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LETTER

Impacts of climate change on land management and wildland fire smoke in the Southeastern United States

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Abstract

Although prescribed fire is frequently used in the Southeastern United States, land managers in the region and across the country plan to expand burning to mitigate wildfire and achieve other ecological goals. However, smoke management is often considered a barrier to prescribed fire. Additionally, climate change will likely affect the frequency of acceptable meteorological conditions for prescribed burning, potentially restricting the use of the practice. Here, we examine the air quality impacts from prescribed fire and wildfire in the Southeastern U.S., the populations affected by smoke in the region, and how these impacts may change under climate change. We rely on projections of wildfire burn area and climate-driven shifts in the frequency of meteorological conditions adequate for prescribed burning, as well as a survey of Southeastern land managers investigating their anticipated response to these changes. Based on this information, we use chemical transport modeling to assess the contributions of wildfire and prescribed fire to air pollution, and project how smoke impacts may vary due to climate change and different land manager responses. We find that prescribed fire is responsible for a significant fraction of regional particulate matter pollution. Populations exposed to the most smoke tend to have higher fractions of people of color and low income. Depending on how land managers respond to changes in atmospheric conditions under climate change, prescribed fire smoke may decrease slightly in the areas with the heaviest burning or increase across much of the Southeast. Projections also show that climate-driven changes in wildfire and prescribed burning may impact compliance with recently updated air quality standards. The analysis assesses the potential consequences of climate change on air pollution over a region in which wildland fire is extensively managed, providing insight into land management strategies that call for increased application of prescribed fire.

1. Introduction

Wildland fires, including wild and prescribed fires, are the largest source of fine particulate matter ($PM_{2.5}$) emissions in the United States [1] and their relative contribution to air pollution will grow as emissions from other sectors decrease [2–5]. Exposure to fire-related $PM_{2.5}$ is associated with various negative health outcomes, including asthma, and chronic obstructive pulmonary disease [6, 7], and is estimated to cause thousands of deaths annually across the U.S [8]. Further, the U.S. population residing in the wildland urban interface (WUI) is at its largest level [9] and wildfire risk is projected to increase in many areas under climate change [10–12]. In the Southeastern U.S., wildfire driven by drought, such as the 2016 Southern Appalachian fires, could become more frequent [13–15]. While residents in the WUI would be at greater risk of direct wildfire damages, climate change may also result in increased exposure to smoke [16–20].

To reduce fuel loads that can lead to catastrophic wildfire, authorities are considering expanded use of prescribed fire (e.g. [21, 22]). In addition to wildfire risk reduction, prescribed fire is used to improve wildlife habitat, support fire-dependent species, and pursue other goals [13, 23]. While the practice provides important benefits, it also generates significant smoke [24]. Many land managers perceive smoke management as a barrier to prescribed fire [25]. These concerns will likely grow under a stricter $PM_{2.5}$ national ambient air quality standard (NAAQS) revised in 2024 [26]. Additionally, climate change can affect meteorological conditions acceptable for burning, further constraining its use [27, 28]. While prior research examining climate-driven changes in smoke pollution has largely focused on wildfire [2, 29, 30] and the Western U.S [18–20], prescribed fire is heavily used in the Southeast [1]. This densely populated region also includes a higher fraction of residents susceptible to health risks associated with smoke exposure [31, 32].

Prior studies have assessed the vulnerability of populations exposed to fire-related smoke but reported inconsistent findings regarding disparities in smoke impacts among racial, ethnic, and socioeconomic groups [32–34]. An analysis of $PM_{2.5}$ trends across the U.S. suggests that air pollution from wildfires is increasing more rapidly in areas with higher income and larger Hispanic populations [35]. Studies focused on prescribed fire smoke have centered on the Southeast but examined limited areas, populations, and seasons [33, 36]. Additional information characterizing and comparing the communities affected by wildfire and prescribed fire smoke is needed [6, 37, 38]. Importantly, differences in the populations benefitting from prescribed fire and those experiencing its air pollution costs may be significant [39]. While analyses of communities near National Forests suggest that vulnerable populations benefit from prescribed fire [40] but experience increased exposure to health risks [41], smoke levels were not considered in these assessments.

Here, we examine the air quality impacts of prescribed fire and wildfire in the Southeastern U.S., the populations affected by smoke in the region, and how these impacts may change under climate change. We rely on projections of wildfire and climate-driven shifts in the frequency of meteorological conditions adequate for prescribed burning, as well as a survey of Southeastern land managers investigating their anticipated response to these changes. Based on this information, we use chemical transport modeling to assess the contributions of wildfire and prescribed fire to air pollution in the Southeast, and project how smoke impacts may vary due to climate change and different land manager responses. Additionally, we examine the implications of climate-driven changes on compliance with $PM_{2.5}$ standards. The analysis assesses the potential consequences of climate change on air pollution over a region in which fire is extensively managed, providing insight into strategies that call for increased application of prescribed fire.

2. Methods

We use a comprehensive air quality modeling system, fire and emissions data, land manager survey results, and projections of meteorology and fire activity under climate change to develop scenarios of fire-related pollution at mid-century across the Southeastern U.S. To analyze the impacts of fires, we conduct annual air quality simulations and quantify the contributions of wildfire and prescribed fire to $PM_{2.5}$ in the region. Demographic and environmental indicators are used to examine the population impacted by smoke under each scenario.

2.1. Study area and socioeconomic analysis

Our analysis focuses on U.S. Environmental Protection Agency (EPA) Region 4 (Alabama, Florida, Georgia, Kentucky, Mississippi, North Carolina, South Carolina, and Tennessee). To characterize populations impacted by smoke, we rely on EPA's EJSCREEN tool, which compiles demographic data and consistent social and environmental indicators at census-block-group (census tract subdivisions with 600–3000 people) level [42]. EJSCREEN demographic data is derived from the American Community Survey's 5 year (2016–2020) estimates. The tool also provides tract-level (county subdivisions with average population of approximately 4000 and spatial dimensions smaller or comparable to this study's air quality modeling resolution) $PM_{2.5}$ and ozone concentration indicators [42]. Here, indicators (fractions of people of color (POC), low income (LI), and very young or older residents) are used to assess if smoke impacts vulnerable populations or locations experiencing a higher environmental burden. Regional distributions of indicators are shown in figure S1. Census block groups experiencing the highest and lowest fire-related $PM_{2.5}$ are classified using Jenks natural breaks, which minimize variance within groups and maximize variance between groups [43].

2.2. Fire emissions and chemical transport modeling

We use EPA's Air QUAlity TimE Series Project (EQUATES) datasets [44] and the community multiscale air quality (CMAQ) model [45] to simulate air pollution associated with wildland fires in 2018. The simulations rely on EQUATES emissions, meteorology, and boundary conditions covering the conterminous U.S. (CONUS), based on the National Emissions Inventory (NEI) and meteorological fields generated with the Weather Research and Forecasting model. NEI fire emissions integrate state-reported fire information, apply the SMARTFIRE2 algorithm to reconcile satellite and ground-based data [1], and are estimated with the BlueSky modeling framework [46]. Here, we examine $PM_{2.5}$, as it is the air pollutant with the largest public health burden [47] and $PM_{2.5}$ specifically from wildland fires is linked to cardiovascular and respiratory effects [6, 7].

We use CMAQ version 5.3.3 (CMAQv5.3) to conduct year-long air quality simulations at 12 km horizontal resolution. CMAQv5.3 includes representations of atmospheric processes important to simulate the impacts of biomass burning on air quality, including treatment of secondary organic aerosols [48]. To isolate the contributions from wildfire and prescribed fire, we perform three 2018 simulations: (1) a baseline simulation with all emissions sources; (2) a simulation excluding wildfire emissions; and (3) a simulation excluding prescribed fire emissions. The impacts of wildfire and prescribed fire are estimated as the difference in $PM_{2.5}$ concentrations predicted by simulations including and excluding each. To assess climate-driven changes in wildfire and prescribed fire impacts, we perform three additional simulations, one simulation with projected wildfire emissions at midcentury and two simulations with prescribed fire emissions projected at midcentury under different burning scenarios. For these simulations, emissions are modified to reflect climate-driven shifts in fire based on projected changes in wildfire burn area [11], projected variations in meteorological conditions favorable for prescribed burning [28], and a survey of Southeastern land managers. While CMAQ simulations cover the CONUS, modifications to fire emissions are only applied to Southeastern states (EPA Region 4). Modeled 24 h average $PM_{2.5}$ concentrations in the baseline simulation reflect monitor observations and largely meet recommended benchmarks for photochemical model performance [49] (figure S2).

2.3. Wildfire projections

Future wildfire emissions in the air quality simulations are based on wildfire projections in Prestemon, *et al* [11]. developed from statistical models of annual burn area in the Southeastern U.S. that consider temperature, precipitation, potential evapotranspiration, forest land use, population, and personal income data. These projections of annual county-level wildfire burn area through 2060 used downscaled data from multiple Coupled Model Intercomparison Project (CMIP3) general circulation models and Special Report on Emissions Scenarios [11]. Here, we rely on mean projected annual burn area in each Southeastern county, including lightning- and human-ignited wildfires. We use a Monte Carlo simulation [50] of the nine regional projections [11] to estimate the mean projected wildfire burn area and average fractional change in area burned. We modify emissions in the future air quality simulation by scaling 2018 wildfire emissions in the baseline simulation according to projected changes in county-level burn area from 2015–2019 to 2055–2059. In the BlueSky Framework, fire emission estimates increase directly with burn area. Figure S3 shows projected changes to wildfire emissions.

2.4. Prescribed fire and land management projections

The projections of Southeast prescribed fire in this study are informed by the projections of burn-relevant meteorology developed by Kupfer *et al* [28]. These use burn permit records to identify 'burn windows' of adequate weather conditions for prescribed fire and rely on downscaled data from an ensemble of Coupled Model Intercomparison Project (CMIP5) global climate models to project the number of days meeting the criteria for acceptable burning conditions [28]. Here, we resample 4 km projections under the high greenhouse gas emissions representative concentration pathways (RCPs) 8.5 scenario to county level and estimate the average change in adequate burning days from 2015–2019 to 2055–2059. Figure S4 shows projected county-level changes in burning days by season.

To project the response of prescribed fire practitioners to climate-induced changes in the frequency of adequate conditions for burning, we surveyed land managers across the Southeast (NCSU IRB Protocol 25159). We developed a 19-question anonymized electronic survey targeted toward adults that use prescribed fire in the region. Responses from participants confirming that they have previously conducted a prescribed burn were analyzed. The survey was shared through multiple Southeastern fire networks, including the Southern Fire Exchange, NC State University Forestry Extension, the Southeast Regional Partnership for Planning and Sustainability (SERPPAS), multiple state prescribed fire councils, and local burn associations. Survey questions and additional details are included in the supplementary information (SI).

In the survey of land managers, we asked, 'If you were faced with fewer *good burning days* in the future, how would this change your burning operations?' Most indicated they would consolidate their burning, supplement with alternative fuel treatments, or burn less (section 3.1). Based on land manager responses, we generate two future prescribed fire scenarios. The Rx1 scenario assumes burned areas will change proportionately with projected changes in the number of available good burning days during the year. Similar to the future wildfire scenario, under Rx1 2018 baseline prescribed fire emissions are scaled to projected changes in number of days appropriate for burning. Prescribed fire emissions are modified according to seasonal projected changes at county-level (figure S4). Scenario Rx1 represents a future in which land managers respond to changes in the frequency of conditions adequate for burning by increasing burning where burning windows are lengthened and replacing burning with alternative land treatments or burning less in locations where opportunities to burn are reduced. In a second scenario, Rx2, we conserve 2018 total burned area across the modeling domain but assume that prescribed fire will shift following projected changes in the temporal distribution of days adequate for prescribed burning across the year. To do this, projected changes in the average monthly fraction of annual days adequate for burning within each county are applied to the fraction of annual burn area treated within each county each month (e.g. if the fraction of adequate burning days in a month increases from 0.1 to 0.15 for a county, a 50% increase, the fraction of area burned in the county during the same month is assumed to also increase by 50%). This shifts burn area from months with the largest projected decreases in number of days available for burning to other months, while maintaining the total annual burn area in each county unchanged (e.g. figure S5). No burning was shifted to months in which no acres were burned in 2018. Baseline prescribed fire emissions in each county were scaled to the resulting change in monthly burn area (figure S6). Scenario Rx2 represents a future in which land managers maintain current levels of fuel treatment under climate change by consolidating burning into the days with adequate conditions for prescribed fire.

3. Results

3.1. Land manager perspectives

A total of 223 survey responses from 13 states were analyzed. Eleven participants were automatically exited from the survey after indicating they had not conducted a prescribed burn and seven responses were excluded from analysis based on invalid or absent ZIP codes. Most responses came from fire practitioners in Florida ($n = 85$) and North Carolina ($n = 51$). Response distribution across the region is detailed in the SI.

When asked if they are 'able to use prescribed fire as often as [they] would like,' less than half of respondents agreed or somewhat agreed that they can currently burn as often as wanted. Most also indicated that they are definitely or probably concerned about climate change affecting their burning practices. Most respondents believe climate change will affect their practices in less than 30 years, with close to a third stating that it is already affecting them. When asked how a climate-induced reduction in 'good burning days' would change their burning operations, nearly 70% indicated that they would attempt to consolidate their burning (i.e. burn a larger area on fewer available days), while close to 40% indicated that they would supplement with alternative fuel treatments (e.g. mechanical removal) or burn less. Land manager survey responses are summarized in figure 1.

3.2. Wildfire and prescribed fire impacts on regional air quality

In the baseline simulation, regional average population-weighted annual $PM_{2.5}$ concentration was 6.6 μg m^{-3}. Annual $PM_{2.5}$ concentrations ranged from 5 μg m^{-3} in the Appalachian Mountains region to 10–13 μg m^{-3} in some urban centers (figure 2(A)). The contributions of wildland fire to annual average $PM_{2.5}$ concentrations ranged from 0.4 to 2.3 μg m^{-3} and resulted in a fire-related population-weighted concentration of 0.8 μg m^{-3} (figure 2(B)). The highest fire-related pollution was over southeast Alabama, southwest Georgia, and northwestern Florida (AL–GA–FL), and areas along the Mississippi River. Together, wildfire and prescribed fire accounted for 10%–15% of annual average $PM_{2.5}$ modeled across most of the region and 20%–30% in the most impacted areas (figure 3(A)). Separating the contributions of wildfire and prescribed fire indicates that in 2018 most regional $PM_{2.5}$ pollution from wildland fire was attributable to prescribed fire, but there were areas with high wildfire-related $PM_{2.5}$ in Florida, North and South Carolina, and near the Alabama–Georgia border. Across much of the region, wildfire and prescribed fire emissions each contributed 5%–10% of modeled annual average $PM_{2.5}$ concentrations, although in the AL–GA–FL region this fraction was 15%–25% (figures 3(B) and 3)). Prescribed fire had the largest impact on $PM_{2.5}$ during March in five states (GA, MS, NC, SC, TN), while in others the greatest prescribed fire impacts were in January (FL), October (AL), and December (KY).

3.3. Sociodemographic composition of areas impacted by smoke

Areas with high and low $PM_{2.5}$ pollution associated with each fire type during the baseline year (2018) were identified using Jenks Natural Breaks classification [43]. Approximately two million residents in the Southeastern U.S. experience the highest levels of smoke (>1.2 μg m^{-3} annual $PM_{2.5}$). The populations most exposed to smoke have higher fractions of POC and LI relative to populations experiencing the least smoke and regional average (figure 4). The disparities are larger for prescribed fire smoke (44% POC and 41% LI among people experiencing high smoke) than for wildfire smoke (40% POC and 38% LI). The fraction of older adults (>64 years) is larger in areas with high wildfire smoke compared to those with low wildfire smoke, but the opposite is true for prescribed fire smoke. Fractions of very young residents (>5 years) in areas with high or low smoke from either fire type are close to the regional average. The population in areas with high smoke also experiences higher overall ambient $PM_{2.5}$, relative to the regional average.

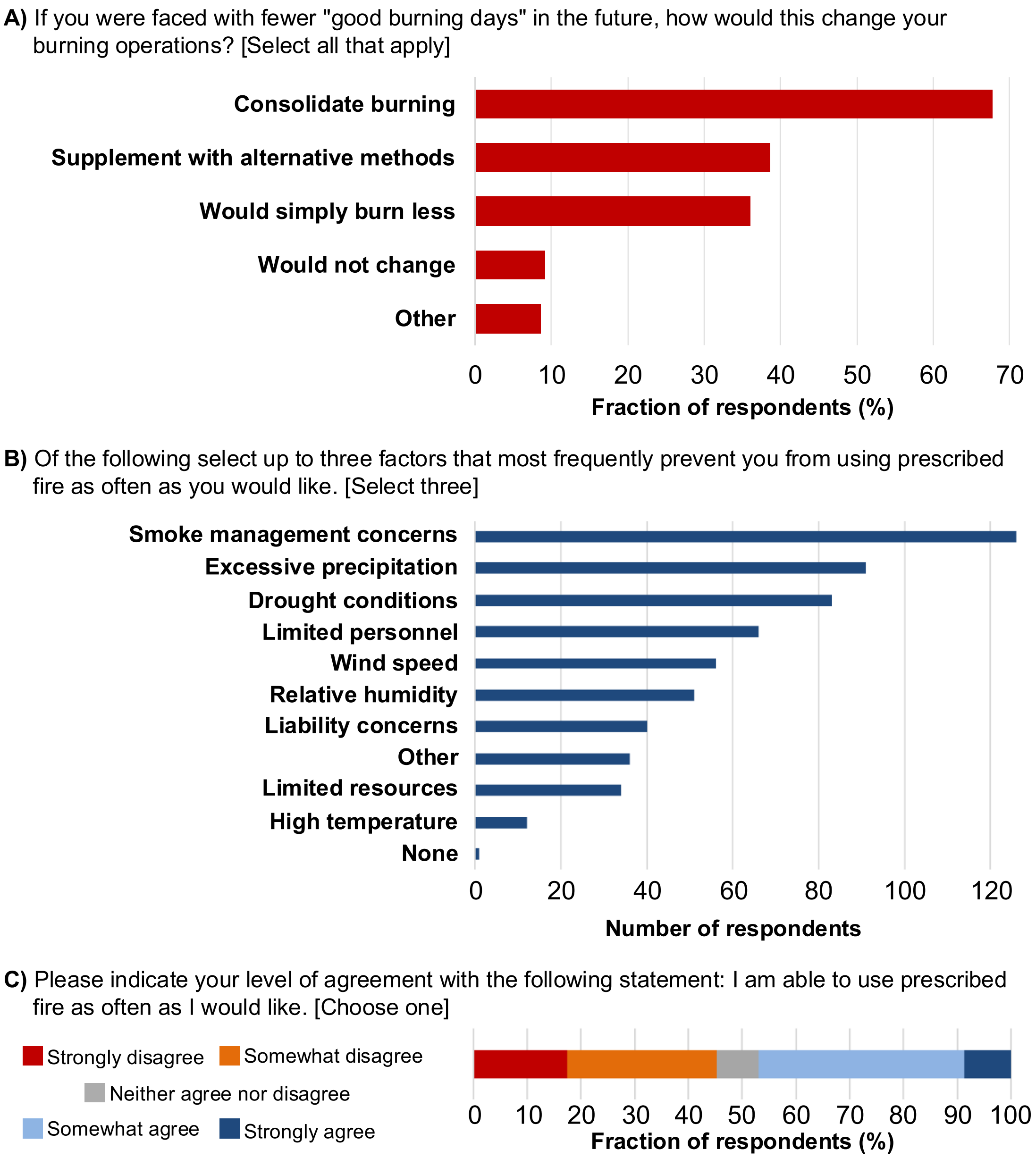

Figure 1. Results of Southeastern land managers survey questions regarding: (A) anticipated response to a reduction in the frequency of acceptable burning conditions under climate change; (B) the factors most frequently preventing the use prescribed fire; and (C) the ability to use prescribed fire as often as desired. The survey included 223 total respondents. Respondents were able to select more than one option in (A) and up to three factors in (B).

The areas experiencing $PM_{2.5}$ from prescribed fires above the region's population-weighted average (i.e. $>0.47\ \mu g\ m^{-3}$) similarly have higher fractions of LI (41%), although the fraction of POC is close to the regional average (38%). The population experiencing wildfire-related $PM_{2.5}$ above the region's population-weighted average (i.e. $>0.35\ \mu g\ m^{-3}$) has higher fractions of both POC and LI, relative to the complete Southeast region (39% and 40%, respectively). In contrast, areas predicted to experience fire-related $PM_{2.5}$ below regional population-weighted average concentrations tend to have lower fractions of POC and LI population, for both prescribed fire (37% each) and wildfire (36% and 38%, respectively).

3.4. Wildfire smoke in the Southeast under climate change

In the simulation of future wildfire and air quality under climate change, most of the Southeast experiences a 5%–10% increase in annual fire-related $PM_{2.5}$ at midcentury (2055–2059), relative to baseline concentrations. The increase is 10%–15% in sections of Alabama and North Carolina and 20% or greater over an area extending from Georgia to North Carolina (figure 5). Projected changes varied across the year and were largest between December and May. The highest climate-induced impacts were projected in March and April, when significant wildfire occurred in North and South Carolina (figure 6).

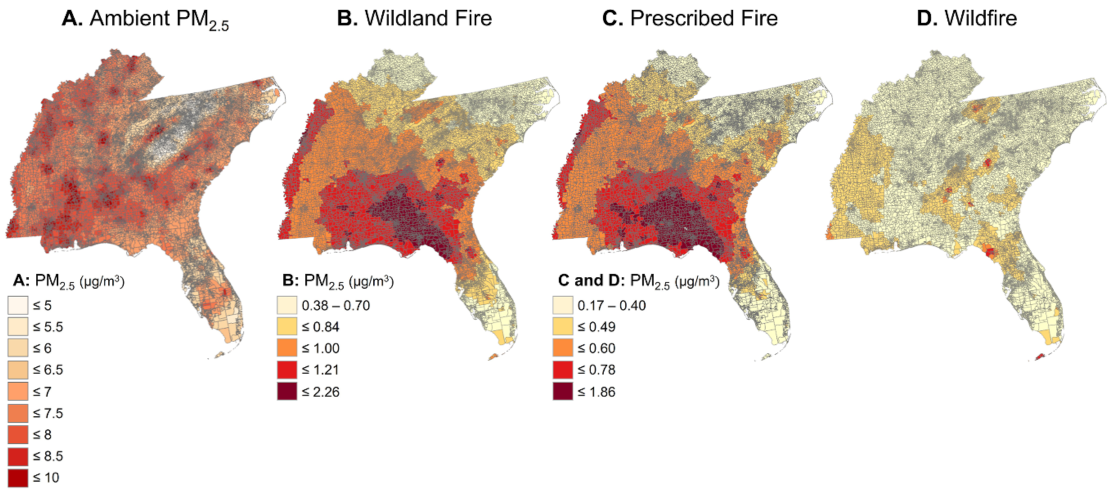

Figure 2. Simulated annual average $PM_{2.5}$ concentrations in the Southeastern U.S. associated with: (A) all emission sources; (B) wildland fire (wildfire + prescribed fire); (C) prescribed fire; and (D) wildfire. Jenks Natural Breaks used for B (wildland fire $PM_{2.5}$), and C and D (prescribed fire $PM_{2.5}$).

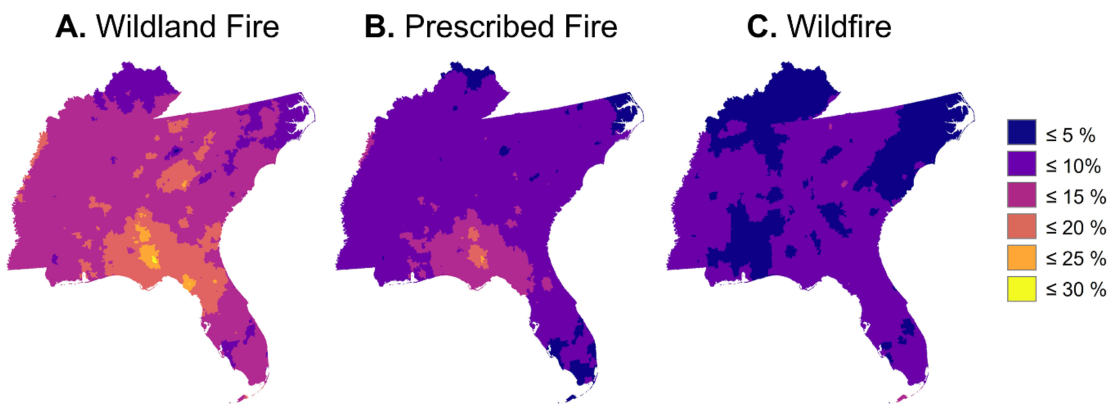

Figure 3. Fraction of simulated annual average $PM_{2.5}$ concentrations in the Southeastern U.S. attributable to: (A) wildland fire (wildfire + prescribed fire); (B) prescribed fire; and (C) wildfire.

Socioeconomic disparities in exposure to high smoke persist in the future wildfire simulation. Based on the baseline population distribution, the fractions of POC (42%) and LI (38%) in areas projected to have the most wildfire smoke are larger than regional averages (39% POC and 35% LI). The projected disparity for POC is larger relative to the baseline scenario. As wildfire varies greatly from year to year, these projections reflect wildfire activity in the baseline simulation. However, they provide insight into the potential magnitude of wildfire air quality impacts under a warming climate.

3.5. Prescribed fire smoke pollution in the Southeast under climate change

Scenario Rx1 examines the consequences of a climate-induced change in the frequency of days with meteorology adequate for burning, where land managers proportionally modify baseline areas treated with prescribed fire. Under the Rx1 scenario, midcentury annual $PM_{2.5}$ concentrations associated with prescribed fire decrease by 1%–5% across Florida and southern Georgia and Alabama, relative to the baseline simulation, with some areas experiencing a larger reduction (figure 5). Minor changes are predicted over a large portion of the Southeast, but a 1%–5% increase in prescribed-fire-related $PM_{2.5}$ is projected in some areas within the north and west of the domain reflecting an increase in the number of burning days. Sub-annually, changes in fire-related $PM_{2.5}$ modeled under Rx1 reflect projections of monthly changes in the frequency of days adequate for burning (figure 6). Small increases in smoke concentrations are projected from November to February. From March to December, there is a decrease in $PM_{2.5}$ from prescribed fires across much of the Southeast, with the largest relative reductions in June–September. Overall, projected changes in annual-average $PM_{2.5}$ under the Rx1 scenario are small and regional population-weighted annual $PM_{2.5}$ concentration remains largely unchanged at midcentury.

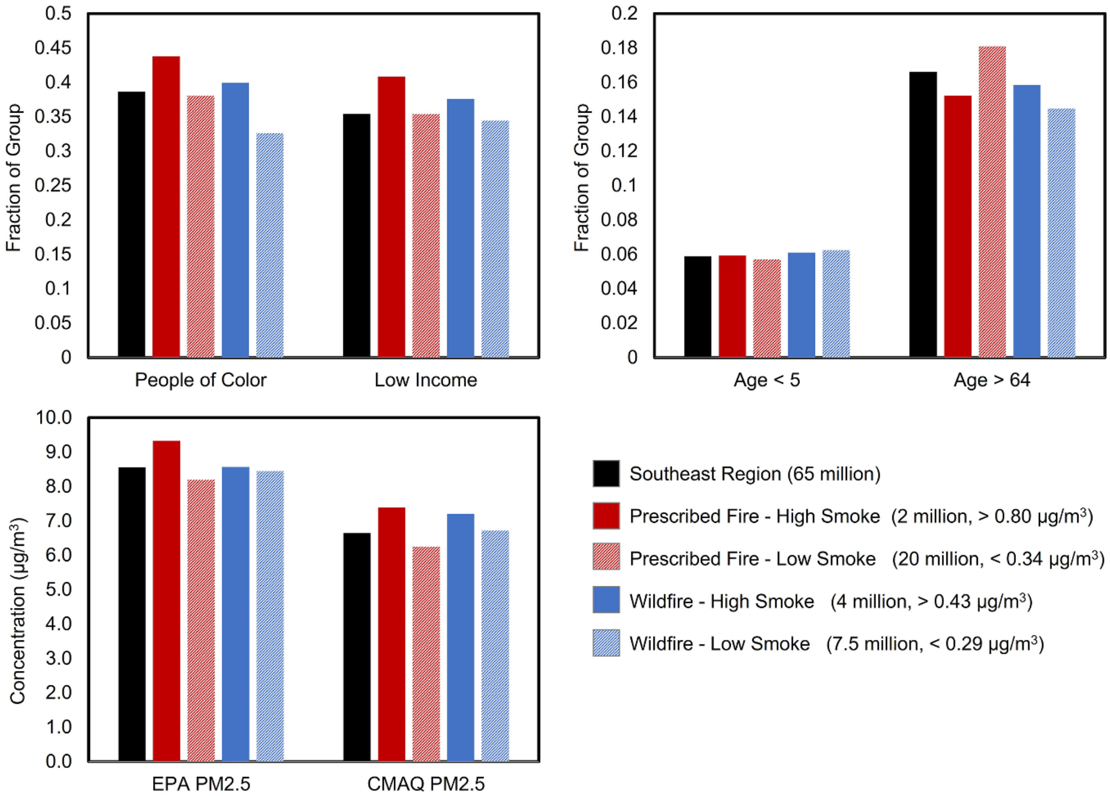

Figure 4. Sociodemographic and environmental indicators in areas identified as experiencing high and low smoke pollution from prescribed fire and wildfire. High and low smoke census block groups are determined using Jenks Natural Breaks classification for simulated annual average fire-related $PM_{2.5}$ concentrations. High and low concentration thresholds and population in each category are indicated in legend. Black bars show regional averages for Southeastern U.S. Indicators include fractions of population of color, low income, age <5 years, and age >64 years. Annual average ambient $PM_{2.5}$ concentrations ($\mu g\ m^{-3}$) in each area estimated from EJSCREEN (EPA $PM_{2.5}$) and this study's simulations (CMAQ $PM_{2.5}$) are also shown.

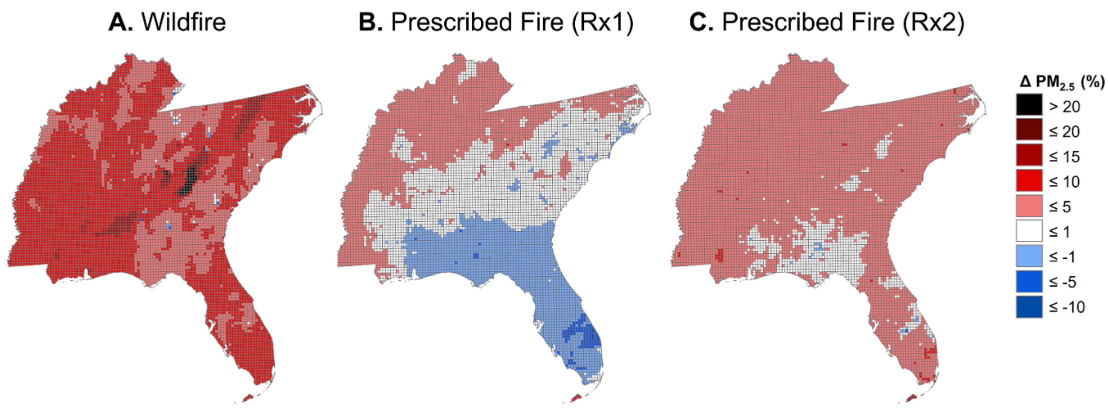

Figure 5. Projected changes (%) in annual-average fire-related $PM_{2.5}$ concentrations under future wildfire and prescribed fire (Rx1, Rx2) scenarios, relative to baseline simulation.

Scenario Rx2 represents future prescribed fire smoke if land managers respond to a climate-induced change in days adequate for burning, while maintaining total area treated unchanged. Although annual area burned and total emissions are conserved, redistributing summer burning to other months with different meteorological conditions increases annual fire-related $PM_{2.5}$ at midcentury by 1%–5%, relative to baseline, across most of the region (figure 5). In specific locations, increases of 5%–10% are projected. Regional population-weighted annual $PM_{2.5}$ from prescribed fires increases by 2.4% under Rx2, although the change in annual population-weighted total $PM_{2.5}$ is minor. As in the Rx1 scenario, projected $PM_{2.5}$ concentrations decrease under Rx2 during summer months, with larger reductions in some locations. However, this scenario also leads to region-wide increases in fire-related $PM_{2.5}$ from October to April at midcentury (figure 6). Projected increases exceed 10% over large areas of the Southeast

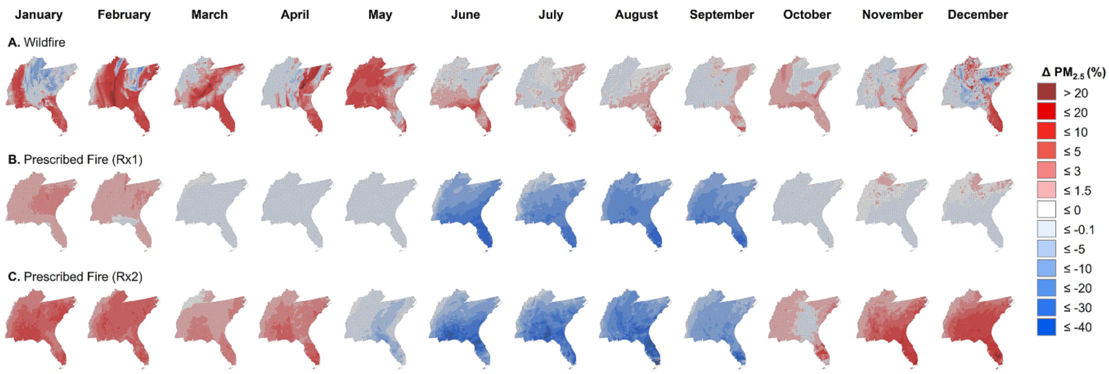

Figure 6. Projected changes (%) in monthly fire-related $PM_{2.5}$ concentrations modeled under future wildfire and prescribed fire (Rx1, Rx2) scenarios, relative to baseline simulation.

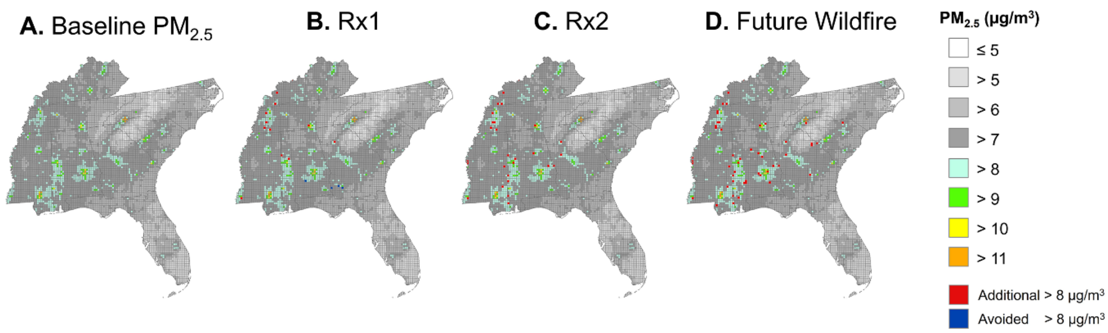

Figure 7. Annual average ambient $PM_{2.5}$ concentrations simulated under (A) baseline, (B) Rx1 and (C) Rx2 future prescribed fire, and (D) future wildfire scenarios. Red-colored cells indicate locations where baseline annual $PM_{2.5}$ is below 8 μg m^{-3} but increases to greater than 8 μg m^{-3} (close to 2024 NAAQS level of 9 μg m^{-3}) in future prescribed fire or wildfire scenarios. Blue-colored cells indicate locations where baseline annual $PM_{2.5}$ is above 8 μg m^{-3} but decreases to less than 8 μg m^{-3} in scenario Rx1.

from November to February and are largest during November and December. The monthly fraction of ambient $PM_{2.5}$ attributable to prescribed fire across the Southeast is highest during December and corresponds to an approximately 5% region-average increase in population-weighted monthly fire-related $PM_{2.5}$. At local scale, the largest impacts under Rx2 were projected in November and December, with increases in fire-related $PM_{2.5}$ that exceed baseline concentrations by over 50% at some locations.

Comparing scenarios Rx1 and Rx2 shows that prescribed burning may vary significantly depending on land managers response to changes in meteorological conditions and that these decisions can have consequences for smoke pollution. In both scenarios, socioeconomic disparities in exposure to high smoke concentrations remain largely unchanged. Similar to the baseline scenario, population fractions of POC (43%–44%) and LI (40%–41%) in areas experiencing the most smoke under scenarios Rx1 and Rx2 are higher than regional averages (39% POC and 35% low-income). Compared to climate-driven impacts on wildfire smoke, regional impacts on prescribed fire pollution may be smaller. However, modified burning practices driven by climate change can have significant effects on air quality during the burning season at multiple Southeastern locations.

3.6. Projected impacts of future wildland fire on air quality standard compliance

Currently, all areas in the Southeastern U.S. comply with the $PM_{2.5}$ NAAQS. In the scenarios simulated, midcentury climate-driven changes in fire would not cause annual $PM_{2.5}$ concentrations to exceed 12 μg m^{-3}. However, in 2024 the primary annual $PM_{2.5}$ NAAQS level was reduced from 12 μg m^{-3} to 9 μg m^{-3} based on health effects evidence and the Clean Air Scientific Advisory Committee's recommendations to reduce the level to within 8–11 μg m^{-3}, starting a multiyear process to designate attainment/non-attainment areas, develop state implementation plans, and implement plans to attain the updated standard [26]. Based on our analysis, current prescribed fire activity may cause some areas to be at risk of exceeding this strengthened standard (figure 7).

Climate-driven changes in wildfire and prescribed fire at midcentury may impact compliance with the updated NAAQS within the Southeast, were contributions from other sources to $PM_{2.5}$ to remain unchanged (figure 7). In the future wildfire and prescribed fire simulations, fires contribute to annual concentrations above 9 μg m^{-3} at new locations (model grid cells) in Alabama, Georgia, and Tennessee. Projected concentrations at additional locations are close to the NAAQS limit with annual $PM_{2.5}$ levels exceeding 8 μg m^{-3}. In the Rx1 and Rx2 scenarios, most of these locations are in western areas of the region but also include the Atlanta metropolitan area. Under the future wildfire scenario, modeled annual concentrations approach the NAAQS level (>8 μg m^{-3}) at additional Southeast locations, including areas in Alabama, Tennessee, and South Carolina.

4. Conclusions and discussion

Land managers in the Southeast and other U.S. regions intend to increase area treated by prescribed fire [21, 22]. However, changes to the frequency of conditions adequate for burning driven by climate change may restrict burning. Considering the impacts of wildland fire on air quality will be important in developing effective fire management strategies. Here, we find that prescribed fire is responsible for a significant fraction of regional $PM_{2.5}$ concentrations. The areas with the most prescribed fire pollution have higher fractions of POC and LI. Depending on how land managers respond to climate change, prescribed fire pollution could decrease slightly in the areas with the most burning if it is reduced or replaced with different fuel treatments, or increase across much of the region if burning is compressed into fewer days. While prescribed fire has a greater impact on $PM_{2.5}$ in the region, the climate-driven increase in $PM_{2.5}$ projected was larger for wildfires.

There are limitations to this study. The number of wildfires in the Southern U.S. during the analysis's baseline year (2018) is close to the 2014–2023 mean, but wildfire burn area is higher than the 10 year average [51]. Analyses based on other years may yield differing results. Aside from projections of wildfire burn area, the study's simulations do not project potential changes in population or fuel loads [52]. Representation of fuels can significantly influence model-based smoke estimates [53]. In the Rx2 scenario, county-level annual area burned is conserved by redistributing prescribed fire in months projected to experience reduced opportunities to burn to others. This may overlook constraints associated with regulations or operational capacity. Projected changes in wildfire and prescribed fire are based on studies that rely on different models and climate projections. Responses to the land manager survey were collected from all Southeastern states, but fewer were from two with substantial burning (Georgia and Alabama). Climate-driven changes in wildfire smoke transported into the Southeast were not considered but this could have additional limiting effects on burn windows in the future. Future regional fire activity and smoke impacts may also be shaped by policy decisions that affect air pollution regulations and accounting (e.g. exceptional events) or land management activities (e.g. funding and priorities).

This analysis emphasizes several research needs. Among the Southeastern population experiencing the most prescribed fire smoke, percentages of POC and LI, predictors of social vulnerability, are higher. This finding is consistent with prior studies reporting socioeconomic, racial, and ethnic disparities in exposure to ambient $PM_{2.5}$ for U.S. population (e.g. [54, 55]). Here, the disparities associated with air pollution from wildfires and prescribed burns identified are associated with the elevated numbers of vulnerable residents in the areas of the Southeast with the highest fire activity and smoke (figure S1). Strategies to mitigate smoke exposure among these groups are needed. However, examining population disparities at local scale, such as those identified for urban air pollution (e.g. [56]) requires higher resolution smoke fields.

Consolidating and shifting burning in response to climate change in our simulation led to an increase in smoke concentrations across most of the region, even though total area burned remained unchanged. However, longer fire return intervals may reduce the frequency of air quality impacts [57]. Similarly, evaluating the implications of seasonal shifts in burning for different prescribed fire objectives is necessary. Our analysis suggests that altered fire activity could affect NAAQS compliance. Areas that violate the NAAQS are required to develop a state-led multi-year implementation plan to attain the standard, which may include restrictions on prescribed burning and make it significantly more difficult to achieve land management goals. Smoke management is already perceived as a barrier to burning, as shown by the study's land managers survey, and reconciling expanded prescribed fire with fewer burning opportunities will require coordination and attention to air quality. The interplay between wildfire risk and prescribed burning under climate change, and their resulting air pollution, remains a research need. Additional analyses are needed to understand the full costs and benefits of prescribed fire. Clarifying prescribed fire yields and the air quality impacts of different fire regimes across diverse landscapes is needed to inform future fire management, as are comparisons to alternative treatments, such as herbicides, mechanical thinning, or mastication [58, 59].

If climate change limits prescribed fire and planned expansions of burning, widening the range of meteorological conditions considered acceptable for burning, such as mixing height and transport winds criteria, may yield more days to burn [60]. However, careful consideration must be given to the benefits and detriments of altered prescribed fire, including impacts on vulnerable populations [61], as land management plans develop. Future prescribed fire and related smoke pollution in the Southeast, as well as the influence climate change exerts on them, will depend on land and air quality priorities, and the trade-offs deemed acceptable.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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