FINAL REPORT

Comparing the costs of an operational prescribed burning program to those of unplanned wildfires

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List of Abbreviations/Acronyms

ACM2	Asymmetrical Convective Model, version 2
AQS	Air Quality System
CMAQ	Community Multiscale Air Quality Modeling System
BEIS	Biogenic Emission Inventory System
BSP	BlueSky Pipeline
CK	Chestnut Knob
CMAQ	Community Multiscale Air Quality Modeling System
EPA	Environmental Protection Agency
FB	Fuel bed
FCCS	Fuels Characterization Classification System
FEPS	Fire Emission Production Simulator
NC State Parks	North Carolina Division of Parks and Recreation
NCFS	North Carolina Forest Service
NEIC	National Emissions Collaborative
NME	Normalized mean error
NMB	Normalized mean bias
PBL	Planetary boundary layer
PM	Particulate Matter
$PM_{2.5}$	PM with aerodynamic diameter smaller than 2.5 microns
PR	Party Rock
SMARTFIRE	Satellite Mapping Automatic Reanalysis Tool for Fire Incident Reconciliation
U.S.	United States
WRF	Weather Research and Forecasting model

Keywords

Air pollution, air quality, air quality management, air quality modeling, biomass burning emissions, fire emissions, land management prescribed fire, smoke, smoke exposure, smoke impacts, wildfire

Acknowledgements

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1. Abstract

Wildland fire, wildfire and prescribed burning, plays important roles in the ecosystems of Southeastern United States. Wildfires and related smoke can damage property and human health. In contrast, prescribed fire can reduce the occurrence, size, and severity of uncontrolled wildfires and is a commonly practiced land management strategy. However, prescribed fire is also a significant source of air pollutants. Although several studies have separately explored specific impacts of prescribed fire and wildfire on air pollution, assessments analyzing the trade-offs between the costs of prescribed burning and avoided impacts of wildfire are needed to support effective fire management approaches. In this project, an analysis was conducted to compare the air quality externalities of wildfire and prescribed fire smoke pollution. We developed an approach to examine the smoke impacts of prescribed burning and the wildfire air pollution avoided with prescribed fire treatment by simulating historical and hypothetical wildland fire scenarios with an emissions and air quality modeling framework. Fires occurring on North Carolina State Parks were used a case study for the analysis. The study finds that although prescribed fires can affect air quality, their air quality benefits can be higher than their air pollution impacts. In the case study, the population benefiting from reduced wildfire air pollution is significantly larger than the population that would be affected by prescribed fire smoke. Still, neighboring communities may experience lower smoke concentrations on additional days due to prescribed fire treatment.

2. Objectives

The main objective of this project was to estimate and compare air pollution externalities associated with prescribed fire and wildfire. This project aimed to achieve this by building and extending the Student Investigator's doctoral research focused on fire, air quality, and health impacts modeling. Additionally, an objective of the Graduate Research Innovation project was to conduct the analysis comparing wildfire and prescribed impacts within an operational prescribed burning program. The analysis thus focuses on wildland fires occurring on North Carolina State Parks managed by the North Carolina Division of Parks and Recreation (NC State Parks). With cooperation from the NC State Parks' land management program, a case study focused on wildfires that occurred within State Parks in 2016 and prescribed burns carried out on State Parks land during the same year was examined.

3. Background

Wildland fire is an essential component of many environments. However, wildland fires are also a major source of air pollution. They represent the largest source of fine particulate matter ($PM_{2.5}$) emissions, the air pollutant with the largest attributable burden of disease, in the United States (U.S. EPA, 2018). Wildfires can damage property and the smoke they emit adversely impacts public health (Liu et al., 2015; Reid et al., 2016). In contrast, prescribed fire is frequently used in land management to reduce the risk of uncontrolled wildfires and achieve other objectives. Still, prescribed burns are a significant source of air pollutants, especially in burn-intensive areas such as the Southeast (U.S. EPA, 2018).

Analyses objectively comparing the air pollution costs and benefits of prescribed fire have not been conducted (Altshuler et al., 2020; Hunter & Robles, 2020; Waldrop et al., 2012). Prescribed fire can protect the public from severe air pollution from wildfires by lowering the risk and magnitude of wildfires (Zhao et al., 2019). Several studies have attempted to address the costs of implementing prescribed fires and suppressing wildfires (Myers et al., 2012; Bagdon & Huang, 2016), but have not considered smoke-related health impacts. Other analyses have investigated the impacts of wildland fire smoke (Fann et al., 2018; Black et al., 2017; Cascio, 2018; Reisen et al., 2015), but few have assessed the impacts of prescribed fire (Navarro et al., 2018). Several studies have analyzed smoke from wildfires (e.g., Baker et al., 2016; Navarro et al., 2016) or prescribed fires (e.g., Huang et al., 2019; Ravi et al., 2018; Tian et al., 2008; Zeng et al., 2008) in isolation or combined (e.g., Larsen et al., 2017; Wilkins et al., 2018).

No study has systematically compared smoke pollution from prescribed fire to that of wildfires. Such analyses are difficult due to differences in the nature

and smoke pollution associated with wildland fires and prescribed burns (Jaffe et al., 2020; Navarro et al., 2018). Previous studies examining the benefits of prescribed fire have focused on their ability to reduce fuel loads (Arthur et al., 2017; Waldrop et al., 2016), wildfire risk (Addington et al., 2015; Kalies & Yocom Kent, 2016), carbon emissions (Krofcheck et al., 2019; Wiedinmyer & Hurteau, 2010), or other air pollutant emissions (Hyde & Strand, 2019; Liu et al., 2017). To develop policies able to meet both land management and air quality goals, the air quality tradeoffs of wildfires and prescribed burns need to be better understood.

In this project, we aimed to present a methodology to model and compare the air quality impacts of prescribed fire to those of wildfires. We compared the air pollution caused by wildfires and prescribed fires within NC State Parks with a computational framework that uses a state-of-the-science regional chemical-transport model. We then used an approach that weighs impacts and benefits of prescribed fire by modeling connected wild and prescribed fire scenarios. In the analysis, wildfire smoke pollution prevented with prescribed fire is compared to the smoke pollution from prescribed burns intended to reduce the risk and severity of the wildfires. Specifically, we examine two of the largest wildfires recorded on NC State Parks' land as a case study for this analysis. The project examines historic wildfires and prescribed burns in a region with a significant population living at the wildland-urban interface.

4. Materials and Methods

Fire data: North Carolina Division of Parks and Recreation land management program

The North Carolina Division of Parks and Recreation (NC State Parks) maintains an active land management and prescribed burning program. NC State Parks administers over 125,000 acres of fire-prone land and oversees over 5,000 acres per year of prescribed burns. Here, we focus on wildland fire on NC State Parks' land in the year 2016 (Figure 1). Consistent with other years, in 2016 the program conducted 57 prescribed burns. Among them, 58% were captured by the Satellite Mapping Automatic Reanalysis Tool for Fire Incident Reconciliation (SMARTFIRE) algorithm and database system. The average size of the fires was 55 acres, while those detected by SMARTFIRE had an average size of approximately 100 acres. In addition, two major wildfires occurred within the NC State Parks in 2016, which makes this year a unique case study. The Party Rock wildfire was spotted at Chimney Rock State Park on November 5 and burned a total of 7,142 acres, including 2,489 acres within the park. The Chestnut Knob wildfire began at South Mountain State Park on November 6 and burned 6,435 acres within the park, making it the largest ever recorded by NC State Parks.

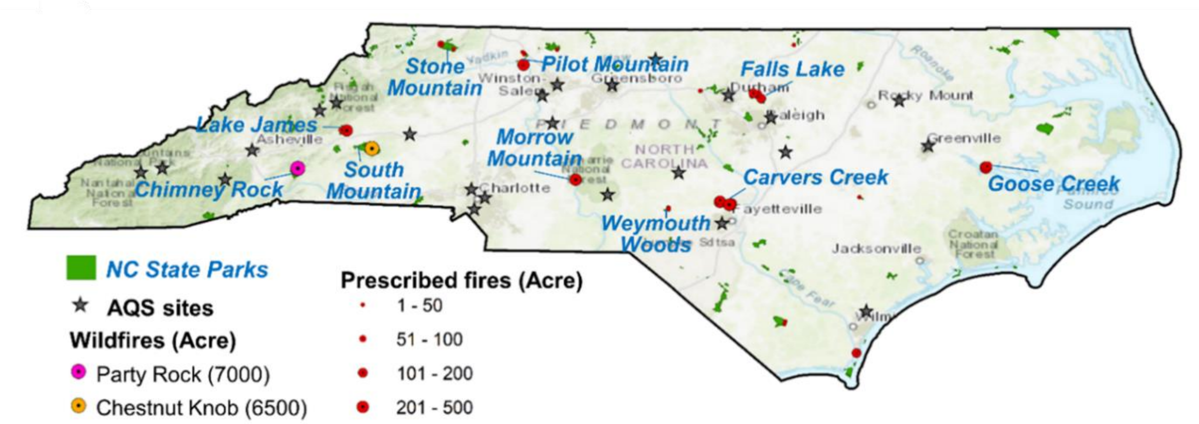

Figure 1. Locations of prescribed burns conducted at NC State Parks in 2016, and two wildfires (Party Rock and Chestnut Knob) that occurred at Chimney Rock and South Mountain State Parks. State Parks and air quality monitoring sites (AQS) in North Carolina are also shown.

Air quality modeling framework

We used the Community Multiscale Air Quality Modeling System (CMAQv5.2.1) to simulate air quality in 2016 across a 948 km x 612 km domain centered over North Carolina at 4-km horizontal grid resolution. As inputs, CMAQ uses initial and boundary atmospheric concentrations, emissions from multiple sectors, and simulated meteorology. Initial and boundary conditions are derived from an annual 2016 CMAQ simulation conducted at 12-km resolution for a larger domain covering the Eastern U.S. Emissions for all sources other than wildfires at NC State Parks, including electric generating units, industrial sources, oil and gas operations, commercial marine vessels, agricultural fires, prescribed fires, wildfires, and other area sources, are based on the 2016 beta emissions inventory developed by the National Emissions Collaborative (NEIC, 2019). Emissions for the prescribed burns and wildfires on NC State Park are estimated using the BlueSky Pipeline (BSP) emission modeling framework (Larkin et al., 2009). Biogenic emissions are based on the Biogenic Emission Inventory System (BEIS) version 3.6.1 modeling system (Bash et al, 2016). Meteorological fields used to drive the air quality model were simulated at 4-km horizontal resolution with the Weather Research and Forecasting model (WRF version 4.1) (Powers et al., 2017), using the Kain-Fritsch parameterization (Kain & Kain, 2004) and the Asymmetrical Convective Model, version 2 (ACM2) planetary boundary layer (PBL) scheme (Pleim, 2007).

To evaluate model performance, we compared modeled base-case $PM_{2.5}$ concentrations with those observed at the U.S. Environment Protection Agency's Air Quality System (AQS) monitoring sites (U.S. EPA, 2009), and estimated normalized mean bias (NMB) and normalized mean error (NME) for CMAQ predictions relative to measurements of $PM_{2.5}$ concentration. Modeled 24-hr average $PM_{2.5}$ concentrations generally capture observed concentrations in 2016. Overall, the average normalized mean error (NME: -4.14%) and normalized mean bias (NMB: 34.48%) across the modeling domain, which considers observation-model value pairs for all 25 AQS stations in North Carolina, meet recommended benchmark model performance goals (NMB: <±10%, NME: <35%) (Emery et al., 2017). Figure 2 shows the NME and NMB averaged across sites and the values at each of the monitoring stations. Our result suggests that at approximately 80% of the locations recommended air quality modeling performance targets for NME and NMB (NMB: < ±30%, NME: <50%) are met (Emery et al., 2017).

Wildland fire emissions and fuel consumption were modeled using the BlueSky Pipeline (BSP) emission modeling framework (Larkin et al., 2009). BlueSky includes the Satellite Mapping Automatic Reanalysis Tool for Fire Incident Reconciliation (SMARTFIRE v2) for fire detection (Larkin & Raffuse, 2015), the Fuels Characterization Classification System (FCCS v3) to model fuel loads (Ottmar et al., 2007), CONSUME v5 to estimate fuel consumption (Ottmar, 2009), and the Fire Emission Production Simulator (FEPS v2) to estimate emission rates (Anderson et al., 2004). In addition to SMARTFIRE-detected burn area, for the Party Rock and Chestnut Knob wildfires we also used day-to-day ground-based burn area information from NC State Parks to generate a second set of emission profiles with BSP. Using wildfire emissions estimates from two sources, we conducted two base simulations: (1) a base case using SMARTFIRE detections for the Party Rock and Chestnut Knob wildfires; and (2) a base case using ground-based data for these two wildfires.

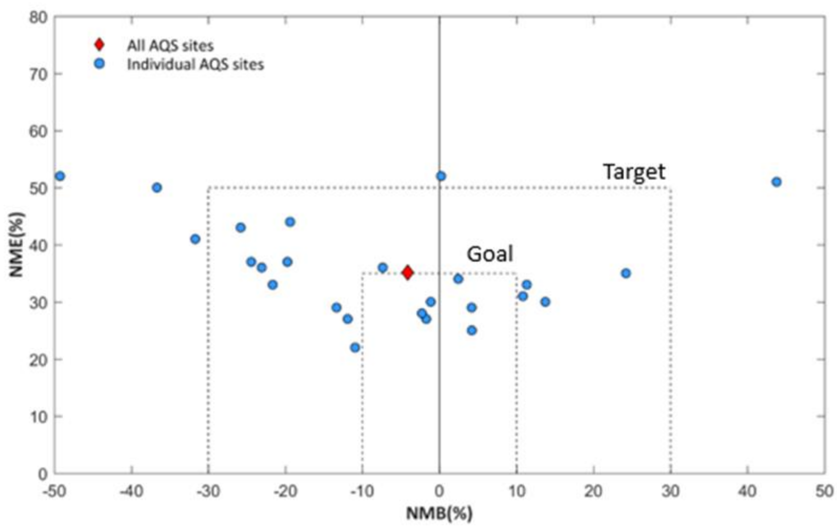

Figure 2. Model performance statistics at North Carolina AQS monitoring sites. X-axis and Y-axis indicate values of normalized mean bias (NMB) and normalized mean error (NME) of model prediction relative to AQS site observations. Dotted lines show performance targets and goals for regional-scale air quality modeling recommended by Emery et al. (2017).

Quantifying air quality impact of wildland fires

The air quality impacts of 2016 prescribed fires conducted in NC State Parks were estimated as the difference between CMAQ simulations including and excluding fire emissions. To weigh the effects of the burning program, we compared the aggregated annual impact of all prescribed burns with that of the two uncontrolled wildfires that occurred on NC State Parks land during the same year. We estimated daily (24-hr average) fire-attributable $PM_{2.5}$ from the Party Rock and Chestnut Knob wildfires, as the difference between model simulations including and excluding emissions from these events. We then compared the aggregated annual impact of the wildfires with that of all 57 prescribed fires. We also assessed population-weighted pollution by weighing aggregate fire-related $PM_{2.5}$ concentrations by population density.

In this analysis, we investigated two wildfires that occurred within NC State Parks land, the Party Rock (PR) and Chestnut Knob (CK) fires, in 2016. The PR wildfire began at Chimney Rock State Park on November 5, 2016 and burned over 7,000 acres of park land over 15 days. The CK wildfire began at South Mountains State Park on November 6, 2016 and burned over 6,000 acres over 16 days. We estimated the air quality impacts of the PR and CK fires by comparing $PM_{2.5}$ concentrations under a base case simulation relying on ground-based wildfire data to those simulated in the absence of PR and CK fire emissions. We also compared this base-case simulation to a simulation using SMARTFIRE against the simulation with no PR and CK wildfire emissions to estimate the air quality impact of the wildfires when relying on SMARTFIRE detections exclusively. We examined the differences between the two base case simulations to weigh the sensitivity of modeled smoke pollution from the fires to the source of burn area data.

In our analysis of air quality trade-offs of prescribed fire, we projected the air quality impacts of prescribed fire treatment at the site of the PR and CK wildfires by modeling hypothetical fires at the parks on days suitable for burning throughout the year. We considered prescribed fire treatment for the complete area burned by the CK and PR fires within NC State Parks land, 6,435 and 7,142 acres respectively, by simulating a series of hypothetical 500-acre prescribed fires at Chimney Rock and South Mountain State Parks over the course of 13 and 14 days. We modeled the hypothetical prescribed burns at the parks on a selection of days throughout the first half of 2016 with no rain and ventilation rates suitable for burning according to the North Carolina smoke management guideline (NCFS, 2016). The daily ventilation rate at each state park was calculated by multiplying modeled PBL height with modeled transportation wind. We generated two 500-acre prescribed fire emission profiles based on existing fuel bed properties at each of the parks. By comparing air pollutant concentrations predicted by CMAQ simulations including and excluding emissions from the hypothetical burns, we quantified the impacts of these 27 hypothetical prescribed fires.

To estimate the avoided air quality impact from the PR and CK fires that would be attained with prescribed fire treatment, we predict the smoke impacts of these wildfires post-treatment, i.e., those that would have occurred if prescribed fire had been previously applied to the area burned. We generated post-treatment PR and CK wildfire emission profiles with BSP using post-treatment fuel loads and assuming the wildfire burn areas remain unchanged. To estimate post-treatment fuel loads, we simulated the consumption of underlying vegetative fuels during the prescribed fire treatment with BSP and subtracted it from pre-existing fuel loads. Based on simulations driven by pre- and post-treatment wildfire emissions, we estimated the air quality impacts of the PR and CK wildfires would the areas affected have undergone recent prescribed fire. The difference in $PM_{2.5}$ concentrations predicted by CMAQ simulations with pre- and post-treatment wildfire emissions is considered the avoided wildfire impacts attained by prescribed burning.

5. Results and Discussion

Air quality impacts of prescribed fire in an operational land management program

Prescribed fires on NC State Parks have limited air quality impacts

NC State Parks' prescribed fires in 2016 had small regional impacts, mostly affecting areas directly downwind of fire locations, as shown in Figure 3. The annual aggregated air quality impact of all 2016 fires suggests that prescribed fires had the largest effects around Carvers Creek, Falls Lake, and Goose Creek, Lake James, Morrow Mountain, and Pilot Mountain State Parks (Figure 4a). Among all parks, air quality near Carvers Creek State Park was most negatively affected during this period. A total of 1,820 acres were treated here, causing an annual average increase in daily-average $PM_{2.5}$ concentration at the park of 0.4 μg m^{-3}. However, population-weighted cumulative $PM_{2.5}$ impacts indicate that the Raleigh, Durham, and Fayetteville areas had the largest populations negatively affected by smoke from the prescribed fires in 2016 (Figure 4b). Higher smoke pollution from nearby Carvers Creek State Park is primarily responsible for high population-weighted concentrations at Fayetteville. Likewise, higher population density along with moderate smoke from Falls Lake State Park led to higher impacts in the Raleigh-Durham area. Overall, the burning program exposes only 0.7% of the domain-wide population to a fire-related increase in $PM_{2.5}$ greater than 3 µg m^{-3} on at least one day. Over 50% of this population is in the Raleigh-Durham or Fayetteville regions.

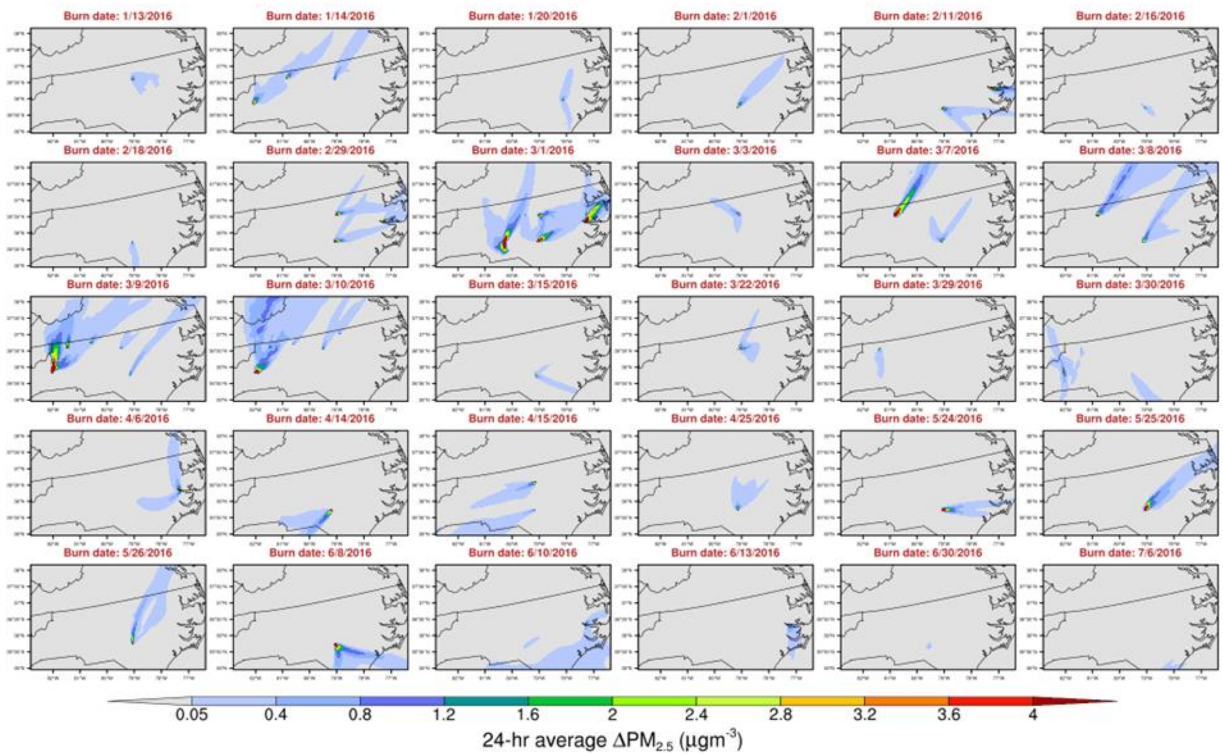

Figure 3. Increase in 24-hr $PM_{2.5}$ concentrations associated with NC State Parks' 2016 prescribed burning program on days with at least one prescribed fire larger than 20 acres. Panel titles indicate burn dates.

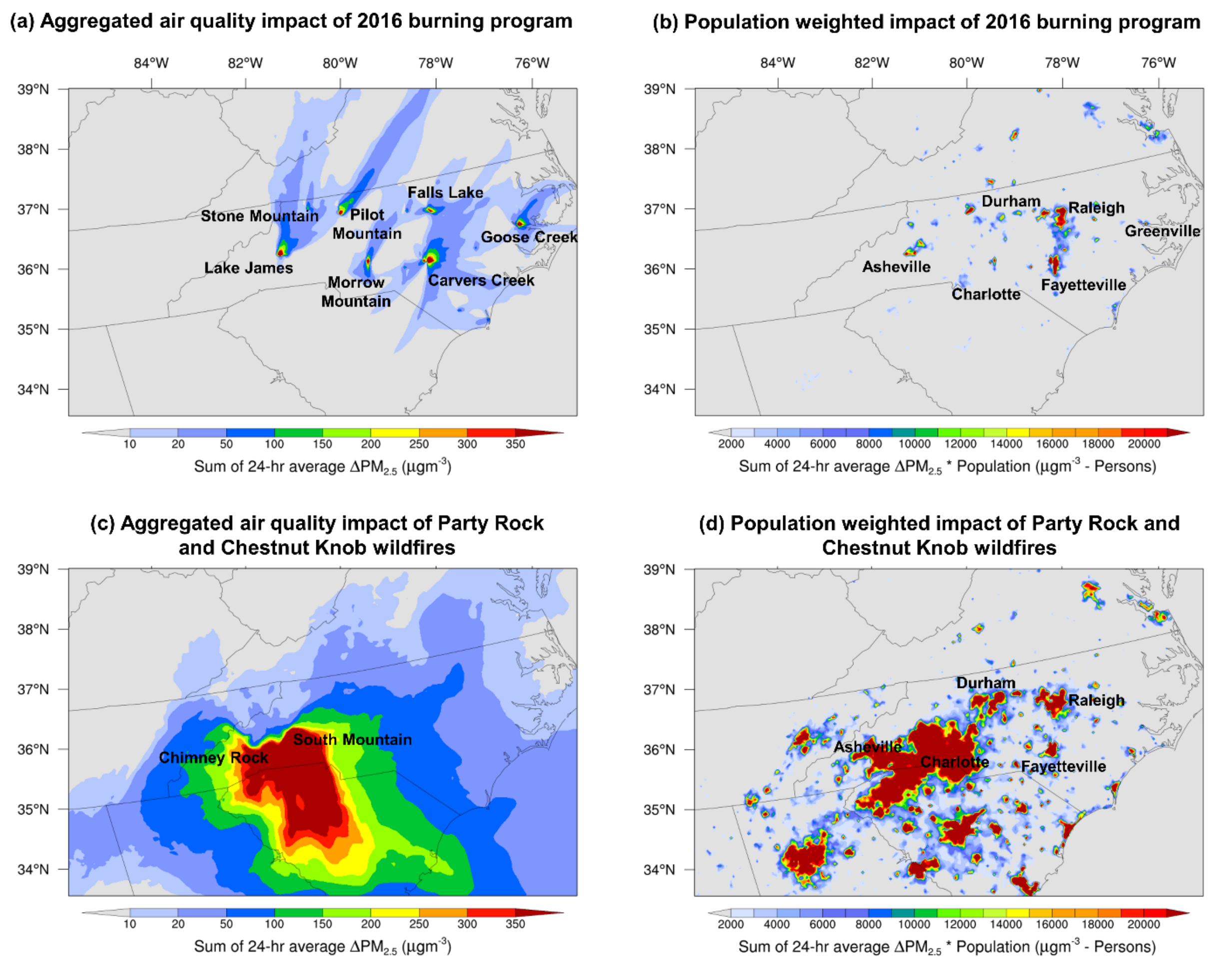

Figure 4. Aggregated air quality impacts associated with NC State Parks' 2016 prescribed burning program, and the Party Rock and Chestnut Knob wildfires. Annual sum of fire-related increases in 24-hr average (a) $PM_{2.5}$ concentrations and (b) population-weighted $PM_{2.5}$ concentrations associated with prescribed burning program fires. Annual sum of fire-related increases in 24-hr average (c) $PM_{2.5}$ concentrations and (d) population-weighted $PM_{2.5}$ concentrations associated with the two wildfires that occurred at Chimney Rock and South Mountain State Parks.

Air quality impacts of prescribed fire vary significantly across burn and locations

Smoke concentrations and transport associated with prescribed burn emissions vary by day and park. Figure 5 shows smoke concentration, magnitude and location of downwind impacted population, and size of individual burns occurring at the six NC State Parks with the most burning activity in 2016. Our analysis of 57 prescribed fires conducted in 2016, revealed a statistically significant positive association between the fire-related $PM_{2.5}$ concentrations at the park and burn size, with a correlation coefficient of 0.85. The analysis also showed an average increase in fire-related $PM_{2.5}$ concentrations of 1.3 ± 0.2 μg m^{-3} per 10 acres increase in burn area. Impacts differ depending on park location. For example, a 160-acre burn increased $PM_{2.5}$ concentration by 10 to 18 μg m^{-3} depending on the park. Burns of similar size do not always lead to similar increases in $PM_{2.5}$, even within the same park. For instance, three similar-sized (~95-acre) fires occurring on different days at Carvers Creek State Park produced maximum $PM_{2.5}$ concentrations ranging from 5 to 20 μg m^{-3}.

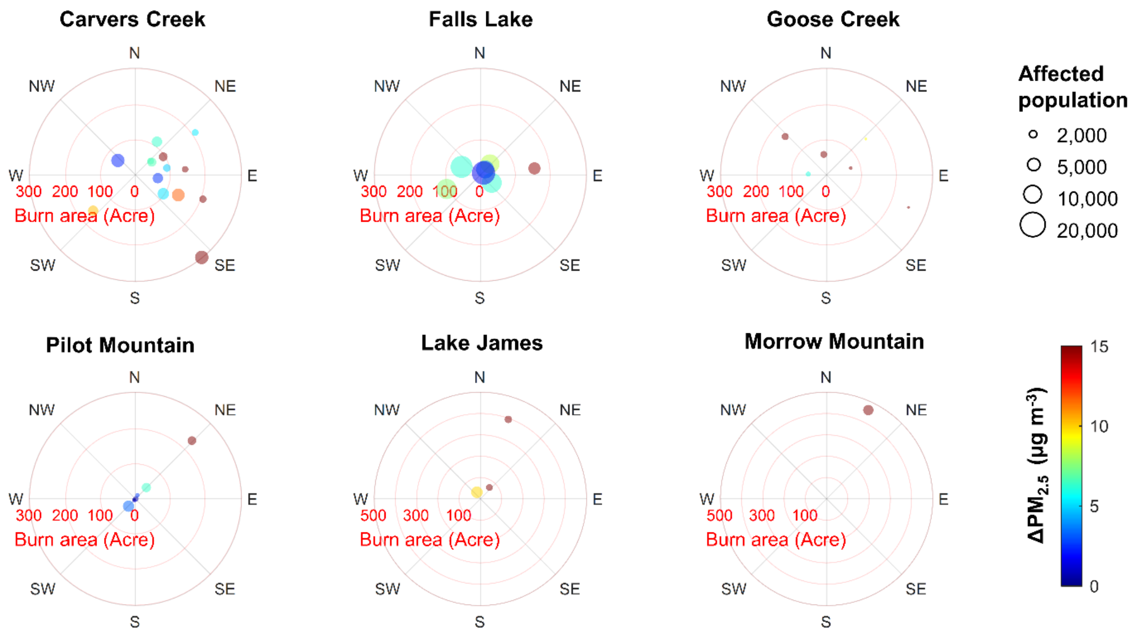

Figure 5. $PM_{2.5}$ concentration, magnitude and location of downwind affected population, and area burned for individual prescribed fires conducted at the six NC State Parks with the highest burn activity in 2016. Circle colors represent the simulated increase in 24-hour $PM_{2.5}$ concentration at park. Circle sizes represents the total population exposed to fire-related $PM_{2.5}$ within 20 km. The distance and location of the circles from the center of the plots denote area burned and the direction of downwind affected population relative to the fire, respectively.

In terms of affected population, the prescribed burns at NC State Parks' typically expose less than 5,000 residents to a fire-related increase in $PM_{2.5}$ within 20 km of the burns, except for few burns at Falls Lake State Park. Fires causing similar levels of fire-related ambient $PM_{2.5}$ can expose a populations 3 to 4 times larger to smoke at Falls Lake State Park compared to Carvers Creek State Park, due to higher population density around the park. In addition to population distribution, the affected population also depends on wind speed and direction, as shown in Figure 5. For example, a 395-acre burn at Lake James generated pollutant concentrations 8 times higher than those from a much smaller burn (35 acres) at the park on a different day, but affected 2.5 times less population. The results highlight that beyond burn size and location, burn-day meteorology is critical to reduce the smoke exposure and minimize the population affected by land management.

Air quality impacts of 2016 wildfires in NC State Parks land

Wildfires on NC State Parks had significant air quality impacts in 2016 and substantially larger impacts than prescribed fires

The air quality simulations conducted to assess the effects of 2016 wildfires on NC State Parks' land show a significant impact of the PR and CK wildfires on regional air quality. The magnitude of fire-related $PM_{2.5}$ concentrations and affected downwind area associated with these two wildfires varies slightly depending on the fire-activity data used (Figure 6). In general, the satellite images of PR and CK wildfire smoke plumes (Figure 6a) are consistent with $PM_{2.5}$ concentrations modeled using either SMARTFIRE (Figure 6b) or ground-based information (Figure 6c) at the time of the satellite overpass (2:00 PM local time). The differences in the simulations based on the two distinct sources of fire data, do not indicate a consistent or systematic difference between them (Figure 6d). However, the SMARTFIRE-based simulation tends to predict lower fire-related $PM_{2.5}$

concentrations than the ground data-based simulation on cloudy days and the following day. This is evident in some of the time-varying predictions of fire-related $PM_{2.5}$, such as those at the Asheville and Charlotte AQS sites. In the subsequent analyses, we relied on the base-case simulation that used ground-based fire information for the PR and CK fires. Based on this simulation, the PR and CK wildfires are estimated to have increased daily $PM_{2.5}$ concentration by 35 μg m^{-3} on average at South Mountain and Chimney Rock State Parks while they were occurring from November 5 to November 21. The maximum modeled $PM_{2.5}$ increases attributable to the two wildfires at the parks was 111 μg m^{-3} and 77 μg m^{-3} on November 13 at the South Mountain and Chimney Rock State Parks, respectively.

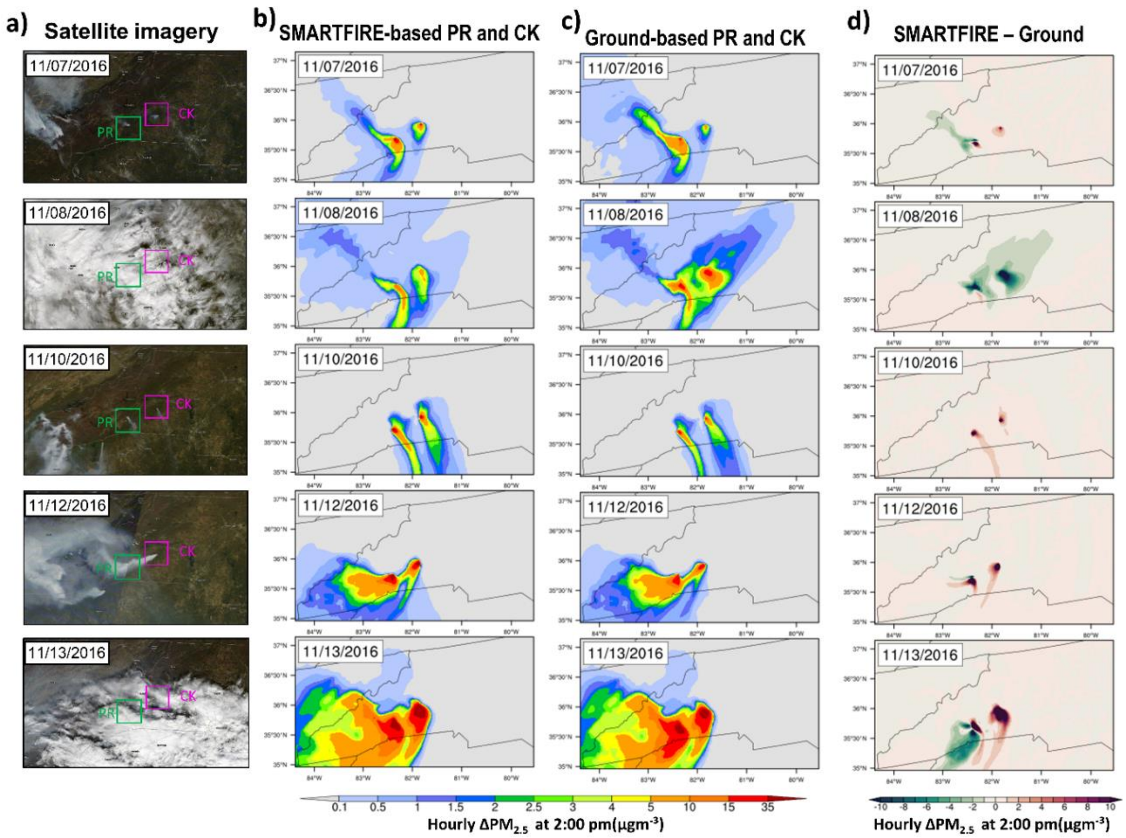

Figure 6. Daily impacts of Party Rock (PR) and Chestnut Knob (CK) wildfires on air pollution during their occurrence on November 2016. (a) MODIS (Aqua) satellite imagery of PR and CK wildfire plumes at 2:00 pm local time on 5 selected days. Modeled impact of PR and CK wildfires on hourly-average $PM_{2.5}$ concentrations at time of satellite overpass based on simulations using (b) SMARTFIRE fire data, and (c) ground-reported burn area. (d) Difference in modeled hourly-average $PM_{2.5}$ concentrations based on the two fire data sources used [(b) –(c)].

Compared to the localized impacts of the prescribed burns, the two wildfires are estimated to have had significant regional-scale air quality impacts (Figure 4c). According to our simulations, the PR and CK wildfires increased annual average $PM_{2.5}$ concentrations at these parks by 2.9 and 2.1 μg m^{-3}, respectively. As they occurred in the western region of the state, the two wildfires mostly affected southwestern North Carolina locations, such as Asheville and Charlotte. However, long-distance transport of smoke reached north and central areas of North Carolina (e.g., the Raleigh-Durham and Winston-Salem metro areas), as well as out-of-state population in Georgia and South Carolina. Wildfire smoke from these two wildfires exposed one-fifth of the population in the modeling domain to an increase in $PM_{2.5}$ greater than 3 µg m^{-3} for at least one a day, around 30 times higher than the population affected by the entire NC State Parks burning program in 2016.

A comparison of the air quality costs and benefits of wild and prescribed fire

We examined the trade-offs between the smoke impacts of prescribed burning and the wildfire air pollution avoided with prescribed fire fuel treatment by simulating historical and hypothetical wildland fire scenarios with an emissions and air quality modeling framework. In this project, we simulated the air pollution impacts of the two large wildfires that occurred at North Carolina State Parks in 2016, the Party Rock (PR) and Chestnut Knob (CK) fires. We then modeled prescribed fire and post-treatment wildfire air pollution scenarios respectively based on existing fuel loads at the parks and estimated fuel reductions from prescribed burning.

Prescribed fire treatment can reduce wildfire-related air pollution

We projected the air quality impacts of prescribed fire treatment at Chimney Rock and South Mountains State Parks by modeling hypothetical fires at the parks on days suitable for burning throughout the year. We consider prescribed fire treatment for the complete area burned by the CK and PR wildfires within NC State Parks land, 6,435 and 7,142 acres respectively, by simulating a series of hypothetical 500-acre prescribed fires at Chimney Rock and South Mountain State Parks over the course of 13 and 14 days. We generated two 500-acre prescribed fire emission profiles based on existing fuel bed properties for each of the parks. By comparing air pollutant concentrations predicted by CMAQ simulations including and excluding emissions from the hypothetical burns, we quantified the impacts of these 27 hypothetical prescribed burns.

The effect of prescribed fire treatment on fuel loads and fire emissions varies by park. Both South Mountain and Chimney Rock State Park fuels were represented in our simulations by two basic FCCS fuel beds: (1) FB-275 (chestnut, white, northern red oak dominated forest) and (2) FB-404 (yellow poplar, sugar maple, white ash, and basswood dominated forest). A 500-acre prescribed fire was estimated to consume close to 11.9 tons per acre burned at South Mountain, slightly higher than the 11.5 tons per acre consumption rate at Chimney Rock. Overall, 500-acre prescribed burns were estimated to reduce the available fuel loads by 16% to 29% depending on fuel bed and park. Wildfire fuel consumption and $PM_{2.5}$ emissions were estimated to decrease by 24% to 38% with prescribed fire treatment. Figures 7 and 8 show simulated increases in daily-average $PM_{2.5}$ concentrations associated with the PR and CK wildfires post prescribed fire treatment and hypothetical prescribed fires. The 500-acre burns increased daily-average $PM_{2.5}$ concentrations at the parks by 4.3 to 10.4 µg m^{-3}.

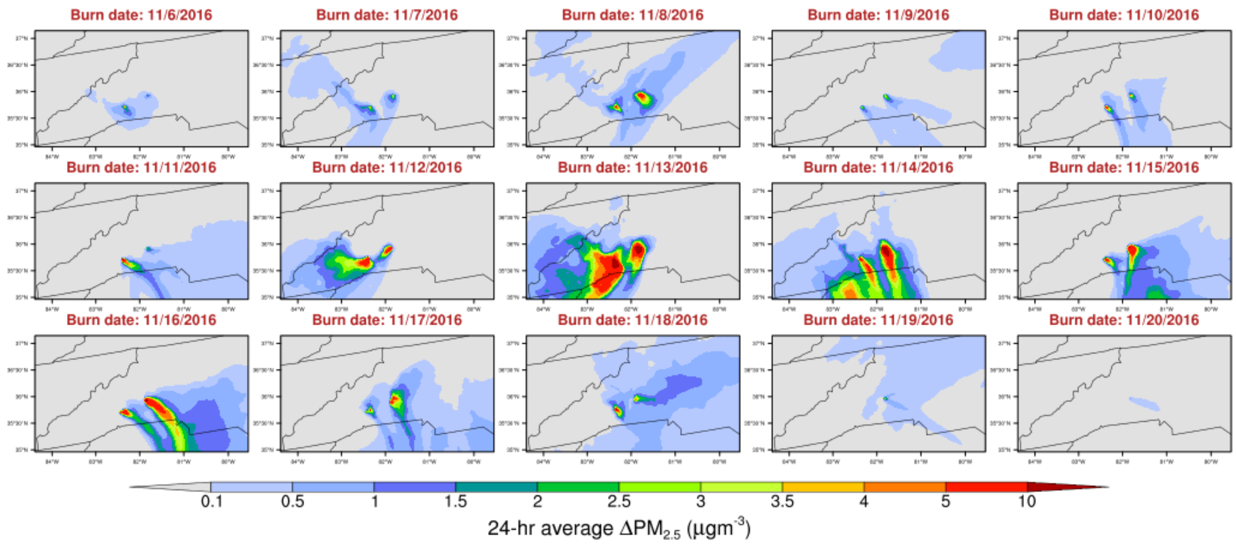

Figure 7. Simulated increase in 24-hr average $PM_{2.5}$ concentrations associated with the PR and CK wildfires at Chimney Rock and South Mountain State Parks after prescribed fire treatment, from November 6 to November 2016.

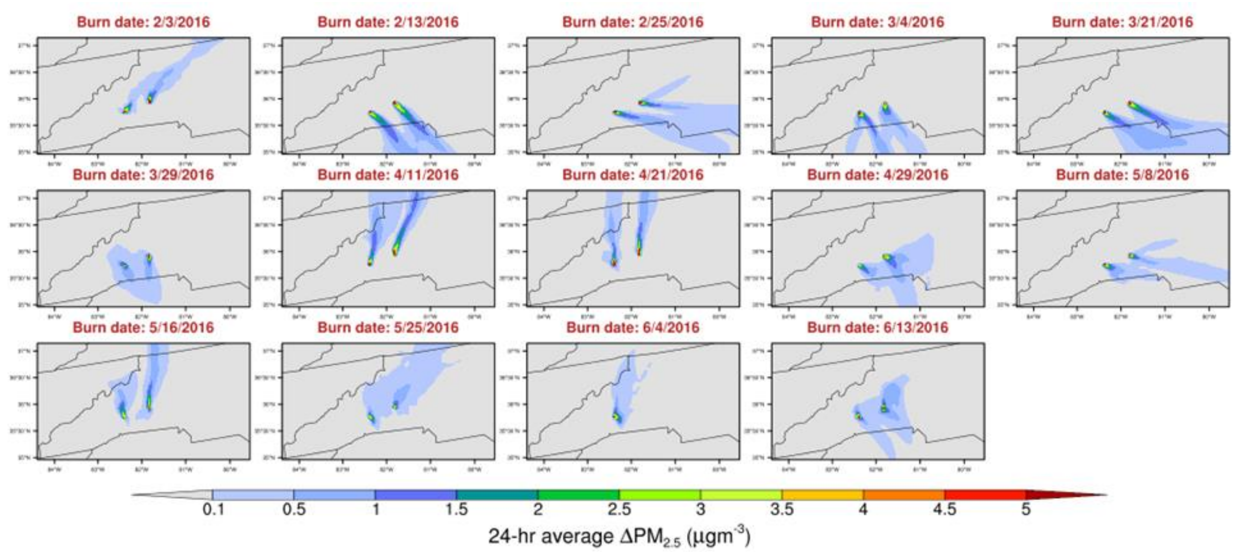

Figure 8. Simulated increase in 24-hr average $PM_{2.5}$ concentrations associated with the hypothetical 500-acre prescribed fires modeled at Chimney Rock and South Mountain State Parks on burn days.

The air quality benefits of prescribed fire treatment resulting from avoided wildfire pollution can exceed the pollution caused by the prescribed burns

The summed air quality impacts of the PR and CK wildfires and hypothetical prescribed fires are shown in Figure 9 and indicate that the wildfire $PM_{2.5}$ pollution avoided by prescribed fire treatment is greater than the $PM_{2.5}$ pollution caused by prescribed fire emissions. Compared to the historical PR and CK wildfire impacts, the extent and magnitude of simulated wildfire-related $PM_{2.5}$ pollution are reduced in the post-treatment simulations. Prescribed fire treatment leads to a maximum reduction of 26 μg m^{-3} at South Mountain State Park on the day with the highest wildfire impacts. Overall, the hypothetical prescribed fire treatment reduces annual average $PM_{2.5}$ concentrations associated with the PR and CK wildfires by 23% (0.32 μg m^{-3}) and 24% (0.36 μg

m^{-3}) at Chimney Rock and South Mountain respectively. The prescribed fire themselves would increase the annual average 24-hr $PM_{2.5}$ concentrations at Chimney Rock and South Mountain State Parks by 0.28 and 0.27 µg m^{-3}, respectively. Further downwind from the parks, the avoided wildfire pollution resulting from prescribed fire treatment clearly outweighs the impact of the hypothetical burns.

Daily variations in smoke pollution under each fire scenario simulated are presented in Figure 9e. The figure shows the average increase in daily fire-related $PM_{2.5}$ concentrations associated with the PR and CK wildfires or hypothetical wildfires within a 100 km ×100 km window centered on the State Parks. As shown, the impacts of prescribed fires vary based on burn-day meteorology and mostly affect air quality during the day of the burn only. The daily increases in prescribed fire-related $PM_{2.5}$ concentrations are much smaller than the daily wildfire-related $PM_{2.5}$ increases, as well as the wildfire $PM_{2.5}$ impacts avoided with prescribed fire treatment. Within the 100 km^2 window examined, prescribed fires would increase daily $PM_{2.5}$ by 0.4 to 1.3 µg m^{-3} on the day of the burn. In contrast, prescribed fire treatment would decrease daily $PM_{2.5}$ wildfire impacts within the window under the post-treatment wildfire scenario by 0.1 to 2.8 µg m^{-3}.

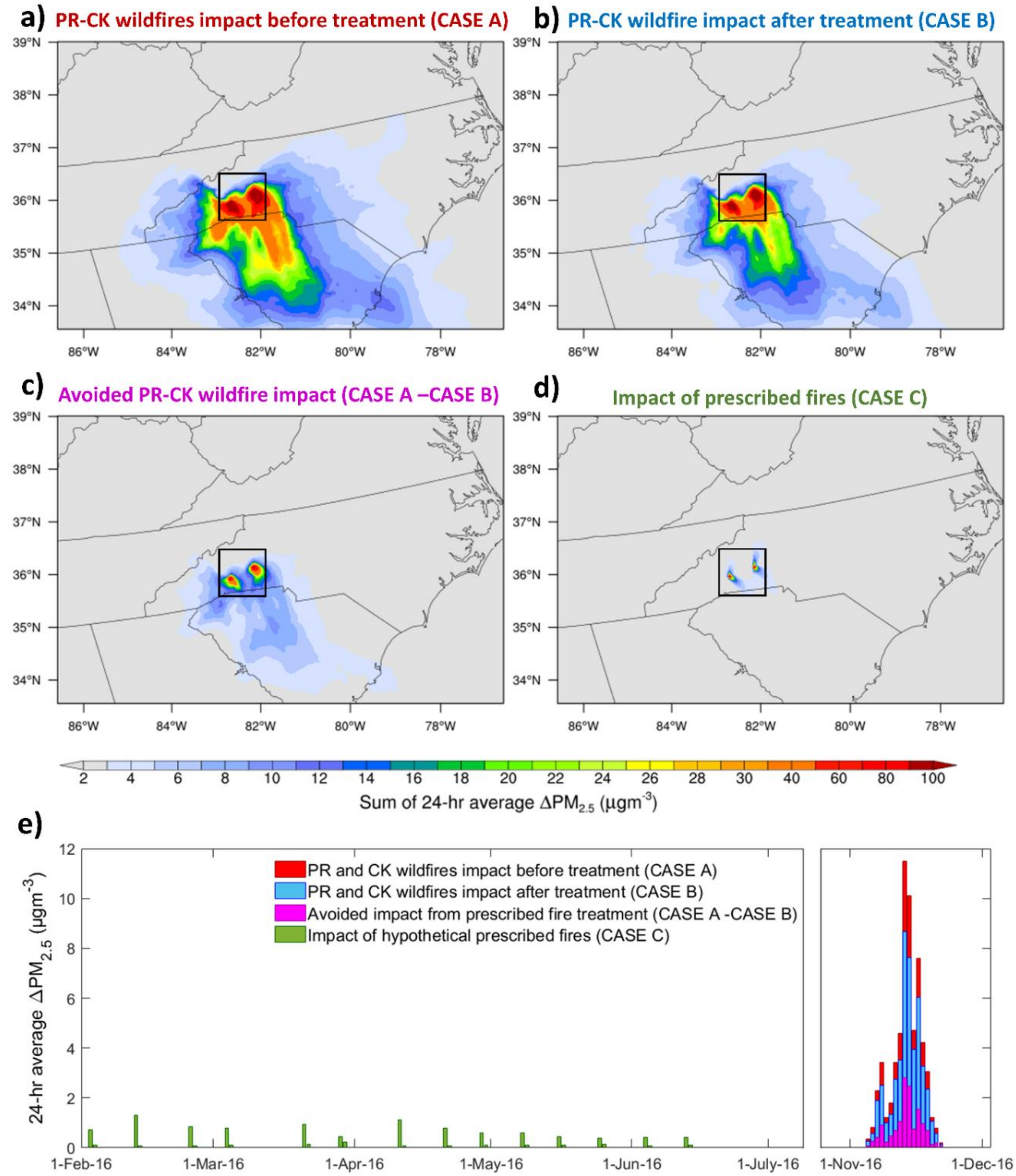

Figure 9. Air quality trade-offs and benefits of wildfire and prescribed fire smoke. (a) Impact of PR and CK wildfires before prescribed fire treatment (CASE A); (b) Impact of post-treatment PR and CK wildfires (CASE B); (c) Avoided impact of PR and CK wildfires attained by prescribed fire treatment; (d) Impact of hypothetical prescribed fires (CASE C); (e) temporal distribution of impacts under different scenarios. Figures 3a to 3d show the sum of 24-hr average increases in $PM_{2.5}$ concentrations attributable to the wildfires and prescribed burns simulated at Chimney Rock and South Mountain State Parks under the scenarios considered. In panel (e), impacts are estimated as average fire-related increases to 24-hour $PM_{2.5}$ concentrations within the 100 km2 windows centered on the State Parks shown on panels (a-d).

Air quality modeling of wildland fire in NC State Parks finds that more people benefit from prescribed fire than are negatively impacted

Similar to downwind affected area, the population favored by avoided wildfire smoke after prescribed fire treatment is larger than the population affected by prescribed burning smoke (Figure 10). Here, favored population is defined as the total population who would experience smoke from the PR and CK wildfires at a given ambient $PM_{2.5}$ level on fewer days had land treatment been conducted at the State Parks relative to the historical wildfire scenario. The affected population is defined as the total population that would experience prescribed fire smoke at a given ambient $PM_{2.5}$ level for at least one additional day due to the prescribed burning in the hypothetical treatment scenario. The population in downwind grid cells closest to the parks is most affected (Figure 10b), while the populations from North Carolina and out-of-state metropolitan areas, including Charlotte, Raleigh-Durham, and Atlanta, are favored by avoided wildfire smoke as a result of prescribed fire treatment (Figure 10a).

Overall, the hypothetical prescribed fire treatment is estimated to expose ~0.7 million people to an ambient $PM_{2.5}$ concentration increase of over 1μg m^{-3} for at least one day, while it prevents ~9.6 million from exposure to that level of wildfire smoke pollution for at least 1 day (Figure 10c). Additionally, we summarize the downwind population that would experience a larger or smaller number of days with different levels of fire-related smoke pollution had prescribed fire treatment been conducted in Figure 10c. The population either being favored or affected decreases rapidly as the number of days considered is increased. For example, over 70% of the population favored by prescribed fire treatment experience an ambient fire-related $PM_{2.5}$ concentration greater than 1μg m^{-3} on one fewer day. Only 0.4% of the favored population experiences a reduction greater than 1μg m^{-3} in daily wildfire-related $PM_{2.5}$ on more than 4 days. In contrast, over 2.5% of the affected population experience 24-hour $PM_{2.5}$ >1μg m^{-3} associated with prescribed fire for more than 4 days. These results highlight the fact that prescribed fire treatment reduces the severity of wildfire air pollution, but exposes the nearby population to prescribed fire smoke on more days. However, considering both the population impacted and frequency of the smoke impacts reveals that favorable changes to wildfire pollution brought about by land treatment significantly outweigh air pollution resulting from the hypothetical prescribed burns themselves.

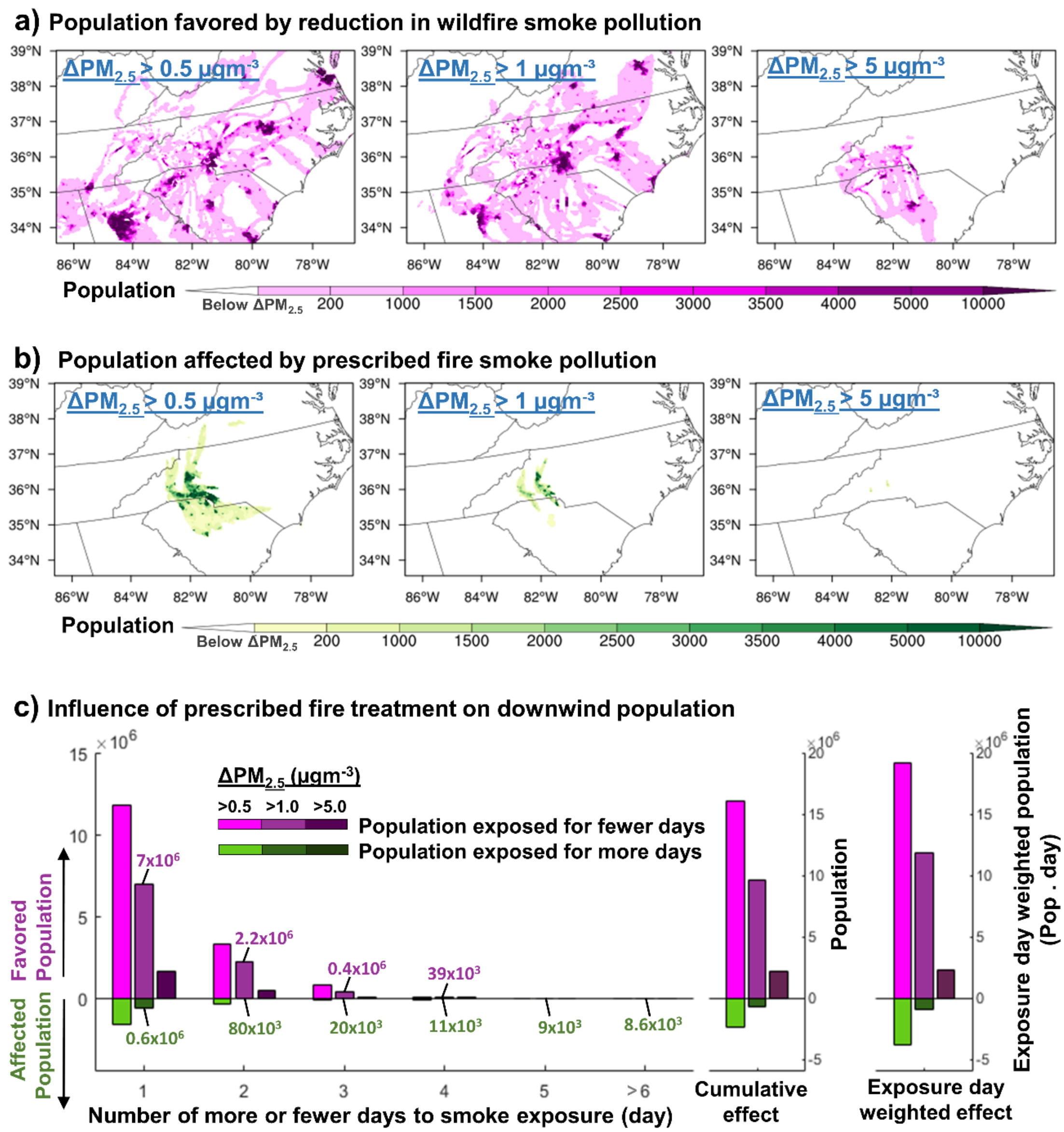

Figure 10. Spatial and temporal distribution of population affected and favored by prescribed fire treatment at Chimney Rock and South Mountain State Parks, based on 3 levels of fire-related $PM_{2.5}$ (>0.5μg m^{-3}, >1μg m^{-3}, >5μg m^{-3}). (a) Spatial distribution of population that would experience at least 1 fewer day of wildfire smoke associated with the PR and CK wildfires as a result of prescribed fire treatment at the parks. (b) Spatial distribution of population affected by prescribed fire smoke for at least one day. (c) Domain-total affected and favored population by the number of additional or fewer days with fire-related $PM_{2.5}$ at the 3 levels considered. Bars labeled as cumulative effect show the total number of affected or favored population in 2016. Bars labeled exposure weighted cumulative effect show the sum of affected or favored population multiplied by the corresponding number of additional or fewer days with smoke pollution at each level.

6. Conclusions: Key Findings and Implications for Management/Policy and Future Research

Key Findings and Implications for Management/Policy

In this section the key findings of this research are extracted from the results and discussion above and their implications for management and policy are highlighted.

1) The modeling analysis conducted in this study indicates that the air quality impacts of an operational prescribed burning program (North Carolina Division of Parks and Recreation in 2016) are limited and largely concentrated in areas neighboring the burns. Air quality impacts can vary significantly by location and burn conditions.
2) Compared to prescribed fire, wildfires can have much larger air quality impacts that extend over greater areas and expose substantially higher population to smoke. In our comparison of wildland fire on NC State Parks land in 2016, aggregated smoke impacts of all fires realized by the program was substantially lower than that of the two wildfires that occurred within the State Parks land during that year.
3) Prescribed fire can lead to net air quality benefits by reducing the air pollution impacts of wildfires. Our simulations of prescribed burning effects on NC State Park’s land show that reductions in fuel loads achieved with prescribed fire treatment can significantly reduce pollutant emissions and transport associated with wildfire.
4) Our comparison of the air quality cost and benefits of prescribed fire and wildfire finds that the air quality benefits of prescribed fire, achieved by reducing the wildfire pollution, can largely exceed the air pollution impacts of the prescribed burning. In the analysis of the NC State Parks burning program, the population that would benefit from reduced pollution from wildfires in 2016 is larger than the population affected by prescribed fires needed to treat the land affected by wildfires by millions of residents.
5) Although a larger population likely benefits from improved air quality resulting from prescribed burning programs, prescribed fire can expose nearby communities to smoke pollution more frequently. It is important to understand and mitigate the negative impacts of prescribed fire smoke on these communities, especially for groups that are socially vulnerable communities or disproportionately impacted by smoke.

Future Research

To better compare the air pollution costs and benefits of wildfire and prescribed fire, improved data, modeling tools, and observations are needed. To accurately simulate regional-scale impacts of small-intensity prescribed fires, it is necessary to have more complete data describing prescribed burning activities and conduct integrated modeling and field research. Improved compilations of multi-year prescribed burn data across the U.S. would improve our understanding of prescribed fire effects on fire regimes, and better represent their impact within the modeling framework. A high spatial and temporal resolution fire-weather-atmospheric modeling framework, with improved representations of plume rise, plume chemistry, fire emissions, and diurnal profiles is needed to address some of the uncertainties in existing air quality models when applied to fire-related pollution. Additionally, continued measurements of fuel loads, emission factors, soil properties, PBL heights, and pollutant concentrations are also needed to improve and evaluate model performance. Such integrated modeling and measurement efforts would also be useful to assess the ability of new high-resolution satellite products to detect low-intensity and short-duration prescribed fires.

Future work coupling fire-spread models with an emissions and air quality modeling framework would be useful to better represent changes and interactions in wildfire likelihood and severity under different land management scenarios. Additionally, our sensitivity analyses highlight the need for research to improve fire location data, burn detection algorithms, and parameterizations of fire emission, especially during cloudy days. In particular, studies examining real-time fuel loads and consumption, fire behavior, and pollutant emission would aid in assessing the possible sources of uncertainties that might be leading to underestimation of peak pollutant concentrations relative to monitor observations, in chemical transport model simulations of wildland fire smoke.

7. Literature Cited

Addington, R. N., Hudson, S. J., Hiers, J. K., Hurteau, M. D., Hutcherson, T. F., Matusick, G., & Parker, J. M. (2015). Relationships among wildfire, prescribed fire, and drought in a fire-prone landscape in the Southeastern United States. International Journal of Wildland Fire, 24(6), 778–783.

Afrin, S., & Garcia-Menendez, F. (2020). The Influence of Prescribed Fire on Fine Particulate Matter Pollution in the Southeastern United States. Geophysical Research Letters, 47(15).

Altshuler, S. L., Zhang, Q., Kleinman, M. T., Garcia-Menendez, F., Moore, C. T., Hough, M. L., et al. (2020). Wildfire and prescribed burning impacts on air quality in the United States. Journal of the Air and Waste Management Association, 70(10), 961–970.

Arthur, M. A., Blankenship, B. A., Schörgendorfer, A., & Alexander, H. D. (2017). Alterations to the fuel bed after single and repeated prescribed fires in an Appalachian hardwood forest. Forest Ecology and Management, 403, 126-136.

Bagdon, B., & Huang, C. (2016). Review of Economic Benefits from Fuel Reduction Treatments in the Fire Prone Forests of the Southwestern United States. Southern Fire Science Consortium. 11p.

Baker, K. R., Woody, M. C., Tonnesen, G. S., Hutzell, W., Pye, H. O. T., Beaver, M. R., et al. (2016). Contribution of regional-scale fire events to ozone and PM2.5 air quality estimated by photochemical modeling approaches. Atmospheric Environment, 140, 539–554.

Bash, J. O., Baker, K. R., & Beaver, M. R. (2016). Evaluation of improved land use and canopy representation in BEIS v3.61 with biogenic VOC measurements in California. Geoscientific Model Development, 9, 2191–2207.

Black, C., Tesfaigzi, Y., Bassein, J. A., & Miller, L. A. (2017). Wildfire smoke exposure and human health: Significant gaps in research for a growing public health issue. Environmental Toxicology and Pharmacology, 55, 186-195.

Cascio, W. E. (2018). Science of the Total Environment Wildland fire smoke and human health. Science of the Total Environment, 624, 586–595.

Emery, C., Liu, Z., Russell, A. G., Odman, M. T., Yarwood, G., & Kumar, N. (2017). Recommendations on statistics and benchmarks to assess photochemical model performance. Journal of the Air and Waste Management Association, 67(5), 582–598.

Fann, N., Alman, B., Broome, R. A., Morgan, G. G., Johnston, F. H., Pouliot, G., & Rappold, A. G. (2018). The health impacts and economic value of wildland fire episodes in the U.S.: 2008–2012. Science of the Total Environment, 610–611, 802–809.

Hunter, M. E., & Robles, M. D. (2020). Tamm review: The effects of prescribed fire on wildfire regimes and impacts: A framework for comparison. Forest Ecology and Management, 475, 118435.

Huang, R., Hu, Y., Russell, A. G., Mulholland, J. A., & Odman, M. T. (2019). The impacts of prescribed fire on PM2.5 air quality and human health: Application to asthma-related emergency room visits in Georgia, USA. International Journal of Environmental Research and Public Health, 16(13), 2312.

Hyde, J., & Strand, E. K. (2019). Comparing modeled emissions from wildfire and prescribed burning of post-thinning fuel: A case study of the 2016 pioneer fire. Fire, 2(2), 1–16.

Jaffe, D. A., O'Neill, S. M., Larkin, N. K., Holder, A. L., Peterson, D. L., Halofsky, J. E., & Rappold, A. G. (2020). Wildfire and prescribed burning impacts on air quality in the United States. Journal of the Air and Waste Management Association. 70(10), 961-970.

Kain, J. S., & Kain, J. (2004). The Kain - Fritsch convective parameterization: An update. Journal of Applied Meteorology, 43(1), 170–181.

Kalies, E. L., & Yocom Kent, L. L. (2016). Tamm Review: Are fuel treatments effective at achieving ecological and social objectives? A systematic review. Forest Ecology and Management, 375, 84–95.

Krofcheck, D. J., Loudermilk, E. L., Hiers, J. K., Scheller, R. M., & Hurteau, M. D. (2019). The effects of management on long-term carbon stability in a southeastern U.S. forest matrix under extreme fire weather. Ecosphere, 10(3), e02631.

Larkin, N. K., O'Neill, S. M., Solomon, R., Raffuse, S., Strand, T., Sullivan, D. C., et al. (2009). The BlueSky smoke modeling framework. International Journal of Wildland Fire, 18(8), 906–920.

Larkin, S., & Raffuse, S. (2015). Emissions Processing-SmartFire Details. In EPA's 2015 Emission Inventory Conference. San Diego, California. Retrieved from https://www.epa.gov/sites/production/files/2015-09/documents/emissions_processing_sf2.pdf

Larsen, A. E., Reich, B. J., Ruminski, M., & Rappold, A. G. (2017). Impacts of fire smoke plumes on regional air quality, 2006–2013. Journal of Exposure Science and Environmental Epidemiology, 28(4), 319-327.

Liu, J. C., Pereira, G., Uhl, S. A., Bravo, M. A., & Bell, M. L. (2015). A systematic review of the physical health impacts from non-occupational exposure to wildfire smoke. Environmental Research, 136, 120–132. https://doi.org/10.1016/j.envres.2014.10.015

Liu, X., Huey, L. G., Yokelson, R. J., Selimovic, V., Simpson, I. J., Müller, M., et al. (2017). Airborne measurements of western U.S. wildfire emissions: Comparison with prescribed burning and air quality implications. Journal of Geophysical Research, 122(11), 6108–6129.

Myers, R. J., Powell, W., & Megalos, M. (2012). Prescribed burning cost recovery analysis on nonindustrial private forestland in North Carolina. In Proceedings of the 16th Biennial Southern Silvicultural Research Conference. e-Gen. Tech. Rep. SRS-156. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station. 230-234 (pp. 230–234).

Navarro, K. M., Cisneros, R., O'Neill, S. M., Schweizer, D., Larkin, N. K., & Balmes, J. R. (2016). Air-quality impacts and intake fraction of PM2.5 during the 2013 Rim Megafire. Environmental Science and Technology, 50(21), 11965–11973.

Navarro, K. M., Schweizer, D., Balmes, J. R., & Cisneros, R. (2018). A review of community smoke exposure from wildfire compared to prescribed fire in the United States, Atmosphere, 9(5), 185.

Powers, J. G., Klemp, J. B., Skamarock, W. C., Davis, C. A., Dudhia, J., Gill, D. O., et al. (2017). The weather research and forecasting model: Overview, system efforts, and future directions. Bulletin of the American Meteorological Society, 98(8), 1717–1737.

Ottmar, R. (2009). Consume 3.0 — A Software Tool for Computing Fuel Consumption. Fire Science Brief, (55), 1–6.

Ottmar, R. D., Sandberg, D. V., Riccardi, C. L., & Prichard, S. J. (2007). An overview of the Fuel Characteristic Classification System - Quantifying, classifying, and creating fuelbeds for resource planning. Canadian Journal of Forest Research, 37(12), 2383–2393.

Pleim, J. E. (2007). A Combined Local and Nonlocal Closure Model for the Atmospheric Boundary Layer. Part I: Model Description and Testing. Journals.Ametsoc.Org, 46(9), 1383–1395.

Ravi, V., Vaughan, J. K., Wolcott, M. P., & Lamb, B. K. (2018). Impacts of prescribed fires and benefits from their reduction for air quality, health, and visibility in the Pacific Northwest of the United States. Journal of the Air & Waste Management Association, 69(3), 289-304.

Reid, C. E., Brauer, M., Johnston, F. H., Jerrett, M., Balmes, J. R., & Elliott, C. T. (2016). Critical review of health impacts of wildfire smoke exposure. Environmental Health Perspectives, 124(9), 1334–1343.

Reisen, F., Duran, S. M., Flannigan, M., Elliott, C., & Rideout, K. (2015). Wildfire smoke and public health risk. International Journal of Wildland Fire, 24(8), 1029–1044.

Tian, D., Wang, Y., Bergin, M., Hu, Y., Liu, Y., & Russell, A. G. (2008). Air Quality Impacts from Prescribed Forest Fires under Different Management Practices. Environmental Science & Technology, 42(8), 2767–2772.

U.S. EPA. (2018). 2014 National Emissions Inventory, version 2 Technical Support Document, U.S. Environmental Protection Agency. Research Triangle Park, North Carolina. Retrieved from https://www.epa.gov/sites/production/files/2018-06/documents/nei2014v2_tsd_09may2018.pdf

Waldrop, T. A., Goodrick, S. L., Harper, C. A., Towne, G., Dixon, M. J., Mobley, H. E., et al. (2012). Introduction to Prescribed Fire in Southern Ecosystems. Science Update SRS-054, Asheville, NC: U.S. Department of Agriculture forest Service, Southern Research Station. 80 p., 54, 1-80.

Waldrop, T. A., Hagan, D. L., & Simon, D. M. (2016). Repeated application of fuel reduction treatments in the southern Appalachian Mountains, USA: Implications for achieving management goals. Fire Ecology, 12(2), 28–47.

Wiedinmyer, C., & Hurteau, M. D. (2010). Prescribed fire as a means of reducing forest carbon emissions in the western United States. Environmental Science and Technology, 44(6), 1926–1932.

Wilkins, J. L., Pouliot, G., Foley, K., Appel, W., & Pierce, T. (2018). The impact of US wildland fires on ozone and particulate matter: A comparison of measurements and CMAQ model predictions from 2008 to 2012. International Journal of Wildland Fire, 27(10), 684–698.

Zeng, T., Wang, Y., Yoshida, Y., Tian, D., Russell, A. G., & Barnard, W. R. (2008). Impacts of prescribed fires on air quality over the Southeastern United States in spring based on modeling and ground/satellite measurements. Environmental Science and Technology, 42(22), 8401–8406.

Zhao, F., Liu, Y., Goodrick, S., Hornsby, B., & Schardt, J. (2019). The contribution of duff consumption to fire emissions and air pollution of the Rough Ridge Fire. International Journal of Wildland Fire, 28(12), 993–1004. https://doi.org/10.1071/WF18205

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9. Appendix B: List of Completed/Planned Scientific/Technical Publications/Science Delivery Products

Detailed List of Deliverables

Articles in Peer-reviewed Journals

(1) Afrin, S. and F. Garcia-Menendez (2021). Potential impacts of prescribed fire smoke on public health and socially vulnerable populations in a Southeastern U.S. state. Science of the Total Environment, 794, 148712, doi: 10.1016/j.scitotenv.2021.148712.
(2) Afrin, S.*, K. R. Baker, S. N. Koplitz, and F. Garcia-Menendez (In preparation). Evaluating the Air Quality Benefits and Tradeoffs of Prescribed Fire in the Southeastern U.S. Submission planned for Environmental Science & Technology.
(3) Afrin, S.*, K. R. Baker, S. N. Koplitz, and F. Garcia-Menendez (In preparation). An Analysis of Smoke Mitigation in a Southeastern U.S. Prescribed Burning Program. Submission planned for International Journal of Wildland Fire.

Graduate Theses

(1) Afrin, S. (2021). Evaluating the Impacts of Prescribed Fire on Air Quality and Public Health in the Southeastern U.S. North Carolina State University.

Conference or Symposium Abstracts

(1) Afrin, S.*, F. Garcia-Menendez, S. N. Koplitz, and K. R. Baker. "The air quality trade-offs of wildfire and prescribed burning", Annual Community Modeling and Analysis System (CMAS) Conference, online, October 28, 2020
(2) Afrin, S.*, F. Garcia-Menendez, S. N. Koplitz, and K. R. Baker. "Model performance and sensitivity analysis of 2016 Western North Carolina wildfire events", International Smoke Symposium, online, April 21, 2020
(3) Afrin, S.*, F. Garcia-Menendez, S. N. Koplitz, and K.R. Baker. "Smoke exposure of an operational prescribed burning program", *International Smoke Symposium*, online, April 23, 2020

Posters

(1) Afrin, S. and F. Garcia-Menendez. "A machine-learning model for prescribed fire smoke in the Southeastern U.S.", American Geophysical Union Fall Meeting, New Orleans, LA, December 15, 2021
(2) Afrin, S., F. Garcia-Menendez, S. N. Koplitz, and K. R. Baker, "The air quality trade-offs of wildfire and prescribed burning", American Geophysical Union Fall Meeting, online, December 17, 2020

Webinars

(1) Afrin, S. and F Garcia-Menendez, "Potential Impacts of Prescribed Fire Smoke on Air Quality, Public Health, and Socially Vulnerable Populations in the Southeastern U.S.", Southern Fire Exchange Webinar, August 12, 2021, https://www.youtube.com/watch?v=3fTLlJj05bg.

10.Appendix C: Metadata:

Fire and smoke data

Prescribed fire and wildfire data, and modeled air pollution concentrations used for this study are publicly available at:

https://drive.google.com/drive/folders/1HyOwptbJKk22tlWUHb1q4Apv-0MotGdp?usp=sharing

Prescribed fire and wildfire data used for this study are available as a spreadsheet titled "NC_State_Parks_Wildland_Fire_2016.xlsx" accessible through the data weblink above. The spreadsheet includes data for all prescribed fires and wildfires that occurred on NC State Parks land in 2016 and used as a basis of this study. Fire ID, unit, burn area, date, and state park are included.

Air quality modeling results in NetCDF (network Common Data Form) file format describing multidimensional $PM_{2.5}$ concentrations attributable to prescribed fires and wildfire that occurred on NC State Parks land in 2016 are accessible through the data weblink above. The simulations, generated with the CMAQ air quality modeling system as described in Methods, are used as a basis to compare the air quality costs of prescribed burns and wildfires in this study. These include the following files:

1. "Daily_PM25_O3_4km_NC_State_Parks_RXfires_2016.nc": 24-hour average $PM_{2.5}$ and O_3 ground-level concentrations associated with emissions from all prescribed fires conducted on NC

State Parks in 2016. Concentrations are gridded, 4-km horizontal resolution, ground-level concentrations across NC and neighboring regions included on the modeling domain considered covering NC and neighboring areas. O_3 concentrations are reported as daily maximum 8-hour average concentration.

2. "Daily_PM25_O3_4km_NC_State_Parks_Wildfires_2016.nc": 24-hour average $PM_{2.5}$ and O_3 ground-level concentrations associated with emissions from all wildfires fires that occurred on NC State Parks in 2016. Concentrations are gridded, 4-km horizontal resolution, ground-level concentrations across NC and neighboring regions included on the modeling domain considered covering NC and neighboring areas. O_3 concentrations are reported as daily maximum 8-hour average concentration.