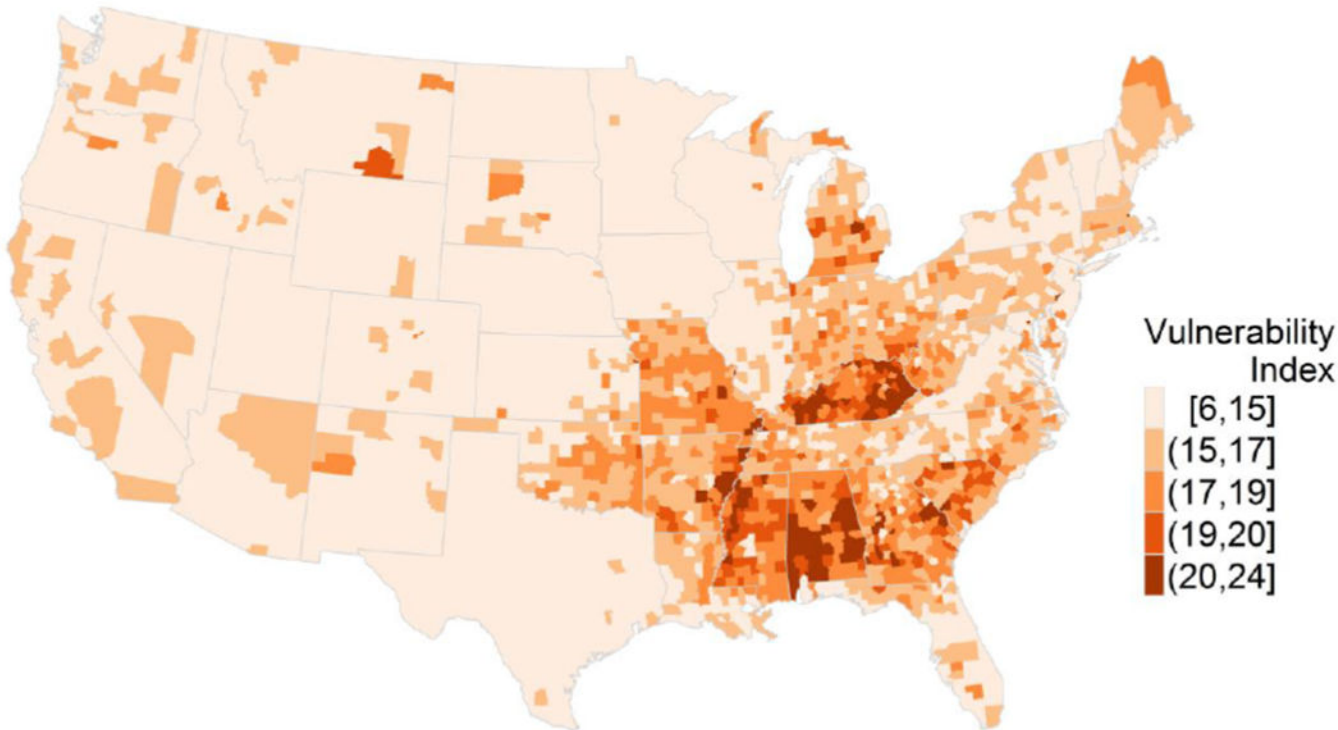

Figure 2.

National map of the Community Vulnerability Index (CVI). The break points 15, 17, 19, and 20 correspond to the 50th, 75th, 90th, and 95th percentile of CVI scores respectively.

EPA Author Manuscript

EPA Author Manuscript

Table 1.

Population size at risk summarized by annual average fire-$PM_{2.5}$ (2008-2012). Population size is given in millions.

$PM_{2.5}$ (μg/m3)	Adult Asthma	Pediatric Asthma	COPD	Hypertensive	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

Table 2.

Population size at risk by Cumulative Vulnerability Index and frequency of unhealthy fire-$PM_{2.5}$ days between 2008 and 2012. Population size is given in millions.

	CVI Bins	[6,15]	(15,17]	(17,19]	(19,20]	(20,24]	Total
	Population	157.7	98.5	33.4	10.6	6.5	306.7
Days with 15 - 35 μg/m3	[1,5)	69.6 (44.1%)	29.9 (30.4%)	8 (24.1%)	2.1 (20.1%)	0.7 (10.5%)	110.4 (36%)
	[5,10)	16.6 (10.5%)	23.5 (23.9%)	8.8 (26.5%)	2.1 (19.9%)	2.13 (32.9%)	53.1 (17.3%)
	[10,76]	39.5 (25%)	22.9 (23.3%)	13.6 (40.6%)	3.8 (35.5%)	2.7 (42.3%)	82.4 (26.9%)
Days with >35 μg/m3	[1,5)	28.5 (18.1%)	14.4 (14.6%)	11 (32.9%)	2.8 (26.8%)	1.4 (22.3%)	58.2 (19%)
	[5,10)	9.9 (6.3%)	5.4 (5.5%)	2.2 (6.7%)	0.8 (7.1%)	0.9 (13.2%)	19.1 (6.2%)
	[10,55]	6.9 (4.4%)	2.8 (2.8%)	0.3 (0.9%)	0.2 (1.6%)	0.1 (2.1%)	10.3 (3.4%)