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Particulate Air Pollution from Wildfires in the Western US under Climate Change

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Abstract

Wildfire can impose a direct impact on human health under climate change. While the potential impacts of climate change on wildfires and resulting air pollution have been studied, it is not known who will be most affected by the growing threat of wildfires. Identifying communities that will be most affected will inform development of fire management strategies and disaster preparedness programs. We estimate levels of fine particulate matter ($PM_{2.5}$) directly attributable to wildfires in 561 western US counties during fire seasons for the present-day (2004-2009) and future (2046-2051), using a fire prediction model and GEOS-Chem, a 3-D global chemical transport model. Future estimates are obtained under a scenario of moderately increasing greenhouse gases by mid-century. We create a new term “Smoke Wave,” defined as ≥2 consecutive days with high wildfire-specific $PM_{2.5}$, to describe episodes of high air pollution from wildfires. We develop an interactive map to demonstrate the counties likely to suffer from future high wildfire pollution events. For 2004-2009, on days exceeding regulatory $PM_{2.5}$ standards, wildfires contributed an average of 71.3% of total $PM_{2.5}$. Under future climate change, we estimate that more than 82 million individuals will experience a 57% and 31% increase in the frequency and intensity, respectively, of Smoke Waves. Northern California, Western Oregon and the Great Plains

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Supplementary information
We prepared one document of supplementary material including four tables and four figures supporting the paper.

are likely to suffer the highest exposure to widlfire smoke in the future. Results point to the potential health impacts of increasing wildfire activity on large numbers of people in a warming climate and the need to establish or modify US wildfire management and evacuation programs in high-risk regions. The study also adds to the growing literature arguing that extreme events in a changing climate could have significant consequences for human health.

Keywords

wildfire; climate change; air pollution; $PM_{2.5}$

1 Introduction

Climate change has increased the frequency, intensity and spread of wildfires (Spracklen et al., 2009). In the coming decades, wildfires are anticipated to pose a growing threat (Interagency Working Group on Climate Change and Health, 2010), especially in the western US, where wildfires are common (Brown et al., 2004; Littell et al., 2009; Westerling et al., 2006). Smoke from wildfires contains large abundances of fine airborne particulate matter ($PM_{2.5}$) (Ammann et al., 2001; Dennis et al., 2002; Lighty et al., 2000; Sapkota et al., 2005). This pollutant is known to harm human health when produced by other sources (e.g., transportation, industry). Chronic exposure to $PM_{2.5}$ can lead to chronical diseases or reduced life expectancy (e.g. Pope et al., 2009; Puett et al., 2009). Acute exposure to $PM_{2.5}$ is associated with various health outcomes, from increased medication use or respiratory symptoms (e.g. Gielen et al., 1997), to hospital admissions or death (e.g. Dominici et al., 2006; Schwartz et al., 1996). Previous research also found that elevated total ambient $PM_{2.5}$ during or after wildfires may be associated with acute health outcomes (Liu et al., 2015).

While wildfires are estimated to contribute ~18% of the total $PM_{2.5}$ atmospheric emissions in the US (Phuleria et al., 2005), the contribution of wildfire smoke to $PM_{2.5}$ during days exceeding regulatory $PM_{2.5}$ standards is not known. Current literature on wildfires and climate change has been limited to estimates of future area burned (Balshi et al., 2009; Flannigan et al., 2005) and changes in the locations and intensity of wildfires (Fried et al., 2004; Krawchuk et al., 2009). A few studies have examined the impacts of increasing wildfire on grid-level particulate matter in the western US (Spracklen et al., 2009; Yue et al., 2013), but no study has quantified which populations will experience increased smoke exposure. It is not clear, for example, how wildfires will affect human health in remote regions of the western US. There is thus a need to understand on relevant spatial scales how levels of $PM_{2.5}$ generated specifically from wildfires affect present-day air quality, how these levels will change in the future under climate change, and which communities are anticipated to be most affected.

Estimating the ambient levels of air pollution that can be attributed specifically to wildfire is challenging, even in the present-day. This difficulty arises because most pollutants, including $PM_{2.5}$, have numerous sources in addition to wildfires. Air pollution data obtained from monitoring stations cannot distinguish between ambient levels of $PM_{2.5}$ from wildfires and $PM_{2.5}$ from other sources. In addition, monitoring data on $PM_{2.5}$ are temporally and spatially sparse. To overcome these difficulties, we used the chemical transport model GEOS-Chem. The $PM_{2.5}$ concentrations from GEOS-Chem can be classified according to emission source and the hourly, gridded results can fill in observational gaps. Simulated particulate matter in GEOS-Chem has been extensively validated against observations, including in the western US (Spracklen et al., 2007; Zhang et al., 2014).

We estimated wildfire-specific $PM_{2.5}$ levels in the western US in the present day (2004-2009) and in the future (2046-2051) under climate change using GEOS-Chem and a newly developed fire prediction model (Interactive Map: [*journal url to be added - see:* http://khanotations.github.io/smoke-map/, *password: smokewavemap15]*. For both the present day and the future, our goals were to: 1) estimate the concentration of wildfire-specific $PM_{2.5}$ and its contribution to total $PM_{2.5}$ and 2) identify communities and populations that are expected to experience high exposure to wildfire-specific $PM_{2.5}$.

2 Methods

The study domain was the western US (561 counties) (Interactive Map), where wildfire is a frequent occurrence (Westerling et al., 2006). To estimate daily wildfire-specific $PM_{2.5}$ levels for the present-day (2004-2009) and the future under climate change (2046-2051) (Intergovernmental Panel on Climate Change (IPCC), 2001), we used GEOS-Chem v9-01-03 driven by assimilated meteorology from the NASA Global Modeling and Assimilation Office (GMAO) Goddard Earth Observing System (GEOS-5) product. The model was run with the nested grid option, which uses the native GEOS-5 horizontal resolution of 0.5°×0.667° over North America. Boundary conditions are obtained from a 2×2.5 global GEOS-Chem simulation. The model includes black carbon and primary organic particles from wildfires, but not secondary organic particles, whose production in fire plumes is highly uncertain (e.g. Wonaschutz et al., 2011). The output has been validated at both daily and seasonal scales using ground-based or aircraft measurements. Our study focuses only on the climate impacts on wildfire activity, and not on the climate impacts on the transport and fate of smoke in the atmosphere. Details about GEOS-Chem spatial resolution and validation can be found in Supplementary Methods 1.

For wildfire emissions, we relied on a fire-prediction model (Yue et al., 2014; Yue et al., 2013). The fire-prediction model was developed by quantifying relationships between observed area burned and key meteorological variables based on an ensemble of 15 climate models simulating the A1B climate scenario. The model does not take ignition into account since wildfire-specific $PM_{2.5}$ is a strong function of area burned, not of ignition type. Here we extended the approach of Yue et al (2013) by estimating area burned at much finer spatial resolution (0.5°×0.667° in the present study vs. 4° × 5° in Spracklen et al (2009) and Yue et al. (2013)). As in Yue et al. (2014), we improved projections of area burned in California by including the effects of elevation, population, fuel load, and the Santa Ana winds. We built on the work of Yue et al. (2014) by using this improved characterization to calculate changes in wildfire-specific $PM_{2.5}$ in California. The results from the fire prediction model were then implemented into GEOS-Chem model. Our use of multi-model climate projections allowed us to identify robust trends in area burned in the future climate and quantify the uncertainty in our projections. Further details on the fire prediction method, including uncertainty analysis, can be found in Supplementary Methods 2.

We estimated present-day and future area burned by applying the fire-prediction model to simulated meteorological fields archived from an ensemble of 15 climate models in the Coupled Model Intercomparison Project (CMIP3) of the IPCC. For 2046-2051, the climate models follow the A1B scenario (Meehl and Stocker, 2007), which projects moderate growth of greenhouse gas emissions, representing a relatively conservative estimate of future warming due to increased greenhouse gases with balanced reliance on fossil and non-fossil fuels (Intergovernmental Panel on Climate Change (IPCC), 2001). The climate models show a large range in their projections of key variables associated with weather conditions conducive to wildfires by the mid-century. We therefore used a multi-model approach: we first calculated the future change in area burned for each model separately and then determined median changes for the model ensemble (Yue et al., 2013). The predicted median increase from present day to future in area burned ranged from 10% to 170%, depending on the ecosystem (Yue et al., 2014; Yue et al., 2013).

Finally, we calculated both non-wildfire and wildfire-specific $PM_{2.5}$ in GEOS-Chem. Following Yue et al. (2013), we used estimates of biomass burned derived from the median area burned (present day and future), together with emission factors for carbonaceous species (Andreae and Merlet, 2001). The transport and lifetime of $PM_{2.5}$ is calculated online in GEOS-Chem using GEOS-5 meteorology. Output from GEOS-Chem consisted of 24-hour averages of $PM_{2.5}$ during the fire season (May-October) for the present day (2004-2009) and at mid-century (2046-2051).

We estimated $PM_{2.5}$ levels using three GEOS-Chem simulations: 1) “all-source present-day $PM_{2.5}$,” defined as total $PM_{2.5}$ levels, including from wildfires and all other sources; 2) “non-fire $PM_{2.5}$,” defined as present-day $PM_{2.5}$ levels excluding the contribution from wildfires; and 3) “all-source future $PM_{2.5}$,” defined as future $PM_{2.5}$ levels from wildfires and all other sources. The “non-fire $PM_{2.5}$" simulation used the same model setup as the “all-source present-day $PM_{2.5}$” simulation, except wildfire emissions were turned off. Non-fire sources for $PM_{2.5}$ in the model include transportation, industry, and power plants (Querol et al., 2004). Future $PM_{2.5}$ levels from non-fire sources could differ significantly from present-day levels due to many factors, including technological changes and climate change (Tai et al., 2012). For this study, in order to isolate the influence of climate change on wildfire $PM_{2.5}$, we modelled future non-fire $PM_{2.5}$ concentrations are the same as in the present day. Calculation of future non-fire $PM_{2.5}$ is outside the scope of this study. Grid-level wildfire-specific $PM_{2.5}$ levels in both the present day and future were therefore calculated by subtracting the “non-fire $PM_{2.5}$” concentrations from the “all-source” $PM_{2.5}$ concentrations. Using this method, a small portion (~2%) of wildfire-specific $PM_{2.5}$ concentrations were negative and were set to zero. Wildfire-specific $PM_{2.5}$ was zero on days when no smoke traversed a given grid cell. Daily county-level wildfire-specific $PM_{2.5}$ levels were estimated as weighted averages from gridded exposure estimates using as weights the area of each grid cell within a county. Daily county-level estimates of all-source $PM_{2.5}$ were calculated using the same method. We conducted sensitivity analysis estimating wildfire-specific $PM_{2.5}$

levels in each county for 2004-2009 using population-weighted averaging for 412 counties in 11 complete states in the study domain (Supplementary Table A.2).

To characterize prolonged air pollution episodes from wildfires, we defined the term “smoke wave” as ≥2 consecutive days with wildfire-specific $PM_{2.5}$ $>98^{th}$ quantile of the distribution of daily wildfire-specific $PM_{2.5}$ values in the modeled present-day years, on average across the study area. We emphasize that smoke waves do not define wildfire events; we use this term to characterize the air pollution episodes resulting from one or multiple wildfire events. Based on this definition, we classified each day in each county during the study period as a smoke wave day or non-smoke-wave day. We also defined the length and intensity of a smoke wave as the number of days in the smoke wave and the average levels of wildfire-specific $PM_{2.5}$ during smoke wave days, respectively. We estimated the length of a smoke wave season as the number of days between the first and last smoke wave day in a fire season. Sensitivity analysis included alternate smoke wave definitions for intensity. Similar approaches have been used in studies of heat waves (Anderson and Bell, 2011). Unlike previously applied measures of wildfire-specific $PM_{2.5}$, which focused on seasonal or monthly means (Yue et al., 2014), the smoke wave concept can capture the high concentration, sporadic, and short-lived characteristics of wildfire-specific $PM_{2.5}$. Such characteristics are of great value to epidemiological studies. We estimated and compared smoke wave characteristics for the present day and the future.

We created a Fire Smoke Risk Index (FSRI) for each county for the present day and a separate FSRI for each county for the future. The FSRI combined information on the number of smoke waves per year, average smoke wave intensity, and average smoke wave length (Supplementary Table A.1). FSRI values ranged from 0 to 5, with 0 representing the lowest level (no smoke waves in that county in that time period) and 5 representing the highest level of wildfire-specific $PM_{2.5}$ based on the combined metrics of frequency, intensity, and length of smoke waves.

For the present day and future, we estimated the number of persons residing in each county, using Integrated Climate and Land Use Scenarios (ICLUS v1.3) Population Projections (US Environmental Protection Agency, 2011b) for the A1B scenario. This population projection simulated economic development, population migration, fertility and mortality in the US to estimate future county-level population in the A1B scenario (US Environmental Protection Agency, 2011a). Specifically, for the present day, we estimated the number of persons in each county using the 2005 values, and for future years we used 2050 population projections from ICLUS. To estimate the size of populations for children and the elderly in each county in the future, we combined US Census survey estimates for children (<18 years of age) and the elderly (>64 years of age) in 2005 (US Census, 2005) with nationally representative population growth rates for each age group (US Census National Population Projections, 2012). We also used county-level 2010 Census data to indicate which counties have a high fraction of populations (e.g., by race, poverty, age) that are potentially vulnerable to health effects from $PM_{2.5}$ (Liu et al., 2015).

We created an interactive map visualizing county-level smoke wave characteristics (number of smoke waves per year, length of smoke waves in days, and intensity) and county-level

FSRI values for the present day and under climate change (Interactive Map). The map also ranks counties in each state by total number of smoke waves over the 6-year period, total number of smoke wave days, average length of smoke wave in days, average smoke wave intensity (wildfire-specific $PM_{2.5}$), FSRI for the present day and future, and the difference between future and present-day FSRI values. These features in the map therefore highlight which counties experienced the highest wildfire-specific $PM_{2.5}$ (as indicated by smoke wave characteristics and FSRI) in the present day and the future, regardless of population. The map also includes county-level population size and population density for the present day and the future. This feature of the map can be used to identify counties suffering the highest exposure to wildfire pollution based on both exposure to wildfire-specific $PM_{2.5}$ and number of people affected. The general public and policy makers can use this map to examine the present and future fire smoke exposure risk in states and counties of interest.

3 Results

Wildfires as a source of $PM_{2.5}$ in the present day

In western US counties during wildfire seasons in the years 2004-2009, we found that wildfires are an important source of total ambient $PM_{2.5}$. Wildfire contributed on average 12.0% of total daily $PM_{2.5}$ in the 561 counties (Figure 1). On days with total $PM_{2.5}$ exceeding regulatory standards for daily $PM_{2.5}$ ($35 \mu g/m^3$), 71.3% of total $PM_{2.5}$ could be attributed to wildfires, based on an average across counties (Supplementary Figure A.1). On days with total $PM_{2.5}$ exceeding the WHO 24-hour standard for $PM_{2.5}$ ($25 \mu g/m^3$) wildfire contributed 64.2% of total $PM_{2.5}$ (Supplementary Figure A.1) (Krzyzanowski and Cohen, 2008).

Wildfire-specific $PM_{2.5}$ levels under climate change

Under climate change, the average wildfire-specific $PM_{2.5}$ level for the years 2046-2051 was estimated to increase approximately 160%, and the maximum wildfire-specific $PM_{2.5}$ level was estimated to increase by >400% (Supplementary Table A.3, Supplementary Figure A.2, Interactive Map).

Smoke waves and their characteristics in the present day and under climate change

Supplementary Figure A.3(a) shows the number of smoke waves in each county over 6-year periods in the present day and in the future under climate change. Smoke wave characteristics differ by region (Interactive Map). Overall for both the present day and the future analyses, northern California, the Pacific Northwest, and forests in the northern Rocky Mountains experienced more smoke waves than other areas. Smoke waves in these counties also tend to last longer and have higher intensity. These counties are heavily forested with abundant fuel to drive smoke waves. Counties in the northern Rocky Mountains are also strongly affected by smoke waves as they are located downwind of fires in dense forests. Overall, climate change is anticipated to increase the frequency, intensity, and length of smoke waves (Table 1, Supplementary Figure A.3). We estimated that the frequency (number of smoke waves/year) will increase from an average across counties of 0.98 smoke waves/year (range 0-4.00/year) in the present day to 1.53/year (0-4.83/year) under climate change in the 2050s. Twenty counties free from smoke waves in the present day are anticipated to experience at least one smoke wave in the future 6-year period under climate change. The average smoke wave intensity (wildfire-specific $PM_{2.5}$ level) is expected to increase an average 30.8% and the length of the smoke wave season is estimated to increase by an average of 15 days. Increases in smoke wave frequency, intensity, length, and length of smoke wave season in the future compared with these of the present day are all statistically significant ($p<0.01$).

The estimated changes in smoke wave characteristics related to climate change appeared spatially heterogeneous (Interactive Map). Among the 561 counties, 55.6% (312 counties) are anticipated to face more intense smoke waves in the future, 19.3% to have less intense smoke waves, and 25.1% to have no change in intensity. We estimated that most counties in the forests of the northern Rocky Mountains and coastal counties will experience a 10-40 $\mu g/m^3$ increase in smoke wave intensity (wildfire-specific $PM_{2.5}$) under climate change, while eastern Rocky Mountains counties will have less intense smoke waves (Figure 2a). More than 40% of counties are anticipated to have longer smoke waves under climate change (Figure 2b). Counties in the Rocky Mountains are more likely to have prolonged smoke waves under climate change compared to the present day. The 20 counties with fewer future smoke waves were primarily located in northern California and northern Nevada. More than 60% of counties are anticipated to face more smoke wave days under climate change (Figure 2c), 6.8% to have fewer smoke wave days, and 32.2% to have no change. The change in the number of smoke wave days and change in number of smoke waves (Figures 2c and 2d) had similar spatial distributions. Although we estimated that a small number (6.8%) of counties will have fewer smoke wave days under climate change, the future smoke waves were generally estimated to have higher average intensity. We estimated that more than 62.5% of counties, mainly in northern Rocky Mountains, Colorado, and southern California, will face extended fire seasons, by as much as 69.5 days (Figure 2e).

Fire Smoke Risk Index (FSRI) in the present day and under climate change

FSRI was designed to summarize overall wildfire risk based on duration, intensity, and frequency of smoke waves. The percent of counties at each level of the FSRI are shown in Supplementary Table A.4 for the present day and in the future under climate change. We estimated that the number of counties with the highest wildfire smoke risk (FSRI of 5) will increase from 22 (3.9% of 561 counties), in the present day, mostly in coastal Oregon and coastal northern California, to 97 (17.3% of 561 counties) under climate change, expanding to western Oregon, northwestern California, Idaho and western Montana (Figure 3, Interactive Map). These maps also highlight counties with children, elderly, or those living in poverty comprising more than 25% of the population, and counties with populations that are more than 50% non-white. Of the 137 counties with FSRI of 0 in the present day, we estimated that 20 counties will face at least one smoke wave in the future (FSRI ≥1), primarily in southwestern Nevada, eastern Utah, and northern New Mexico. The regions estimated to suffer the highest increase in wildfire smoke risk are central Colorado, southeastern Idaho, southern Montana, and eastern Washington (Supplementary Figure A.4, Interactive Map).

Number of individuals expected to experience smoke wave under climate change

We estimated that approximately 57 million people were affected by at least one smoke wave during in the study region for the present-day 6-year period (2004-2009). In the future (2046-2051), with climate change as modeled under the A1B scenario and with population growth, more than 82 million people are likely to be affected by at least one smoke wave, an increase of 43.9%. The changes in smoke waves, combined with demographic trends, are anticipated to result in 7 million more children and 5.7 million more elderly people affected by smoke waves under climate change compared with the present day (Supplementary Table A.5).

4 Discussion

To our knowledge, this is the first study to estimate daily ambient levels of wildfire-specific $PM_{2.5}$ at the county scale across the western US and to map the frequency and intensity of wildfire-$PM_{2.5}$ episodes (smoke waves) in the present day and in the future under climate change. We introduced the concept of a smoke wave, defined as ≥2 consecutive days with high levels of wildfire-specific $PM_{2.5}$, which uniquely summarizes the frequency, duration, and intensity of air pollution from wildfires. Our study demonstrated that smoke waves are likely to be longer, more intense, and more frequent under climate change, which raises health, ecological, and economic concerns.

Wildfire-specific $PM_{2.5}$ can impose economic burdens by impacting medical care, tourism, and property values, and costs of forest suppression. It can cause ecological damage and also affects visibility, which can impact transportation, aesthetics, and tourism (Hystad and Keller, 2008). Increased wildfire activity damages property and raises suppression and recovery costs (Flannigan et al., 2009), creating new challenges for wildfire management. Suppressing a large fire can require thousands of firefighters (Dombeck et al., 2004). During 2000-2002, US federal agencies spent over a billion dollars to suppress wildfires, and this expense has grown over time due to increased burned areas (Dombeck et al., 2004).

We found that wildfires are a major contributor to ambient $PM_{2.5}$ levels in the Western US, especially on days when ambient $PM_{2.5}$ levels exceeded the NAAQ standard or the WHO standard. A review paper summarized previous studies on wildfire-related air pollution and health and found that $PM_{2.5}$ levels exceeded the NAAQ standard during or after wildfires in 12 out of 14 studies that reported $PM_{2.5}$ levels pre-, during, or post-wildfires (Liu et al., 2015). Our findings leveraged the results of previous literature and indicated a potential human health concern in affected communities in the future under climate change. In addition, our findings suggested that more fire suppression may be needed in the 2050s in order to lower air pollution levels to reduce the potential health concern.

Smoke waves are likely to be especially deleterious to human health (Delfino et al., 2002; Hänninen et al., 2009; Moore et al., 2006) because of exposure to very high levels of $PM_{2.5}$. We also estimated that substantial populations of elderly, children, people living in poverty, and non-white individuals will be exposed to smoke waves; these populations may be the most vulnerable to the health risks related to exposure to $PM_{2.5}$ from wildfires. Our results, which identify regions and populations of high risk, can aid decision makers in wildfire management, public health, and climate change policies to mitigate the occurrence and associated consequences of wildfires.

Our use of GEOS-Chem produces total $PM_{2.5}$ data with better temporal resolution and spatial coverage than monitoring data. Our wildfire-specific $PM_{2.5}$ estimates have finer spatial resolution than previous wildfire prediction models and incorporate improved predictions of area burned for California. The finer resolution used here leads to more accurate representation of the location of emissions and yields $PM_{2.5}$ exposure estimates at the county level, which are useful for policy purposes. The improved predictions in California account for the irregular terrain in that state and the influence of the Santa Ana winds, factors which are typically not well captured by climate models (Yue et al., 2014). Previous studies linking climate change and wildfire activity in the western US focused on trends in monthly or seasonal mean area burned or carbonaceous aerosol (Spracklen et al., 2009; Yue et al., 2013). In contrast, our study focused on daily $PM_{2.5}$, a metric relevant to human health as documented by numerous epidemiological studies and literature reviews (e.g. Dominici et al., 2006; Liu et al., 2015). Our previous study found that intense smoke waves are associated with a 7.2% (95% confidence interval: 0.25%, 14.63%) increase in respiratory admissions among people ≥65 years in the Western US (Liu et al., 2016). By providing relevant information to the potential health consequences of future wildfires, our study can guide decision makers in developing policy responses and protecting population health.

There are several limitations in this study. Our results may underestimate wildfire-specific $PM_{2.5}$ under climate change, as our fire prediction model did not incorporate the possibility that fire suppression in the western US might lead to an unnatural accumulation of forests, thereby providing fuel that may increase the probability of very large fires (Marlon et al., 2012; Schoennagel et al., 2004). The model also did not include changes in vegetation due to climate change or to CO_2 fertilization, which may result in faster growth of vegetation. Future work could also estimate levels of wildfire-related ozone and non-wildfire $PM_{2.5}$ to develop a comprehensive assessment of wildfire's impact on air pollution. Work is needed in other regions that experience frequent wildfire events, such as the Canadian boreal forests, the Brazilian Amazon, and Southeast Asia (Liu et al., 2015). Future investigations are needed to estimate the health, ecologic, and economic consequences of wildfire smoke using source-specific air pollutant data, and to develop policy frameworks in response to these consequences, especially given anticipated increases in wildfire activity under climate change.

Wildfires are anticipated to be an increasingly important source of $PM_{2.5}$ in the Western US under climate change. While other sources of $PM_{2.5}$, such as from vehicles or power plants, can be regulated, $PM_{2.5}$ from extreme events such as wildfires cannot be fully controlled. Therefore, $PM_{2.5}$ from wildfires may not only impose considerate acute exposure, but also play an important role in population's chronic exposure under climate change. Future policy-making and wildfire management should consider both acute and chronic impacts of air pollution from wildfires. Communities identified in this study as at risk of suffering intense wildfires in the future would benefit from the establishment or modification of public health programs and evacuation plans in response to climate change. Projections of wildfire-specific pollution could aid development of forest management programs, climate change adaptation plans, and community preparedness. Our results will advance understanding of the impacts of climate change on wildfire, and aid in the design of early warning systems, fire suppression policies, and public health programs.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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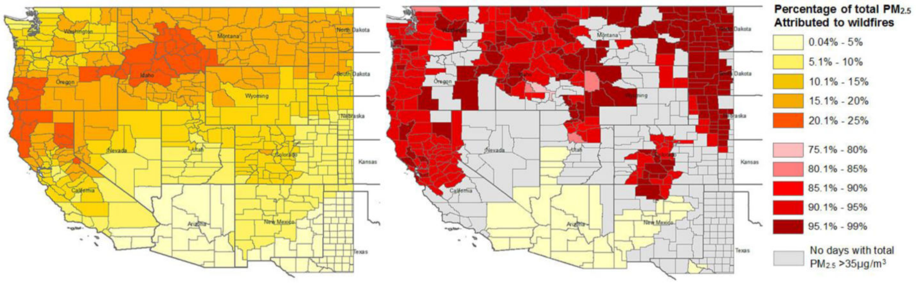

Figure 1.

Fraction of $PM_{2.5}$ attributable to wildfires by county during fire seasons (May-October) in the present day (2004-2009), on all days (left panel), and on the subset of days that had total $PM_{2.5} > 35 \mu g/m^3$ (The National Ambient Air Quality Standards (NAAQS) threshold; right panel).

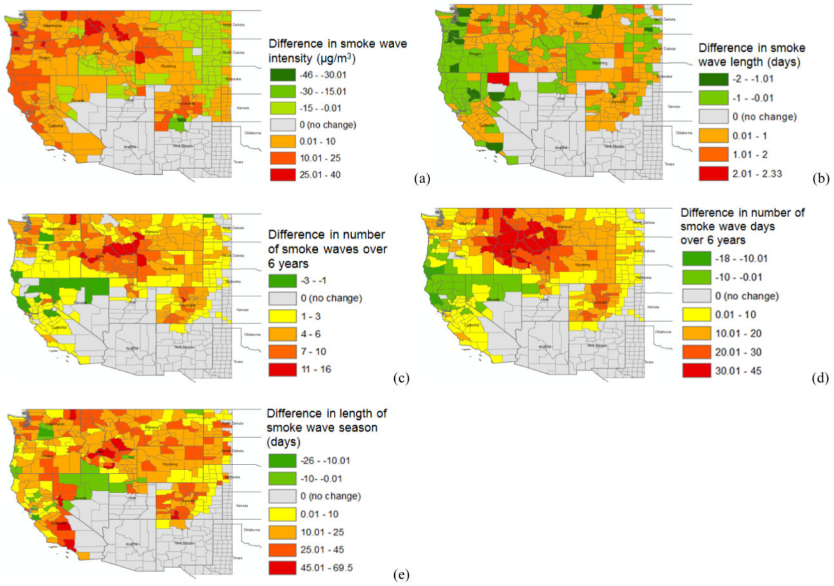

Figure 2.

Difference in smoke wave characteristics in the future (2046-2051) under climate change and in the present day (2004-2009) during fire seasons (May-October). Positive changes (in warm colors) indicate increases under climate change, while negative changes (in cool colors) indicate decreases under climate change. Panels show (a) average intensity of smoke waves; (b) average length of smoke waves; (c) total number of smoke waves during a 6-year period; (d) total number of smoke wave days during the 6-year period; and (e) average length of the smoke wave season.

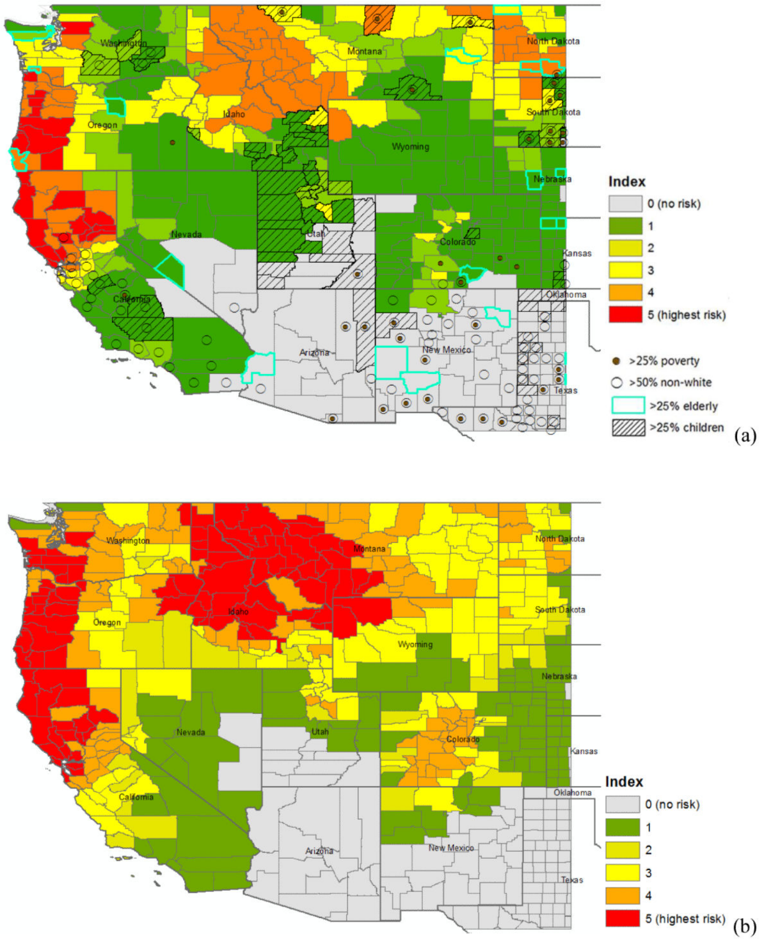

Figure 3.

Fire Smoke Risk Index (FSRI) during fire seasons (May-October). Panel (a) is for present day (2004-2009) and panel (b) is for future (2046-2051) under climate change.

Table 1

Summary Statistics for Present Day (2004-2009) and Future (2046-2051) Smoke Waves during Fire Seasons (May-October).

	No. counties with SW (N=561)	SW days/year	SWs/year	SW intensity (μg/m^3)	SW length (days)	Length of SW season (days)
Present	424	3.13 (2.93)	0.98 (0.8)	15.9 (6.6)	2.95 (0.7)	14.0 (13.4)
Future	440	4.91 (3.45)	1.53 (1.0)	20.8 (8.9)	3.08 (0.5)	29.0 (18.2)

Data are presented as average across counties (standard deviation).