Large mitigation potential of smoke $PM_{2.5}$ in the US from human-ignited fires

Therese S. Carter[1], Colette L. Heald[1,2], and Noelle E. Selin[2,3]

[1]Civil and Environmental Engineering Department, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[2]Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[3]Institute for Data, Systems, and Society, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

Correspondence: Therese S. Carter (tscarter@mit.edu) and Colette L. Heald (heald@mit.edu)

Abstract: Increasing fire activity and the associated degradation in air quality in the United States has been indirectly linked to human activity via climate change. In addition, direct attribution of fires to human activities may provide opportunities for near term smoke mitigation. We analyze how fires associated with human ignitions (agricultural fires and human-initiated wildfires) impact fire particulate matter under 2.5 microns ($PM_{2.5}$) concentrations in the contiguous United States (CONUS) from 2003 to 2018. We find that these agricultural and human-initiated wildfires dominate fire $PM_{2.5}$ in both a high fire and human ignition year (2018) and low fire and human ignition year (2003). Smoke from these human levers also makes meaningful contributions to total $PM_{2.5}$ (~5-10% in 2003 and 2018, respectively). Across CONUS, these two human ignition processes account for more than 80% of the population-weighted exposure and premature deaths associated with fire $PM_{2.5}$. These findings indicate that a large portion of the smoke exposure and impacts in CONUS are from fires ignited by human activities with large mitigation potential that could be the focus of future management choices and policymaking.

1. Introduction

Fires threaten human lives, infrastructure, and ecosystems and are also a major cause of air quality degradation. Concentrations of particulate matter under 2.5 microns ($PM_{2.5}$) from fires alone can exceed both daily and annual air quality standards from the Environmental Protection Agency (EPA) and World Health Organization (WHO) (Carter et al., 2020; Pai et al., 2022; David et al., 2021). These high levels of fire $PM_{2.5}$ can negatively impact health in many ways (respiratory infections, asthma, lung cancer, and heart disease) (Chen et al., 2021; Pope and Dockery, 2006; Brook et al., 2010; Liu et al., 2015; Reid et al., 2016; Williamson et al., 2016). Exposure to fire $PM_{2.5}$ can lead to tens of thousands of pre-mature deaths each year in the contiguous United States (CONUS) (Ford et al., 2018). Fire $PM_{2.5}$ has also been shown to be more toxic (quantified through respiratory hospitalizations) than $PM_{2.5}$ from other sources (Aguilera et al., 2021). The economic damages of wildfires and their associated health impacts can be enormous; Wang et al. (2021) estimate that the 2018 California wildfires incurred \$32.2 billion in smoke-related health costs and \$116.3 billion in other losses.

As fire activity intensifies under climate change (Westerling et al., 2006; Westerling, 2016; Abatzoglou and Williams, 2016), smoke is expected to play a larger role in the degradation of air quality and may overwhelm improvements from decreasing anthropogenic emissions (Fuzzi et al., 2015; Ford et al., 2018; Val Martin et al., 2015; Sarangi et al., 2022) as seen in western US (Kalashnikov et al., 2022). While the effects of climate change on fires are indirectly driven by humans, attributing the proximate causes of wildfires (e.g., human versus natural ignition) can enable the characterization of the potential for near term smoke mitigation. However, assessing to what degree human activity is responsible for fire $PM_{2.5}$ concentrations, especially near population centers, can be complicated because humans impact so many different parts of the fire system, and because separating the natural versus anthropogenic drivers is difficult (Fuzzi et al., 2015; Pai et al., 2022).

Humans dominate fire ignitions in several large fire regions in the US (Balch et al., 2017) and Africa (Andela et al., 2017); depending on the region, this includes both wildfires and agricultural and prescribed burns. Human ignitions are often correlated with railroads and agricultural activities (Fusco et al., 2016), and these human-started wildfires result in more extreme fire behavior and ecosystem impacts (Hantson et al., 2022). Agricultural expansion and intensification has fragmented natural landscapes (Marlon et al., 2008) leading to globally decreasing burned area (Andela et al., 2017). Over the last 40 years, ~91% of the world's population has been living at the wildland-urban interface (WUI), and this number is expected to increase toward the end of the century (Knorr et al., 2016) with associated implications for ignitions and exposure. In the US specifically, the WUI accounts for 9% of total land area (Radeloff et al., 2018) with this percentage projected to double by 2030, mostly in the West (Theobald and Romme, 2007). The 2018 California fires provide a poignant example of the associated impacts of smoke-diminished air quality and of increasing threats to life and property (Wang et al., 2021). Wu et al., (2022) highlighted that human actions (ignitions and suppression) can be at least as important as climate change in modulating future fire activity. While human impacts on land use and suppression have also impacted fire susceptibility, spread, and duration, the direct impacts of human-ignited fires on smoke exposure have not been previously quantified.

2. Data and methods

We quantify the smoke resulting from agricultural fires and human-initiated wildfires, both of which have clear associated management potential (Syphard and Keeley, 2015). We refer to these two fire types collectively as human-ignited fires. We use the Global Fire Emissions Database version 4 with small fires (GFED4s) to specify agricultural fire emissions and the US Forest Service Fire Program Analysis-Fire Occurrence Database (FPA-FOD) to classify wildfires in GFED4s by human vs. natural ignition. We do not explore prescribed fires because they are not delineated in these two datasets. We use the GEOS-Chem chemical transport model to quantify the effects of human-ignited fires on downstream smoke exposure in CONUS.

2.1 Agricultural versus non-agricultural dry matter burned

To analyze the contribution of agricultural fires to smoke, we use the underlying dry matter (DM) burned from agricultural versus not agricultural fires in GFED4s from 1997 to 2018 at 0.25° x 0.25° spatial resolution (Fig. S1). Agricultural fires are prominent in the Central Valley in California and in the southeastern US. The interannual variability of agricultural fires is lowest in these two regions, and highest across the West and northern part of the Northeast where there is less agriculture (Fig. S2).

2.2 US Forest Service Fire Program Analysis-Fire Occurrence Database (FPA-FOD)

To understand how human ignitions of wildfires have changed over time, we explore the FPA-FOD (Short, 2021), which includes information on 2.17 million geo-referenced wildfire records in the US from 1992 – 2018 in a spatial database. See Balch et al., (2017) for an extensive characterization of this dataset. At a minimum, this database includes discovery, and often containment, dates; final fire size; a point location; and a general cause classification (Human, Natural, or Missing data/not specified/undetermined). Following Balch et al. (2017), we exclude fires whose ignition classification is missing (8% of dataset). The human ignition categories are disaggregated in Fig. S3. Prescribed fires for wildland management are not explicitly included in either the FPA-FOD nor GFED4s. Arson decreases from 24% to 14% of human ignitions from 1992 to 2018 while the contribution of debris and open burning increases from 27% to 45%. While the size of all fires varies both regionally and annually, naturally ignited fires are generally larger in size (Fig. S4), particularly in Alaska.

Figure S5 shows that, with substantial year-to-year variability, the percentage of wildfires that are human initiated has increased by 0.3% ± 0.2% per year from 1992 to 2018. Concurrently, primary particle fire (BC and OC) emissions increased in CONUS from 1992 to 2018 (Fig. S5). We attribute daily GFED4s DM for wildfires in each grid cell to the corresponding fire ignition type in the FPA-FOD to estimate emissions from human-initiated wildfires. The FPA-FOD database includes an ignition source for 90% of GFED4s DM in 2018 and 83% in 2003; our resulting attributed fire emissions are therefore a low-end estimate of fire emissions in CONUS. In addition, the FPA-FOD database includes some fires that are not present in the GFED4s inventory. These missing small fires are generally localized events, which previous literature has shown GFED4s underestimates (Giglio et al., 2013; van der Werf et al., 2017; Stockwell et al., 2022). We select two years to span the potential human-initiated wildfire smoke source: Figure 1 shows that 2018 is both a high fire emissions and high human initiated year while 2003 is low for both. Human-initiated wildfires show low interannual variability across the Southeast and high variability across the West, consistent with their episodic nature.

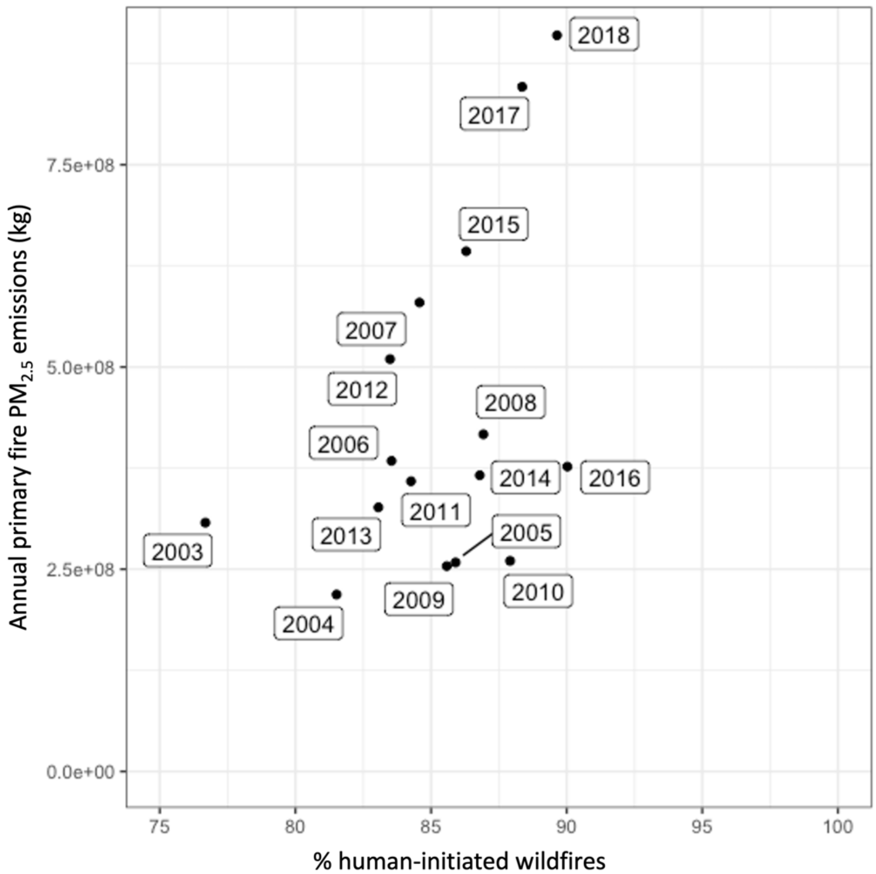

Figure 1: Scatter plot of CONUS annual primary $PM_{2.5}$ (BC and OC) fire emissions against the percentage of wildfires initiated by humans for each year from 2003 to 2018 based on GFED4s and the FPA-FOD.

2.3 The GEOS-Chem model

We use a chemical transport model, GEOS-Chem version 13.3.3, to simulate $PM_{2.5}$ globally at a horizontal grid resolution of 2x2.5° and to generate boundary conditions for nested simulations over North America at 0.5x0. 625°. The model is driven by MERRA2 meteorology. See the SI "Model Configuration" for more details. The aerosol simulation includes primary (emitted) species: black carbon (BC) (Park et al., 2003), organic carbon (OC), sea salt (Jaeglé et al., 2011), and mineral dust (Fairlie, et al., 2007; Ridley et al., 2012), as well as secondary species formed from gas-phase precursors: sulfate, nitrate, and ammonium (Park et al., 2004) and secondary organic aerosol (SOA), using the simple scheme (Pai et al., 2020). Total organic aerosol mass is calculated using an organic matter to OC ratio of 1.4 for hydrophobic and 2.1 for hydrophilic. See SI for more details.

Fire emissions are from GFED4s where emission factors for particles and gases are applied to the underlying DM burned. Anthropogenic emissions are from the global CEDS inventory (McDuffie et al., 2020). Biogenic emissions are calculated online using the MEGANv2.1 framework (Guenther et al., 2012).

We perform a series of simulations zeroing out fire emissions over the United States (all fire, agricultural fire, and human-initiated wildfire), and attribute fire smoke by differencing these simulations with a baseline model. We estimate model $PM_{2.5}$ as follows:

$$PM_{2.5} = (NH_4 + NO_3 + SO_4) * 1.10 + BCPI + BCPO + \left(OCPO + (OCPI * 1.05)\right) * 2.1 + DST1 + DST2 * 0.30 + SALA * 1.86 + SOA * 1.05,$$

Where BCPI is hydrophilic BC, BCPO is hydrophobic BC, OCPO is hydrophobic organic aerosol (OA), OCPI is hydrophilic OA, DST1 is dust aerosol with r_{eff} = 0.7 microns, DST2 is dust with r_{eff} = 1.4 microns, and SALA is fine sea salt. At 35% relative humidity, the growth factor for NH_4, NO_3, and SO_4 is 1.10, for OCPI and SOA 1.05, and for SALA 1.86. We compare simulated $PM_{2.5}$ with surface observations from the IMPROVE network (Chow et al., 2007) and find that, in both years, the model matches observations well, particularly the medians, with a small high bias (normalized mean bias equals 19% in 2003 and 14% in 2018) (Fig. S6).

To calculate population-weighted $PM_{2.5}$ concentrations, we use year-specific population estimates from the Gridded Population of the World (Gridded Population of the World (GPW), v4 | SEDAC, 2022). Details on the health impact calculation follow the methodology of Vohra et al., (2021) with the concentration response function (CRF) from a recent meta-analysis of the association between mortality and PM2.5 (Vodonos et al., 2018) and are provided in the SI in addition to the 95% confidence intervals (CI).

3. Results and discussion

To understand the impact of human-ignited fires on regional daily $PM_{2.5}$ concentrations, we first explore the southeastern US where agricultural fires are important and northern California where human-initiated wildfires were dominant in 2018 (humans started 90% of fires that year per the FPA-FOD). Figure 2 shows that simulated total $PM_{2.5}$ concentrations (black) are much lower in the southeastern US (max ~ 62 μg m^{-3}) than in northern CA where daily $PM_{2.5}$ concentrations reach nearly 5000 μg m^{-3}, far higher than the EPA daily air quality standard of 35 μg m^{-3} (indicated by the grey box). Although the southeastern US is the region where agricultural fires are most prevalent spatially, agricultural fire $PM_{2.5}$ (tan) is low (max = 20 μg m^{-3}); however, when added to other sources, it does contribute to unhealthy air quality (responsible for ~0.03% of grid box days with daily exceedances in the region in 2018). In the southeast, fires (red) only occasionally comprise the majority of total $PM_{2.5}$ while in northern CA fires, human-initiated wildfires (dark blue), account for all the simulated exceedances of the EPA daily air quality standard. These northern CA exceedances are driven by large human-initiated wildfires in July to September (e.g., the Mendocino Complex Fire) and in November (e.g., by Camp Fire). In 2018, human-initiated wildfire $PM_{2.5}$ by itself leads to exceedances in more than 4% of all grid box days in northern CA with an additional 7% of grid box days exceeding the daily standard when human-started wildfire $PM_{2.5}$ is combined with other sources (Fig. S7). Other regions, including southern California and the Northwest experience some daily exceedances due to human-initiated wildfires in both 2003 and 2018, while in other regions (e.g., the northeast, Midwest, and southwest) human-initiated wildfires contribute negligibly to daily $PM_{2.5}$ exceedances.

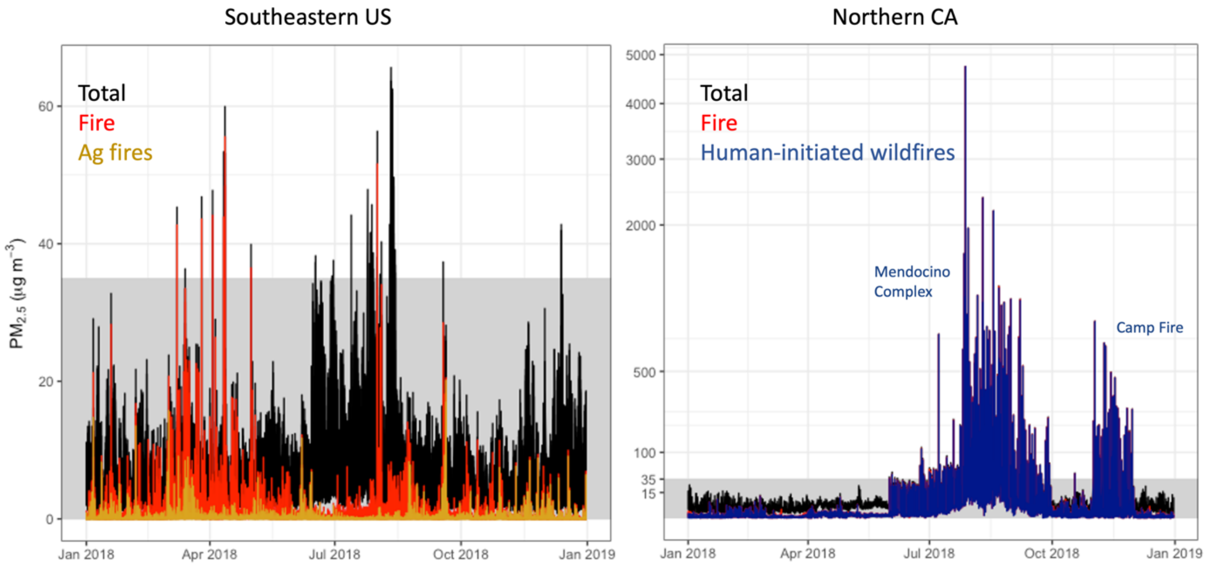

Figure 2: Daily $PM_{2.5}$ in the southeastern US (left) and Northern California) in 2018. Total $PM_{2.5}$ is in black, fire $PM_{2.5}$ in red, agricultural fire $PM_{2.5}$ in tan, and human-initiated wildfire $PM_{2.5}$ in dark blue. A grey shaded bar up to 35 $\mu g\ m^{-3}$ indicates the daily $PM_{2.5}$ standard set by the EPA.

Figure 3 shows annual mean $PM_{2.5}$ concentrations from agricultural fires and human-initiated wildfires across CONUS in both years. We note that simulated fire $PM_{2.5}$ largely (~80-85%) consists of emitted carbonaceous aerosol, with modest contributions from secondary species. Agricultural fires contribute substantially to simulated annual mean fire $PM_{2.5}$ in some US regions (in contrast to the daily comparison), including the Central Valley of California and along the Mississippi River. Maximum annual mean concentrations reach ~2 $\mu g\ m^{-3}$, accounting for more than a third of the $PM_{2.5}$ from fires in both years (Table S1 and Fig. S8). However, their contribution to total annual mean $PM_{2.5}$ across CONUS is much smaller (<1%) (Table S1) than that from human-started wildfires. While 2003 and 2018 show similar spatial patterns, agricultural fire $PM_{2.5}$ concentrations are higher in the southeast in 2003 than in 2018 and in the west in 2018 than in 2003.

$PM_{2.5}$ concentrations from human-initiated wildfires in CONUS dominate fire $PM_{2.5}$, accounting for more than 67% of annual mean fire $PM_{2.5}$ in both years. These concentrations range from 0.3 $\mu g\ m^{-3}$ to 20 $\mu g\ m^{-3}$ across CONUS in 2003 and 0.6 $\mu g\ m^{-3}$ to 99 $\mu g\ m^{-3}$ in 2018 (Fig. 3 and Table S1). We find that human-initiated wildfires are responsible for most fire $PM_{2.5}$ across all of CONUS and that agricultural fires are more significant in the Midwest and Southeast than elsewhere (Fig. S8). The highest human-initiated wildfire $PM_{2.5}$ concentrations in 2003 are centered in Oregon, while in 2018, very high concentrations are simulated across northern California (Fig. 3). However, the footprint of human-initiated wildfire smoke is distributed beyond these source regions, responsible for ~15% of annual mean $PM_{2.5}$ across much of the intermountain west and 10% across the rest of CONUS in both years (Fig. S8). In 2003 and 2018, human-ignited wildfire smoke (agricultural fires and human-initiated wildfires combined) is responsible for 3 and 7%, respectively, of average annual total $PM_{2.5}$ across CONUS (Table S1).

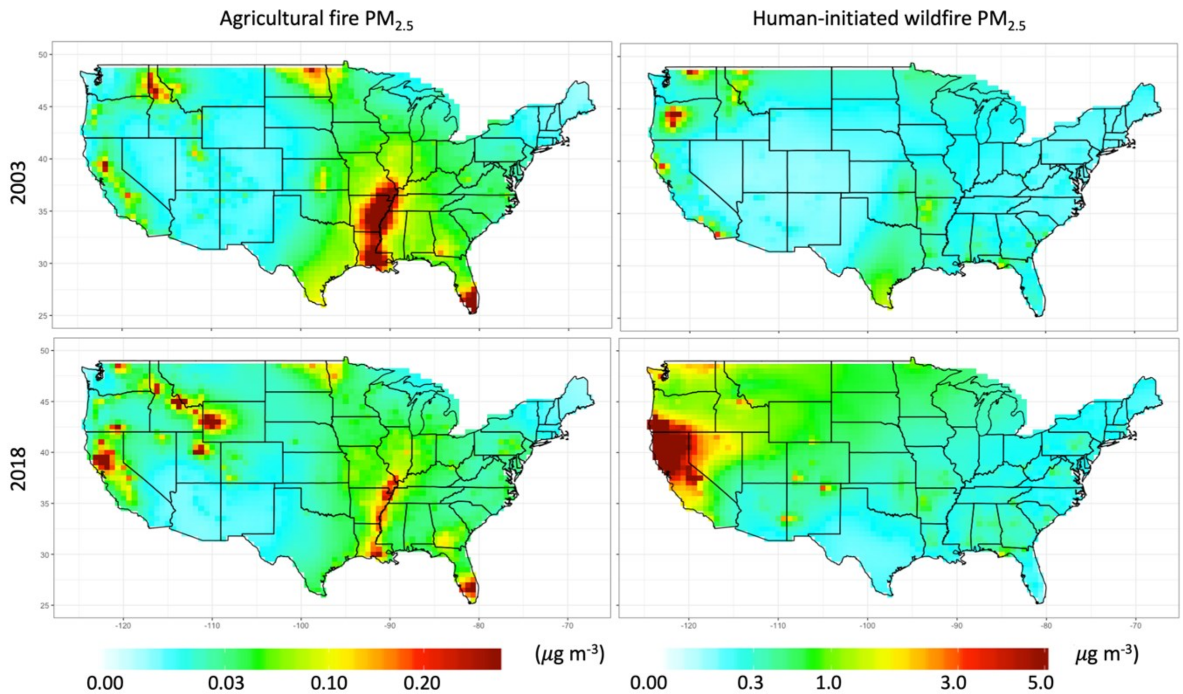

Figure 3: Annual mean surface concentration of agricultural fire (left) and human-initiated wildfire (right) $PM_{2.5}$ in 2003 (top) and 2018 (bottom). Note the different scales.

Figure 4: Annual average population-weighted $PM_{2.5}$ exposure in eight regions (color on map corresponds to title in panels) for 2003 (a low fire emissions and human initiation year [low]) and for 2018 (a high fire emissions and human ignition year [high]). Non-fire $PM_{2.5}$ is shown in black, lighting-initiated wildfire $PM_{2.5}$ in orange, agricultural fire $PM_{2.5}$ in light red, and human-started wildfire $PM_{2.5}$ in dark red. A horizontal bar at 12 $\mu g\ m^{-3}$ indicates the EPA annual standard. The regional designations are what was used in the Fourth National Climate Assessment.

Figure 4 shows the annual average population-weighted exposure associated with non-fire (black), lightning initiated wildfire (orange), and human-ignited (agricultural (light red) and human-initiated wildfire (dark red)) $PM_{2.5}$ in both 2003 and 2018 regionally in CONUS. Total $PM_{2.5}$ is smaller across all regions from 2003 to 2018 with the largest changes in the Northeast, Southeast, and Midwest, generally reflecting decreasing anthropogenic emissions (Fuzzi et al., 2015). Therefore, fires (variability here represented by 2003 versus 2018) increasingly contribute a larger fraction of $PM_{2.5}$ over time (Fuzzi et al., 2015) (and in California can even fully compensate for anthropogenic decreases per Val Martin et al., (2015)). Smoke exposure from agricultural fires is a negligible component of the regional annual means. Lightning ignited wildfires make an important contribution in the Northwest (where the associated annual mean exposure is ~ ¼ and ½ that of human-ignited $PM_{2.5}$ in 2003 and 2018, respectively) and Northern

Great Plains (where the contribution is roughly comparable to that from human-initiated wildfires in both years; see Table S2). However, exposure in California in 2018 is dominated by $PM_{2.5}$ from human-initiated wildfires (41% of all $PM_{2.5}$). Regions generally see larger contributions from human-ignited fires in 2018 than 2003, with, for example, the percentage of total $PM_{2.5}$ exposure from human-ignited smoke higher in 2018 (41%) relative to 2003 (7%) in California, 13 and 2%, respectively, in the Southwest, and 29 and 10% in the Northwest (Table S2). Smoke exposure can be the result of local fires, or transport from fires upwind. Large upwind contributions, such as experienced by states downstream of the west coast in the Northern Great Plains and Southwest, suggest a more limited potential for local mitigation (Fig S9). More details on each of the underlying components of population-weighted exposure are given in Table S2.

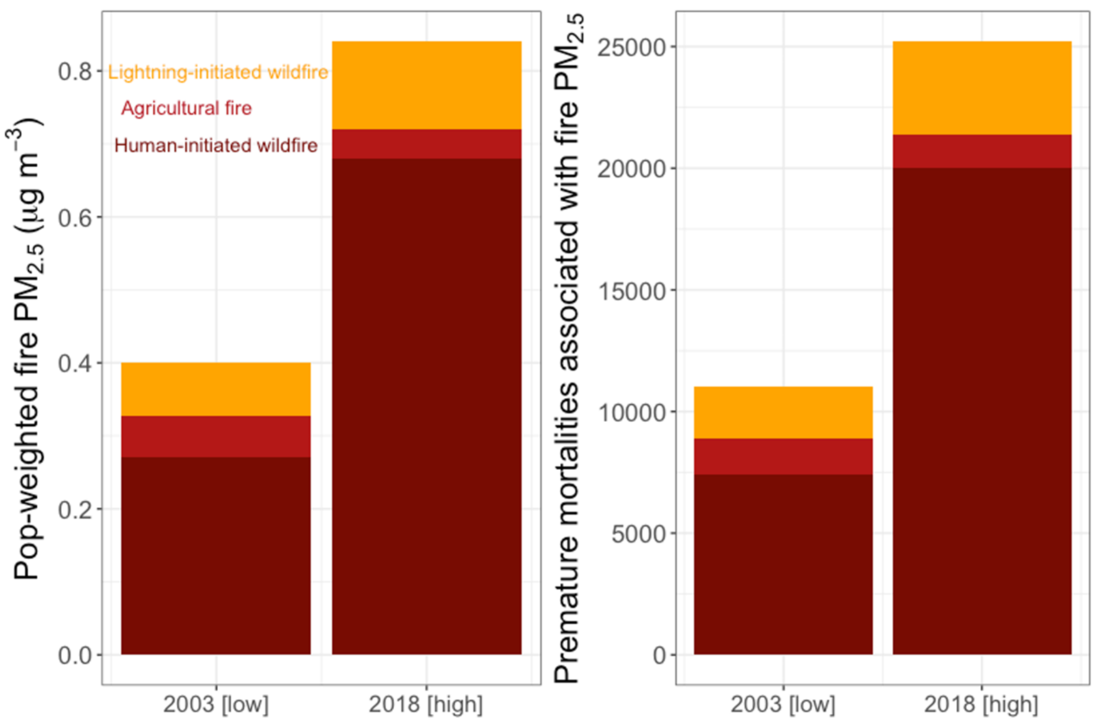

Figure 6: Annual average population-weighted exposure in CONUS from fire-associated $PM_{2.5}$ in 2003 and 2018 (left) and premature mortalities associated with those $PM_{2.5}$ concentrations (right). Human-initiated wildfire $PM_{2.5}$ is in dark red, agricultural $PM_{2.5}$ is in light red, and lightning-ignited wildfire $PM_{2.5}$ is in orange.

Across CONUS, human-ignited fires account for 82% and 86% in 2003 and 2018, respectively, of the simulated population-weighted exposure to fire $PM_{2.5}$ (Fig. 6) (or 83 and 79% of unweighted annual average fire $PM_{2.5}$). This is dominated by human-initiated wildfires (responsible for 68% and 81% of fire-associated exposure). Human-ignited smoke contributes 14% of annual mean total $PM_{2.5}$ exposure across CONUS in 2018 and 6% in 2003. Population-weighted $PM_{2.5}$ exposure associated with agricultural fires (0.057 μg m^{-3}) in 2003 is comparable to that associated with lightning-ignited fires (0.073 μg m^{-3}) and a factor of three lower than lightning-ignited fires in 2018 (Table S2).

Over 80% (81% in 2003 and 85% in 2018) of fire $PM_{2.5}$ -associated premature deaths come from human ignitions (agricultural fires + human-initiated wildfires) in both years (Fig. 6 and Table S3). This number is insensitive to the population change from 2003 to 2018 (i.e., using the 2018 $PM_{2.5}$ concentrations with 2003 population values and distribution gives the same percentage of fire $PM_{2.5}$ exposure from human levers). Agricultural fires have little interannual variability, so they lead to similar premature deaths in both years (1500 in 2003 and 1400 in 2018). We estimate that human-initiated wildfire smoke was responsible for 20,000 premature deaths in 2018 and 7,400 premature deaths in 2003 (Table S3). Other work has attributed similar numbers [17,000 in the year 2000] of premature deaths to fire $PM_{2.5}$ (Ford et al., 2018); we show here that the anthropogenic drivers dominate these premature mortalities.

4. Conclusions

We find that over 80% of smoke in the US is linked to human ignitions (agricultural fires and human-initiated wildfires) over the past two decades. Two health-relevant metrics (the population-weighted annual exposure and premature deaths associated with fire $PM_{2.5}$) are also dominated by these human ignitions. Our results are likely a lower limit because of the known underestimate of small fires with GFED4s and because our attribution of ignition type with the FPA-FOD neglects ~15% of DM in GFED4s. Other pollutants (e.g., O_3) may also be reduced with mitigation of these human levers.

Mitigation of $PM_{2.5}$ exposure from agricultural fire has been extensively studied (e.g., Zhou et al., 2018; Holder et al., 2017), but mitigation approaches for human-initiated wildfires are less well established. For example, state agencies can plan or permit agricultural fires for days where meteorology would minimize health impacts. Lee and Lee, (2018) examine the tradeoffs between firefighting resources (and fire suppression) versus fire ignition prevention efforts in the Republic of Korea, where most fires are anthropogenic, a regime similar to large parts of CONUS, particularly California. They find that the marginal benefit of ignition prevention was larger than that of firefighting helicopters, suggesting that ignition prevention may be more cost effective or at a minimum could be used in concert with fire suppression efforts.

Efforts to limit human ignitions are challenging but could be focused on certain ignition types and geographic areas to maximize their effect. For example, Wang et al., (2021) discuss how health costs and indirect losses associated with future fires could be diminished by focusing fire prevention on areas upwind of large population centers or near important industry or transit infrastructure. Knorr et al., (2016) suggest that future human exposure to wildfires will increase primarily because of population growth close to areas with frequent wildfires (not because of an increase in burned area), implying that suppressing human ignitions close to high density population centers will only grow in importance. Other work (e.g., Abatzoglou et al., 2020; Collins et al., 2016) highlights that, while power line ignitions are a small number of ignitions in the US (Fig. S2) and in Australia, respectively, they pose greater risk to homes, and initiatives in California are already underway to relocate particularly susceptible lines underground. At the local level, more detailed source attribution of fire $PM_{2.5}$ due to ignition type (as available in the FPA-FOD) would also be useful to target mitigation strategies.

The substantial contributions of humans to smoke $PM_{2.5}$ in CONUS may become even more important in the future. In addition to the lengthening fire weather season observed over the past thirty years due to climate change (driven by human activity) (Abatzoglou and Williams, 2016; Jolly et al., 2015), human ignitions extended the fire season in CONUS by more than three months (Balch et al., 2017). In California, where humans now dominate ignitions, these human ignitions combine with extreme fire weather to catastrophic effect, and, as fire weather days become more frequent, mitigating these coincident human ignitions will be key for smoke mitigation (Hantson et al., 2022).

Fires, climate, and society are a complicated interwoven system. This work, by design, attributes the impacts of natural vs. human ignition of fires; it does not address the question of how human impacts on land use and suppression has affected fire susceptibility, spread, and duration. It also does not characterize the counterfactual of human ignitions (i.e., would lightning have sparked a fire in a region if no human ignition had occurred?). However, we note that certain types of human ignitions (i.e., powerlines) are known to lead to more severe fires. Relatedly, a study focused on fire-prone European regions found that thinning and prescribed burning to manage fire risk reduced fire intensity and its risks to human health but that the increased fire emissions associated with prescribed burning could contribute to respiratory problems (Rabin et al., 2022). Nonetheless, our work is the first to delineate a proximate anthropogenic vs natural control on fire smoke exposure. Future work on how the expansion of prescribed burning to limit wildfires, especially in the West, changes $PM_{2.5}$ exposure and air quality across CONUS would help to inform other mitigation avenues. While fire and human interactions are complex, our work suggests that there is considerable potential for mitigating the public health burden associated with smoke exposure.

Data availability statement

The data that support the findings of this study are available at this Zenodo doi:

Acknowledgements

This work was supported by the U.S. National Science Foundation (AGS 1936642). The authors acknowledge Jennifer Balch for useful conversations regarding the human ignition database.

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