FINAL REPORT
Southern Integrated Prescribed Fire Information System for Air Quality and Health Impacts

JFSP PROJECT ID: 16-1-08-1

SEPTEMBER 2020

Mehmet Talat Odman
Georgia Institute of Technology

Fernando Garcia Menendez
North Carolina State University

Cassandra Johnson Gaither
U.S. Forest Service
The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the opinions or policies of the U.S. Government. Mention of trade names or commercial products does not constitute their endorsement by the U.S. Government.
Table of Contents
List of Tables ................................................................................................................................. ii
List of Figures ................................................................................................................................. ii
List of Abbreviations/Acronyms ................................................................................................. iii
Keywords ....................................................................................................................................... iv
Acknowledgements ................................................................................................................... iv
1. Abstract ................................................................................................................................. 1
2. Objectives ............................................................................................................................... 2
3. Background ............................................................................................................................. 2
4. Materials and Methods .......................................................................................................... 4
   Unified Southern U.S. Prescribed Burning Database ................................................................. 4
   Prescribed Fire and Air Quality Integrated Information System .............................................. 5
   Analysis of Observational Air Quality Record and Smoke Emissions-Dispersion Tools Performance ......................................................................................................................... 7
   Comprehensive Simulation of Regional Air Quality Impacts and Data Fusion for Exposure Assessments ................................................................................................................................. 8
   Human exposure, Health Impacts and Affected Communities ................................................... 10
5. Results and Discussion .......................................................................................................... 11
   Unified Southern U.S. Prescribed Burning Database ................................................................. 11
   Prescribed Fire and Air Quality Integrated Information System .............................................. 13
   Analysis of Observational Air Quality Record and Smoke Emissions-Dispersion Tools Performance ......................................................................................................................... 17
   Comprehensive Simulation of Regional Air Quality Impacts and Data Fusion for Exposure Assessments ................................................................................................................................. 22
   Human exposure, Health Impacts and Affected Communities ................................................... 25
6. Conclusions: Key Findings and Implications for Management/Policy and Future Research ................................................................. 29
   Key Findings and Implications for Management/Policy ........................................................... 29
   Future Research ....................................................................................................................... 30
7. Literature Cited ......................................................................................................................... 31
8. Appendix A: Contact Information for Key Project Personnel ............................................... A-1
9. Appendix B: List of Completed/Planned Scientific/Technical Publications/Science Delivery Products: ................................................. B-1
   Detailed List of Deliverables ...................................................................................................... B-1
   Articles in Peer-reviewed Journals .......................................................................................... B-1
   Text Books or Book Chapters ................................................................................................. B-1
   Graduate Theses ...................................................................................................................... B-2
   Conference or Symposium Abstracts ...................................................................................... B-2
List of Tables

Table 1. Prescribed fire data obtained from various states and organizations for the unified database............. 12
Table 2. Data attributes and fields included in permit-based prescribed fire data for NC, GA, and FL................. 12

List of Figures

Figure 1. Integrated information layers of the Southern Integrated Prescribed Fire Information System ........... 5
Figure 2. Daily statewide burn areas for Georgia and Florida during January-April 2015. ................................. 11
Figure 3. A visualization of the unified prescribed fire record for Florida ......................................................... 13
Figure 4. Visualization of the prescribed fire data for North Carolina ............................................................ 14
Figure 5. The air quality forecast and observations for March 10, 2016 ......................................................... 15
Figure 6. Forecast burns and burn impacts for March 10, 2016 ................................................................. 15
Figure 7. Permitted and forecast burns on March 10, 2016 ............................................................. 16
Figure 8. Fire detections, prescribed fire forecast and cloud cover on January 10 and March 22, 2019............ 17
Figure 9. Influence of prescribed burning on PM$_{2.5}$ in the southeastern U.S. ........................................... 18
Figure 10. Variability in PM$_{2.5}$ concentrations (2013-2016) by different types of burns. ............................... 19
Figure 11. Observed and simulated PM$_{2.5}$ and the fire impact on March 9–10, 2018 at Albany, GA ......... 21
Figure 12. Observed, CMAQ-simulated and data-fused PM$_{2.5}$ at Albany, GA ............................................. 22
Figure 13. January–April prescribed fire impacts on PM$_{2.5}$ for 2015–2018 ............................................... 23
Figure 14. Observed versus data-fused PM$_{2.5}$ for January–April of 2015–2018 .............................................. 24
Figure 15. Estimated asthma-related ER visits by county in Georgia for January–April of 2015–2018 ......... 25
Figure 16. Clusters of local spatial autocorrelation: a) burn activity, and b) social vulnerability index (SVI) ....... 27
Figure 17. Prescribed fire health impacts within spatial clusters of burn activity and SVI in Georgia .......... 28
**List of Abbreviations/Acronyms**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>BBEP</td>
<td>Biomass Burning Emissions Product</td>
</tr>
<tr>
<td>BenMAP</td>
<td>Environmental Benefits Mapping and Analysis Program</td>
</tr>
<tr>
<td>BlueSky</td>
<td>A modeling framework designed to predict cumulative impacts of smoke from forest, agricultural, and range fires.</td>
</tr>
<tr>
<td>CDF</td>
<td>Common Data Format</td>
</tr>
<tr>
<td>CMAQ</td>
<td>Community Multiscale Air Quality model</td>
</tr>
<tr>
<td>CO</td>
<td>Carbon monoxide</td>
</tr>
<tr>
<td>CO₂</td>
<td>Carbon dioxide</td>
</tr>
<tr>
<td>DASI</td>
<td>Dispersive Apportionment of Source Impacts</td>
</tr>
<tr>
<td>Daysmoke</td>
<td>An empirical-statistical plume rise and dispersion model for simulating smoke from prescribed burns</td>
</tr>
<tr>
<td>DEASCO3</td>
<td>Deterministic and Empirical Assessment of Smoke's Contribution to Ozone project</td>
</tr>
<tr>
<td>EF</td>
<td>Emission Factor</td>
</tr>
<tr>
<td>EPA</td>
<td>Environmental Protection Agency</td>
</tr>
<tr>
<td>FCCS</td>
<td>Fuel Characteristic Classification System</td>
</tr>
<tr>
<td>FEPS</td>
<td>Fire Emission Production Simulator</td>
</tr>
<tr>
<td>GFC</td>
<td>Georgia Forestry Commission</td>
</tr>
<tr>
<td>GFED</td>
<td>Global Fire Emissions Database</td>
</tr>
<tr>
<td>GIS</td>
<td>Geographic Information Systems</td>
</tr>
<tr>
<td>GOES</td>
<td>Geostationary Operational Environmental Satellite</td>
</tr>
<tr>
<td>HYSPLIT</td>
<td>Hybrid Single Particle Lagrangian Integrated Trajectory Model</td>
</tr>
<tr>
<td>JSON</td>
<td>Java Script Object Notation</td>
</tr>
<tr>
<td>NEI</td>
<td>National Emission Inventory</td>
</tr>
<tr>
<td>NO</td>
<td>Nitric oxide</td>
</tr>
<tr>
<td>NO₂</td>
<td>Oxides of nitrogen</td>
</tr>
<tr>
<td>O₃</td>
<td>Ozone</td>
</tr>
<tr>
<td>PAN</td>
<td>Peroxy Acetyl Nitrate</td>
</tr>
<tr>
<td>PM</td>
<td>Particulate Matter</td>
</tr>
<tr>
<td>PM₂.₅</td>
<td>PM with aerodynamic diameter smaller than 2.5 microns</td>
</tr>
<tr>
<td>PMDETAIL</td>
<td>Particulate Matter Deterministic and Empirical Tagging and Assessment of Impacts on Levels project</td>
</tr>
<tr>
<td>SFE</td>
<td>Southern Fire Exchange</td>
</tr>
<tr>
<td>SIPFIS</td>
<td>Southern Integrated Prescribed Fire Information System</td>
</tr>
<tr>
<td>SQL</td>
<td>Structured Query Language</td>
</tr>
<tr>
<td>TEMPO</td>
<td>Tropospheric Emissions: Monitoring of Pollution</td>
</tr>
<tr>
<td>US</td>
<td>United States</td>
</tr>
<tr>
<td>USDA</td>
<td>United States Department of Agriculture</td>
</tr>
<tr>
<td>USDA-FS</td>
<td>USDA Forest Service</td>
</tr>
<tr>
<td>VOC</td>
<td>Volatile Organic Compounds</td>
</tr>
<tr>
<td>WRF</td>
<td>Weather Research and Forecasting model</td>
</tr>
</tbody>
</table>
Keywords
Air quality, air quality management, air quality modeling, air quality monitoring, Biomass Burning Emissions Product (BBEP), burn acreage, burn activity, burn activity forecasting, burn area, Community Multiscale Air Quality (CMAQ) model, Decoupled Direct Method (DDM), emission contribution, environmental justice, exposure, fine particulate matter (PM₂.₅), fire activity, fire emissions, forecasting, forecast evaluation, Global Fire Emissions Database (GFED), Hybrid Single Particle Lagrangian Integrated Trajectory Model (HYSPLIT), prescribed burning, prescribed fire, respiratory effects, satellite detection, socially vulnerable populations, smoke exposure, source attribution, source impact, wildland fire.

Acknowledgements
Some of the products used in this research were developed in part by funding from NASA Applied Sciences Program under grant NNX16AQ29G. We thank Mark Ruminski of NOAA/NESDIS Satellite Analysis Branch for HMS data, Yang Chen and James Randerson of UC Irvine for GFED4s data, John K. Fish of Florida Forest Service and his staff for Florida open burn authorization data, and Frank Sorrels and Daniel Chan of Georgia Forestry Commission for Georgia prescribed burn permit data.
1. Abstract

As the population increases, air quality regulations continue to tighten, and stricter controls are applied to other pollution sources, understanding the impacts of prescribed burning emissions is becoming more critical for the land managers in the southern U.S. Although air pollution is a regional problem, there was no common record of prescribed fire occurrences and characteristics for the southern U.S. The goal of this research was to develop and deliver an integrated prescribed fire and air quality information system for the Southern Consortium. We developed such a system that brings together prescribed burn and air quality data, and simulation results from state-of-the-science models to address questions regarding the impacts of prescribed burning on air quality, smoke exposure and associated health effects. The system consolidates burn permit records, information from alternative burn tracking systems and satellite products. The reason for our reliance on land-based records more than satellite retrievals is that satellite products are known to underestimate prescribed burn emissions by a factor of 3 to 5. Data has been gathered and analyzed for recent years (2015-2018) in this research, but the system is designed to dynamically update the data going forward.

Data and information compiled were used in emissions, plume rise and air quality and health impacts models to provide a regional scale analysis of the impact of burns. The reason for choosing air quality models over alternatives such as trajectory or dispersion models is that air quality models, by simulating complex atmospheric transport and chemistry processes in presence of emissions from all sources, can provide more accurate estimates of the regional impacts. Fire and air quality managers have access to the data, analyses, tools and other research products through a web-based application. This application also provides links to the daily air quality and prescribed burn impact forecasts being provided by Georgia Tech for dynamic management.

To achieve project objectives, research tasks were broken into 5 subprojects with linkages in between. Subproject 1 established a unified database for prescribed burns based on permit records from southern states\(^1\). This database is at the heart of the integrated prescribed fire and air quality information web-based system built under Subproject 2. In Subproject 3, overlapping fire and observational air quality records were analyzed to quantify discernable impacts of prescribed burning and identify a collection of case studies that can be used to evaluate smoke emissions and dispersion tools. Subproject 4 used state-of-the-science atmospheric modeling and data fusion techniques to simulate the impacts of prescribed burning on air pollution at a regional level. These impacts were used in Subproject 5 to assess the health burden associated with prescribed fire in the South and characterize affected communities.

This research was leveraged by other sponsored projects on dynamic management of prescribed burning, improving the performance of air quality forecasting, and development of air quality fields for exposure assessments. The results were disseminated to the broader scientific community through conference presentations and publications. The implications were described to fire managers in collaboration with the Southern Fire Exchange through webinars. The major outcome of the project has been an increased understanding of the air quality and health impacts of prescribed burning throughout the Southern Consortium.

\(^1\) Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, Oklahoma, South Carolina, Tennessee, Texas, and Virginia
2. Objectives

The project had two major objectives. The first one was to develop an integrated prescribed fire and air-quality information system for the Southern Consortium. Although prescribed fire is a leading source of air pollution in the region, there was no common record of prescribed fire occurrences and characteristics for the southern U.S. One was developed consolidating electronic burn permit records, information from alternative burn tracking systems and satellite products. The second objective was to provide a consortium-level analysis of the impact of prescribed fire. Compiled prescribed fire data and information were used first in emissions estimates, then in simulation models for air quality and health impact analyses. Access to the data and analyses is provided through a web-based application.

3. Background

While prescribed burning is the preferred method for maintaining ecosystems and reducing wildfire risk (among other benefits) in the southern U.S., it is critical that these operations be performed with minimum risk to public health. According to the U.S. Environmental Protection Agency’s (EPA) 2011 National Emission Inventory (NEI), 15% of fine particulate matter (PM$_{2.5}$) emissions in the U.S. are attributable to prescribed burning, of which 27% originate from the Southeast (Davis et al., 2015). Prescribed burning remains one of the most prominent sources of PM$_{2.5}$ in the U.S. and will become increasingly important as other sources are controlled. An improved understanding of the contributions of prescribed burning to smoke emissions, air pollution, exposure and health outcomes would give fire and land managers a more complete picture of the impacts of their programs. The goal of this project was to create a sustainable system that first unifies prescribed fire records across the southern states and then uses that information to address questions regarding the effects of prescribed burning on smoke exposure and air quality in the region. The project aimed to create interest among stakeholders in the South to participate in and generate long-term support for a system, which can be used as the primary platform for sharing prescribed burn data, modeling, and performing analyses, within the context of a changing climate and tightening air quality standards.

As the population increases, air quality regulations continue to tighten, and stricter controls are applied to other pollution sources, the focus will shift to prescribed burning emissions in the southern U.S. The land management community needs a path to improved decision making to cope with the possibility of controls and must be proactive in identifying its own air quality and health impacts. Air pollution is a regional problem and must be dealt with at a regional scale. As a first step to understand the regional impacts and improve the decision process, prescribed burn emissions must be estimated accurately and uniformly throughout the region. Satellites often fail to detect low-intensity prescribed burns; therefore they cannot be used for this purpose. Emissions must be estimated from the bottom up using prescribed burn permit and observation records. The second step is to estimate the impacts of these emissions in the context of emissions from other pollution sources because there are complex interactions between various sources. A prescribed fire plume can mix with a power plant plume or emissions from a highway downwind, and its effect can be increased in the presence of other emissions. Instruments can measure the level of air pollution but they cannot isolate the contribution of prescribed burns. Dispersion and trajectory models would fall short in these situations because they do not account for the complex chemical reactions in the atmosphere, aerosol and cloud interactions, and other processes that become
important at regional scales. The contribution can be estimated accurately only through simulations by air quality models and scaling by the measurements; this is known as fusion of field data with modeling results. Use of regional-scale air quality models is the norm in the management of ozone and particulate matter (PM) pollution. This project built a regional prescribed burn database for estimation of emissions and analyzed the air quality and health impacts of those emissions using state-of-the-science models.

Before this project, there was no unified record of prescribed fire occurrence and characteristics for the southern U.S. There have been several attempts to create one in the past, but those attempts have not been successful due to the lack of uniformity in the type of records kept. For example, the Georgia Forestry Commission (GFC) kept hand written burn permit records until 2010, after which they switched to electronic records. Some states did not even have a permit program at the time of these attempts. Another difficulty preventing unification was the lack of uniformity in the type of information gathered by programs in different states. Florida, for example, has a longer history of electronic record keeping but collects less information than Georgia.

Project outputs include: a common database of prescribed fire occurrence and characteristics, a web-based platform that combines the data with models and analysis tools and makes them easily accessible to burn managers, an expansion of the former Georgia prescribed burn impact forecasts to neighboring states for everyday use in dynamic burn and air quality management, a retrospective analysis of the air quality, health and societal impacts of prescribed burning as an example for continued analyses in the future, and science delivery in the form of publications and conference presentations as well as more active delivery of the research results and products through Southern Fire Exchange webinars. The major outcome of the project has been an increased understanding of the air quality and health impacts of prescribed burning throughout the southern states, benefiting prescribed burning operations throughout the region.

Smoke from burning of biomass can have adverse health effects. Among the constituents of smoke are various gases and aerosols, such as carbon monoxide (C), carbon dioxide (CO$_2$), black carbon and PM$_{2.5}$. Epidemiological studies have shown associations between short-term PM$_{2.5}$ exposure from fires and health endpoints, such as mortality, respiratory effects, and cardiovascular effects. Rappold et al. (2017) found that over 40% of Americans live in areas affected by wildland fires with a moderate or high contribution to ambient PM$_{2.5}$ concentrations. In the southeastern U.S., prescribed burning contributes to about 30% of PM$_{2.5}$ emissions, while only 3% of PM$_{2.5}$ emissions come from wildfires. Therefore, people living in the southeastern U.S. are more likely to experience high and frequent smoke exposure in comparison to those living in other parts of the country due to increasing prescribed burning emissions. Recent epidemiological studies in Atlanta addressed the relationship between source-specific PM$_{2.5}$ exposures and acute health effects, such as respiratory disease and cardiovascular disease (Krall et al., 2017; Sarnat et al., 2008). Sarnat et al. (2008) found positive associations between cardiovascular disease-related emergency room (ER) visits and same-day PM$_{2.5}$ concentrations attributed primarily to prescribed forest burning. Krall et al. (2017) also found evidence of positive associations of respiratory disease-related ER visits with biomass burning PM$_{2.5}$.

Smoke management is regulated by the National Environmental Policy Act and the Federal Clean Air Act. Per these regulations, smoke managers are required by law to consider smoke “sensitive” features such as airports, schools, interstate highways, and Class 1 Areas (national parks and wilderness areas) when planning prescribed burns; however, socially vulnerable populations such as low-income and ethnic and racial minority
groups are not recognized by these mandates. The 1994 Executive Order 12898 directed federal agencies to identify and address “disproportionately high and adverse human health or environmental effects of its programs, policies, and activities on minority populations and low-income populations in the United States” although it is not clear how considerations of the Executive Order and subsequent directives are incorporated into fire management activities of federal agencies.

One recent attempt to assess broadly the impact of smoke plume dispersion on environmental justice or socially vulnerable communities was conducted recently by Johnson Gaither et al. (2015) for the southeastern U.S. That study defined social vulnerability as a generalized state of human precariousness with respect to material well-being, access to information and technical, medical, or legal services. Theoretically, the condition would render an individual or community less able to anticipate, cope, or recover from environmental stressors such as cumulative exposure to smoke. Results of this exploratory analysis indicated significant spatial clustering of high social vulnerability U.S. Census block groups adjacent to block groups with a high number of smoke plumes. Also, analyses for the winter months (when prescribed fires are more common) showed greater per capita plume exposure in socially vulnerable clusters or block groups.

4. Materials and Methods

Unified Southern U.S. Prescribed Burning Database

Previous studies suggested that satellites underestimate fire emissions in the southern U.S. by large factors (Yang et al., 2011; Zeng et al., 2016). Possible reasons for this underestimation are obstruction by clouds or the canopy in understory burns, and the calibration of satellite products with high-intensity wildfires, which do not well characterize the predominantly low-intensity prescribed burns in the Southeast. For this reason, we preferred to build the integrated database of prescribed fires from ground-based information such as burn permit records. We used satellite data to complement burn records when permit-based data were lacking or not available. We evaluated the satellite data through comparisons to permit-based data. We also tracked ongoing parallel efforts to fortify the records with data available from other sources.

To build a unified record of prescribed fire occurrence and characteristics for the southern U.S. we requested data from nine southern states as well as other organizations that kept records. The PI went to the biannual meeting of Southern Group of State Foresters, in Gatlinburg TN February 7-8, 2017, briefed state fire chiefs on this project and informed them how their data will be used. He also gave a similar presentation to the Southeast Fire and Air Quality Workgroup at the Smoke Summit III, on April 11, 2017. We repeated the data request after these meetings and reemphasized the need for cooperation during the Southern Integrated Prescribed Fire Information System (SIPFIS) workshop held at Georgia Tech on August 8, 2017. The primary purpose of the workshop was to seek community input for the development of the prescribed fire and air quality information system. In addition to representatives from the three initial States (FL, GA, and NC), we invited participants from other states through encouragement of the SFE and Southern Group of State Foresters.

Initially, we planned to obtain prescribed burn data from Florida, Georgia and South Carolina to form the nucleus of our common record database. Later, South Carolina preferred not to share data because of privacy

---

2 Alabama, Florida, Georgia, Kentucky, Mississippi, South Carolina, North Carolina, Tennessee, and Virginia
concerns. However, we were able to obtain prescribed burn data from North Carolina, which allowed us to proceed with our initial plan. We searched for the commonalities in the data and restructured them to align the emission relevant information such as the type, acreage, location and time of burn for easy processing. We worked closely with these three states to understand better their current reporting systems and establish data connections for near real-time updates of the common database. We developed a working prototype with the available data. When we contacted the other states, the prototype was available to explain better what we were trying to accomplish, show the benefits of a common record and encourage participation in the project. We also organized a Southern Fire Exchange (SFE) webinar to introduce our prototype to various stakeholders.

**Prescribed Fire and Air Quality Integrated Information System**

The purpose of the Southern Integrated Prescribed Fire Information System (SIPFIS) is to merge prescribed fire, air quality and impacts data into a common information and analysis framework. We designed the system with the following specifications in mind: 1) systematic collection and processing of information from different sources; 2) provision of datasets necessary to complete analyses of prescribed fire impacts on air quality, human exposure and health; 3) open access to all data, modeling tools and study results. The system comprises unique layers of information on a common spatial domain extending over the southern U.S. (Figure 1). The unified record of prescribed burning is an integral component of the framework, providing multi-year data describing fire occurrence and characteristics. Air quality data includes observations from monitoring networks and model-generated concentration fields. Smoke impacts estimated by modeling and statistical analyses are mapped as another layer. Population data at the resolution of census tracts, including population density and demographic and socioeconomic data, are used to quantify smoke exposure and health impacts as a separate layer of information specifically related to prescribed fire. A web-based application provides user-friendly access to all data and analyses, including smoke impacts, exposure and health impacts.

![Figure 1. Integrated information layers of the Southern Integrated Prescribed Fire Information System (SIPFIS)](image)

We started our research by examining the DEASCO3 and PMDETAIL tools because of their similarity to the system we want to develop. Those tools were developed in earlier JFSP projects with the intention to bring
wildfire data together with air quality data (https://wraptools.org). We contacted the developers of DEASCO3 and PMDETAIL and found out that it would be best to develop our own database and application. Another application we examined was NOAA’s e-IDEA (https://www.star.nesdis.noaa.gov/smcd/spb/aq/eidea), which provided additional insight into how a layered information system can be developed.

After exploring several technologies, we decided to use MySQL as our main database system. We created a script to download air quality observations from the AirNow website (http://www.airnow.gov) and ingest them into the MySQL database as a table. Air quality data includes hourly and daily ozone (O3) and fine PM (PM2.5) concentrations. For visualizations, we used Leaflet, an open-source JavaScript library, with OpenStreetMap, an open map database with free API services. We employed PHP scripts to fetch the requested dataset from the MySQL database tables and then used D3, a JavaScript library, to produce dynamic interactive data visualizations online. The prescribed burn data from the unified records were incorporated into the database in a way similar to the air quality data. The fire database includes the permit records as well as satellite-observed fire and forecast burn data (location, time and size). Since permit records are not available for all southern states, gaps were filled with satellite-based fire data. For this, we acquired daily fire data, which consists of location, burned area and emissions, from NOAA’s Hazard Mapping System Fire and Smoke Product available at https://www.ospo.noaa.gov/Products/land/hms.html. Satellite-observed fire and permitted and forecast burn data (location, time and size) are stored in the database, extracted and visualized in a way similar to the air quality data.

After an initial test period by a small group of stakeholders, we opened the web-based application for SIPFIS to the public on May 13, 2018 (https://sipc.ce.gatech.edu/SIPFIS/map/). The SIPFIS website uses Web-based Geographic Information Systems (WebGIS) technologies to display the forecasting products, real time and historical measurements, and earth observation datasets. It provides up-to-date information and analysis tools for use by regional fire, air quality and health managers. We published an article that describes SIPFIS and demonstrates how the information and analysis tools can help users to accomplish fire and air quality management activities, especially those related to assessing environmental and health impacts associated with prescribed burning (Hu et al., 2019). We also developed an online, detailed user guide to assist users with effective usage of the tools and datasets available on the website (https://sipc.ce.gatech.edu/SIPFIS/about.php).

The forecast fire data, which consists of daily burn activity, emissions and air quality impacts, were already being produced for Georgia as part of an ongoing project at Georgia Tech (Odman et al., 2018). Here, the forecasting domain was expanded to include parts of Florida, Alabama, South Carolina, North Carolina, and Tennessee, which border Georgia. To derive county level average daily total and typical burn sizes for each state neighboring Georgia, we used historical burned area data from the Biomass Burning Emissions Product (BBEP), which is blended from various satellite retrievals. Combining the burned area data with meteorological criteria at representative weather stations, we built a new burn activity forecasting model. Prescribed fire emissions are forecast using Fuel Characteristic Classification System (FCCS) fuel loading estimates, as described in Odman et al. (2018). Georgia Tech’s operational forecasting of prescribed burning impacts on air quality in the Southeast continues since January 2018 (previously only in Georgia) and can be accessed at https://forecast.ce.gatech.edu.

SIPFIS is designed in such a way that air quality and satellite-based prescribed fire data are collected automatically moving forward. We import and update ozone and PM2.5 air quality as well as fire observations into the MySQL database on a daily basis. The forecast air quality and fire data are added into the archive through a
dynamic link to Georgia Tech’s HiRes2 forecasting system. However, we could not automate the retrieval of permit-based daily burning data from the state sources; this part still requires obtaining the data from various sources (states and institutions) and manually incorporating them into the unified database.

**Analysis of Observational Air Quality Record and Smoke Emissions-Dispersion Tools Performance**

Information compiled by the integrated system was used to investigate the discernable impacts of burning on pollutant concentrations measured at monitors within the region. Using fire and air quality data available over a domain extending across southern states and multiple years, we systematically searched for correlations between high pollutant concentrations observed at monitoring stations and prescribed burning activity. This analysis had two main objectives:

- Provide a regional view of the impact of prescribed burning on monitored air quality.
- Identify case studies well-suited to evaluate the performance of smoke emissions and dispersion tools.

We analyzed the statistical relationships between prescribed fire and observed ground-level \( \text{O}_3 \) and \( \text{PM}_{2.5} \). Correlations between pollutant concentrations and evidence of prescribed fire occurrence at varying spatial and temporal scales were quantified using different coefficients and controlling confounding effects of meteorology. The analysis calculates the increases in measured \( \text{O}_3 \) and \( \text{PM}_{2.5} \) associated with burning activity for different spatial aggregations ranging from single-monitor to regional.

This analysis also allowed us to identify a number of cases that can be useful to evaluate the ability of existing modeling tools applied to predict the air quality impacts of local prescribed burning activity. We identified several cases exhibiting strong evidence of prescribed burns having a direct and significant impact on \( \text{PM}_{2.5} \) concentrations at a specific monitoring station or a group of sites. We simulated atmospheric transport and chemistry during these cases and used the results in evaluating the performance of smoke modeling tools. We also processed the prescribed fire data to prepare emissions inputs for the simulations with regional-scale air quality models. All available information describing prescribed burning occurrence and characteristics (e.g. location, area, spread, fuel types, and fire meteorology), as well as hourly measured \( \text{PM}_{1.5} \) concentrations, for each case has been compiled and is available through the information system and website. This provides a uniform set of episodes that can be accessed by the fire and air quality communities to evaluate and compare different smoke emissions and dispersion models. We expect this resource to assist in identifying limitations associated with current data and simulations, and support future network and model development efforts.

We used the BlueSky framework (Larkin et al., 2009) by applying a specific sequence of tools to simulate smoke impacts for the case study collection and evaluated predictions against observed concentrations. The tools we used are prevalently used in smoke management: (1) Fuel Characteristic Classification System (FCCS) for characterization of fuels; (2) Consume for total fuel loadings and consumption; (3) the Fire Emission Production Simulator (FEPS) for hourly pollutant emissions; and Hybrid Single Particle Lagrangian Integrated Trajectory Model (HYSPLIT) for three-dimensional smoke dispersion. During the interpretation of simulation results and evaluation of the models, we considered our uncertainty estimates from previous research including the influence of emissions estimates (Davis et al., 2015), spatiotemporal data (Garcia-Menendez et al., 2014), and meteorology (Garcia-Menendez et al., 2013) on smoke dispersion predictions.
Beyond evaluating modeling tools and identifying development needs to improve performance, the smoke simulations served additional purposes. In coordination with fire and air quality managers, we performed case studies to assess the value of current emissions and dispersion tools in fire planning. We retrospectively analyzed if the air quality impacts recorded at monitoring sites during these episodes could have been minimized by modifying burning plans with the aid of numerical tools. In the end, we developed a new impact apportionment tool, Dispersive Apportionment of Source Impacts (DASI), that can be used in determining which burns should be allowed or restricted based on their individual impacts on air quality and public health in areas of concern (Huang et al., 2020b).

The emissions and smoke dispersion modeling above paved the way for the comprehensive air quality simulations below. Regional-scale fire impact predictions derived from air quality models have been shown to be highly sensitive to assumptions about plume rise and the spatiotemporal distribution of fire emissions. We applied the knowledge derived from the analysis of case studies to improve the fire emissions inputs used in air quality simulations. In addition to the modeling under this task, we also collected air quality data using low-cost sensors (Plantower PMS 3003) deployed at high schools in southwest Georgia. These sensors were calibrated against a local reference instrument (a beta attenuation monitor located in Albany, Georgia). The air quality measured by these sensors indicated that the impacts of prescribed burns in the region are large and extensive. We fused these low-cost sensor data with air quality modeling fields to generate fields that characterize the spatiotemporal smoke impacts in Southwestern Georgia (Huang et al., 2020a).

**Comprehensive Simulation of Regional Air Quality Impacts and Data Fusion for Exposure Assessments**

We simulated prescribed burn impacts in the southeastern U.S. during the burn season (January-April), between the years 2015 and 2018 using the Community Multiscale Air Quality (CMAQ) model at 12-km horizontal grid resolution over the eastern U.S. and at 4-km resolution over the Southeast. The meteorological inputs were taken from daily weather forecast simulations with the Weather Research and Forecasting (WRF) model over the same domain. Since the forecast is reinitialized each day with reanalysis data, the meteorological fields created by WRF have sufficient accuracy to be used in this analysis. All emissions other than fires (e.g., industrial, power plant and traffic emissions) were derived from EPA’s NEI-2011 and included in the simulations to capture their nonlinear interactions with the fires. Our original plan was to substitute the fire emissions in NEI-2011, including wildfires and prescribed burns, with the best available fire emissions inventory for the actual years (i.e., 2015–2018). Unfortunately, all we could find was the 2014 NEI from US EPA, Office of Air Quality and Planning. The fire emissions in this particular inventory were generated using the BlueSky framework. Therefore, we decided to generate fire emissions for the years 2015–2018 using the same framework.

We obtained an executable version of the most recent BlueSky framework from of the USDA Forest Service Pacific Northwest Research Station. This executable was for Ubuntu 16.04 while the operating system on our computers were Red Hat Enterprise Linux Server release 6.9. After installing the Ubuntu operating system on one of our computers, we were able to run the BlueSky framework with help from the USDA FS Pacific Northwest Research Station. We have tested BlueSky by generating emissions for the prescribed fires during our 2011 Eglin Air Force Base study where emissions were modeled and compared to measurements. We found that the differences between emissions generated by BlueSky and the measurements were of the same order of magnitude as the differences reported by previous modelers. We proceeded to create prescribed fire emissions
for Georgia between the years 2015–2018 using the Georgia Forestry Commission’s burn permit data and the BlueSky framework. Later, fire emissions inventories became available through the US EPA for the years 2016 and 2017. However, to have consistent emissions through the years 2015–2018, we did not use those inventories.

Our original plan was to conduct two CMAQ simulations: one with and a second without the prescribed burn emissions. Then, we were going to attribute the differences between these two simulations to the prescribed burns. However, our tests have shown that the numerical error in CMAQ is of the same order of magnitude as the difference in most cases (Huang et al., 2020a). Therefore, the difference between the two simulations cannot be relied upon, especially if the fire emissions are locally small, as is the case in most prescribed burns. A more reliable approach that is not prone to numerical errors or the magnitude of fire emissions is the Decoupled Direct Method (DDM) that is formulated to solve for the sensitivity of pollutant concentrations to an infinitesimal change in emissions (Napelenok et al., 2008). We used DDM, which is embedded into the CMAQ model, to calculate the prescribed burn impacts on O3 and PM2.5 concentrations.

Air quality models such as CMAQ may have large biases/errors that vary in space, from one geographic area to another, and time, from one season to another (e.g., Koo et al. (2015)). Health effects studies should not be conducted solely based on modeled data due to model biases/errors and the general underestimation of the acute impacts. To reduce the propagation of these biases into various types of analyses it is common practice to use the air quality model results in a relative sense rather than in an absolute sense. One approach is to scale the modeled responses with the ratio of observed to modeled concentrations (e.g., Odman et al. (2007)). This is similar to the use of “Relative Response Factors” or RRFs as recommended by the EPA for projecting “future design values.” The traditional approach is limited to O3 and PM2.5 values at monitoring locations. On the other hand, the observed data are sparse both in space and in time, especially for PM species. Additionally, there are no observations of the prescribed burn impacts, only observations of air pollution.

Despite their inaccuracies, models are useful tools in determining source-receptor relationships and the source contributions/impacts. To help overcome limitations of modeling, one approach is to merge model results with observations. This is called data fusion. We examined various data fusion methods to find the best one. In one method, two concentration fields are first developed, including one field that assimilated temporal variations of observational data and spatial structure from CMAQ results, and another field that incorporated both spatial and temporal variations from CMAQ results. The two fields are then fused based on estimated weighting factors. This novel hybrid approach accounts for the potential of specific locations being consistently impacted by very local sources leading to observations higher than the surroundings. The hybrid approach can also adjust to having very few or large numbers of monitors (Friberg et al., 2016).

We scaled the model results for prescribed burn impacts with observational data using the data fusion technique as follows. We multiplied the observation-fused daily total PM2.5 fields by the ratio of the burn impact to the total PM2.5 from CMAQ–DDM for each day and each grid cell to generate an “observation-adjusted burn impact” on PM2.5:

\[ O_{AB} = \frac{B}{C} \times DFC \]

where \( B \) is the burn impact from CMAQ–DDM (in \( \mu g/m^3 \)), \( C \) is the total PM2.5 concentrations from CMAQ–DDM (in \( \mu g/m^3 \)), DFC is the total PM2.5 concentration after applying the data fusion method (in \( \mu g/m^3 \)), and \( O_{AB} \) is the observation-adjusted burn impact (in \( \mu g/m^3 \)).
Human exposure, Health Impacts and Affected Communities

The most important concern associated with prescribed fire in the southern U.S. is a potential increase in human exposure to air pollution as a result of rising burning activity in the future. Multiple studies have linked wildfire smoke exposure to adverse health effects (Reisen et al., 2015). Given the influence fire can exert on $O_3$ and PM$_{2.5}$ levels, assessing the impact of prescribed burning on public health is a major concern (Haikerwal et al., 2015). Here, observation-fused fields of regional air quality impacts generated above were used to evaluate the effects of prescribed fire on human health.

To model health impacts we used the Environmental Benefits Mapping and Analysis Program (BenMAP; Sacks et al., 2018)). BenMAP has been used extensively at national, state, and local levels to estimate health impacts resulting from variations in air quality, including Regulatory Impact Analyses to support the development of air pollution regulations. BenMAP relies on concentration-response functions to relate changes in atmospheric pollutant concentrations to health incidence rates as follows:

$$\Delta Y = Y_0 (1 - e^{-\beta \Delta C}) \times \text{Pop}$$

Here, $\Delta Y$ is the burden, $Y_0$ is the baseline incidence rate, $\beta$ is the effect estimate coefficient, $\Delta C$ is the change in pollutant concentration, and Pop is the exposed population. Based on a pool of concentration-response relationships derived from reported epidemiological evidence, we used census-block-level population data and our projections of prescribed burning impacts on ground-level $O_3$ and PM$_{2.5}$ to estimate associated effects on human health. We produced county-level as well as gridded 4x4 km$^2$ resolution estimates of the impacts of prescribed fire on a collection of health endpoints, including asthma-related emergency department visits and hospitalizations.

As mentioned, an earlier study by Johnson Gaither et al. (2015) examined the spatial intersection of social vulnerability and smoke plume dispersion (“hot spots”) across thirteen southern states to determine whether socially vulnerable communities were co-located in areas with an above average number of smoke plumes. Although a positive association was found between socially vulnerable populations and plumes, results of that study are limited in terms of actual impact to human communities. No indicator of actual impact was included in the analyses. Also, since the plume data were from satellites, the study made no distinction between plumes emanating from wildfires and those from prescribed burns. As a result, the study did not provide definitive conclusions with respect to the impact of prescribed fires on socially vulnerable populations. We expanded on that analysis, first by focusing on prescribed burns and then by using smoke related PM$_{2.5}$ concentrations to compare exposures for socially vulnerable (i.e., environmental justice) populations to those of the general population. Our subsequent environmental justice analysis did not evaluate human health impacts, but we did find a positive association between PM$_{2.5}$ concentrations and environmental justice or socially vulnerable populations. This analysis, which has a direct bearing on land managers’ responsibility to both manage their land by means of prescribed burns and to help insure the health and safety of affected populations, was published in the International Journal of Environmental Research and Public Health (Johnson Gaither et al., 2019).
5. Results and Discussion

Unified Southern U.S. Prescribed Burning Database

When available, burn permit records are the most reliable tool for estimating prescribed fire emissions.

To test our hypothesis that satellites do not capture low-intensity prescribed fires adequately, we compared the 2015 and 2016 burn seasons’ (January-April) burned areas from the Biomass Burning Emissions Product (BBEP) and the Global Fire Emissions Database (GFED4s) with the burned areas in Georgia Forestry Commission’s and Florida Forest Service’s burn permit databases. The permit record and BBEP daily state total burned areas were correlated during the first four months of 2015 in Georgia and Florida with $r^2$ equal to 0.57 and 0.48, respectively. However, the slopes of 0.17 and 0.10 indicate that BBEP underestimated burned areas by large factors (Figure 2). Further analysis revealed that even on days when the state total burned areas agreed, there were significant differences between the spatial distributions of the burns. In general, satellite products do not capture a lot of the individual small burns and sometimes misinterpret a cluster of small burns as one large burn (Huang et al., 2018).

![Figure 2. Daily statewide burn areas from NOAA’s Biomass Burning Emissions Product versus those from Georgia and Florida permit records during January-April 2015.](image)

To evaluate the accuracy of the burned areas in permit records we conducted a survey. We called the permit holders in Georgia and asked them to confirm or correct the burned area information in the records for 2016 and 2017. After surveying about 10% of all burned areas, we found that permitted burned areas differ from actual burned areas by 15 to 20% (Huang et al., 2018). Therefore, the large difference between the permit records and the satellite products must be due to the inability of the satellites to detect and quantify the magnitude of small, low-intensity, understory burns. When available, burn permit records are the most reliable tool for estimating prescribed fire emissions. Satellite products must improve significantly before they can be used in estimating burned areas. New products from the most recently launched (e.g., GOES 16, Sentinel 5P) and future (e.g., TEMPO) satellites should be evaluated for their potential to present a unified prescribed database when permit records are not available.
The prescribed fire database includes data from responding states and organizations.

The states and organizations that provided input to the prescribed fire database are listed in Table 1.

Table 1. Prescribed fire data obtained from various states and organizations for the unified database.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>FL</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>GA</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>MS</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>NC</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>TN*</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Tall Timbers**</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
</tbody>
</table>

* Summary data  
** Fire frequencies

Our initial analysis focused on prescribed burn permitting data from the states of Florida, Georgia, North Carolina and Tennessee. We examined the data from these states for emissions-relevant information such as the type, acreage, location and time of the burns. Table 2, for example, compares the attributes of prescribed fire data across GA, FL, and NC. In doing so we have identified shared and dissimilar fields within each state’s electronic prescribed fire records and developed a common data structure for these. For example, we converted the address-based records that we received from the Georgia Forestry Commission to geo-coordinates in an effort to build a common data structure.

Table 2. Data attributes and fields included in permit-based prescribed fire data for NC, GA, and FL.

<table>
<thead>
<tr>
<th></th>
<th>FL</th>
<th>GA</th>
<th>NC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Spatial Information</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Geographic coordinates</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Address</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>County</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td><strong>Temporal Information</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Date</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Scheduled time</td>
<td></td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Burning start time</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Burning end time</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td><strong>Burn information</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Burn type</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Estimated acres</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Estimated fuel consumption</td>
<td></td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Actual acres</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Fuel Type</td>
<td></td>
<td>✔</td>
<td>✔</td>
</tr>
</tbody>
</table>

We explored several visualization technologies to develop a unified prescribed fire database and selected the Tableau data visualization tool to build a user-friendly platform. The software’s mapping functionality is used to position fire data, filter across attributes and access information for select fires and regions. The database can
be accessed through a web-based platform and is available as a component of the project information system. Figure 3 shows a visualization of the burn data included in the unified record over Florida.

Figure 3. A visualization of the unified prescribed fire record for Florida by year and size of the burns overlaid on top of the population data.

In total, we have compiled data for over 2 million records of prescribed burn permits from 2012 to 2017. However, there are several gaps in the records that we were hoping to fill. We have contacted the state agencies in charge of collecting prescribed fire data and requested their cooperation to fill these gaps. Expressed concerns such as proprietary nature of the data prevented us from making further progress. Therefore, as of 31 December 2017, we closed the activities on this task. However, any new data provided by land and forest management agencies in southern states can be added to the database in the future.

Prescribed Fire and Air Quality Integrated Information System

SIPFiS was developed with the permit- and satellite-based prescribed fire data and nationwide air quality data.

We have explored several visualization and database management technologies to develop a prototype for our integrated prescribed fire information system. Our initial analysis has focused on prescribed burn permitting data from the states of Georgia, Florida and North Carolina by identifying shared and dissimilar fields within each state’s electronic prescribed fire records and developing a data processing tool to compile these into a common data structure. As a potential component of the integrated information system, we explored interactive visualization tools based on Tableau data visualization software. We used Tableau’s mapping functionality to position fire data and develop the prescribed fire information layer of the system (Figure 4).
The archive of air quality observations and prescribed fire records goes back to 1 January 2015. Figure 5 shows the air quality layer where PM$_{2.5}$ observations are displayed (in this case green or good at most observation sites but yellow or moderate at several sites) on top of the PM$_{2.5}$ forecast in the background (in this case green or good everywhere). Using Leaflet and OpenStreetMap allows us to overlay air quality observational data on the map. In addition, the use of D3 functions enables the drawing of the time series of air quality data at selected sites next to the map (Figure 5). The PM$_{2.5}$ forecast is provided by Georgia Tech on a daily basis and includes daily burn activity, burn emissions, and burn impact and air quality forecasts for the southeastern U.S (Figure 6). Forecast air quality and burn impact fields are converted from their native netCDF format to raster format and then to polygons in GeoJSON format for overlay on the map, with each contour level as one polygon. The Southern Integrated Prescribed Fire Information System (SIPFIS) is able to display all this information along with air quality observations at the network monitors interactively on the map.
Figure 5. The air quality forecast for March 10, 2016 over northern Florida and southern Georgia together with the air quality data at the observational network (left) and the time series of the air quality at the Columbus Airport site (right).

Figure 6. Forecast burns (blue) for March 10, 2016 over northern Florida and southern Georgia along with the forecast burn impacts (contours) and air quality observations color-coded according to the air quality index.

Figure 7 shows the fire layer where permitted burn locations (yellow triangles) are displayed on the map together with forecasted burn locations (blue diamonds). Once again, it is Leaflet that allows us to overlay prescribed fire data on the map. The forecasted burned areas can be compared to permitted burn areas and locations of satellite detected fires can also be added. Note that any element from the air quality layer can be
overlaid on the same map to analyze the air quality impacts of the fires. Air quality observations are displayed in Figure 7 while both observations and forecast burn impacts are displayed in Figure 6.

SIPFIS is accessible through a web-based application at https://sipc.ce.gatech.edu/SIPFIS/map/. The use of WebGIS technologies allows visualization of air quality and fire datasets on dynamic maps. Users can move around on the map, zoom in/out, and examine air quality and fires in particular locations. SIPFIS can also overlay the modeled air quality and fire impact fields on the same map for easy comparison with air quality observations. We presented the details of the system and demonstrated various analyses to the prescribed fire community through a Southern Fire Exchange webinar (https://www.youtube.com/watch?v=Q7XVO_8Pleg) on October 5, 2018. The observational and forecasting data are available from January 2015 to present. We will continue to operate the information system by adding daily observational and forecast air quality and fire data to its archive. We evaluate our prescribed fire forecasts daily through comparison to satellite fire detections (Figure 8).
Figure 8. Fire detections by Hazard Mapping System (left), a National Oceanographic and Atmospheric Administration product blended from various satellites; our prescribed fire forecast (middle) based on forecast weather and historic fire activity (Odman et al, 2018); and the cloud cover on a) January 10, 2019 and b) March 22, 2019.

Analysis of Observational Air Quality Record and Smoke Emissions-Dispersion Tools Performance

There is a significant positive correlation between prescribed fire and PM$_{2.5}$ air quality in the southeast.

We have concluded an analysis exploring the influence of prescribed fire on observed PM$_{2.5}$ concentrations in the southeastern U.S. We used burning permits georeferenced in Georgia and Florida from 2013 to 2016 as an indicator of prescribed fire activity. For surface PM$_{2.5}$ concentrations, we considered 24-hour average PM$_{2.5}$ concentrations available from all monitors in Georgia (31) and Florida (49) during the period studied. The strength of the relationship between prescribed fire and PM$_{2.5}$ is assessed at all observational sites considered by estimating the bivariate correlation (Pearson correlation coefficient, PCC) between measured concentrations and permitted burn area near each site. We use multiple regression to account for different types of burns in weighing the associations between fire activity and PM$_{2.5}$. Stepwise regression is used to create a generalized linear model at each monitoring site with 24-hour PM$_{2.5}$ concentration as the response variable and surrounding permitted burns for different fire types as predictors. The models are allowed to include a linear term for each predictor—burn area for silvicultural, land clearing and agricultural fires, and pile volume for pile fires. In the stepwise algorithm, a combination of forward and backward selection is used to systematically determine the terms in the final model using the p-value for a chi-squared test of the change in the deviance after adding or removing a term as a criterion (a p ≤ .05 threshold is defined). To assess the explanatory power of a
model we use the adjusted coefficient of multiple determination ($R^2$). We compare the relative importance of each burn type on pollutant concentrations by applying the average increment method. The results of this analysis are described in a manuscript currently in the last stages of review for publication in Geophysical Research Letters. We anticipate publication this manuscript in July, 2020.

Figure 9 shows the bivariate correlation between burn-season PM$_{2.5}$ concentration and nearby total permitted burn area (silvicultural, land clearing, and agricultural) at observational sites considered. In Georgia, all sites show a statistically significant ($p \leq 0.05$) positive correlation (mean PCC = 0.39) with a regression coefficient of 2.2 ± 0.5 μg m$^{-3}$ per 1,000 permitted acres at 95% confidence. Permitted burn area explains over 20% of the variability in burn-season PM$_{2.5}$ concentrations at over a third of the state’s monitors, most located in Georgia’s Upper Coastal Plain. At Albany, the permitted burn area alone predicts close to 50% of the variation in observed concentrations. In comparison, associations between observed PM$_{2.5}$ concentrations and permitted burn area in Florida are weaker (mean PCC = 0.19); while 60% of the monitoring sites reflected a statistically significant correlation with burn area (0.6 ± 0.15 μg m$^{-3}$ per 1,000 permitted acres at 95% confidence), burn area explains over 10% of the variability in concentrations at only 3 locations, all in North Florida.

![Figure 9.](image)

Figure 9. Influence of prescribed burning activity on the observed PM$_{2.5}$ concentrations in the southeastern U.S. (a) 5-day average 24-hour PM$_{2.5}$ concentration at Albany, Georgia, and 5-day average daily acres burned within 60 km of the station. Georgia-average concentration (2013-2016) and burning season are also shown. (b) Relative percentage of days at all monitoring sites considered associated with varying air quality and burning levels during 2013-2016 burning seasons. Observations are 24-hour PM$_{2.5}$ concentrations and burn areas are permitted acres within 60 km of the sites on the day of the observation and previous day. (c) Bivariate correlation between 24-hour PM$_{2.5}$ concentration and permitted burn area within 60 km of site on day of the observation and previous day for 2013-2016 burning seasons. Census-tract burn intensity is also shown.

The influence of fire permits on observed PM$_{2.5}$ concentration can persist for 1-2 days and silvicultural fires have the largest impact at most sites.
The influence of prescribed fire activity on observed air pollution persists for 1 to 2 days. The correlation is strongest when considering the burn area on the day of observation and the previous day. Beyond 1 day prior to the PM$_{2.5}$ observation, the number of monitoring sites with a statistically significant association and strength of the correlations drop considerably. Accounting for burn type can increase the explanatory power of a generalized linear model of observed PM$_{2.5}$. Figure 10 compares the influence of different burn types included as predictors at the sites with the largest explained variability. Silvicultural fires have the largest impact at most sites, but land clearing, agricultural, or pile burns dominate at specific locations. Silvicultural burn area is the dominant predictor at most Georgia sites. However, the weight of agricultural and land clearing burns is also significant at some Georgia locations. In Northern Florida, the dominant burn type varies across sites. At Lake City, pile burns contribute the most to $R^2$, while at Tallahassee land clearing area carries the largest weight.

Figure 10. Variability in 24-hour PM$_{2.5}$ concentrations (2013-2016) explained by multiple linear regression based on different types of burns. Geographic region and contribution of each burn type to $R^2$ are shown for sites with highest explained variability. Permits considered are those within 60 km of site on day of the observation and previous day.

At most sites, the association between air quality and permitted burning is stronger than the association with satellite-derived burn area or important meteorological drivers

The association between fire activity and PM$_{2.5}$ pollution is stronger for permit-based burn areas than burn areas derived from satellite detections. With few exceptions, the association is stronger when correlating PM$_{2.5}$ with permitted burn area (>85% of sites). Across statistically significant sites, the mean correlation based on permitted area is 55% higher than that based on satellite-derived burn area. To further place the association between PM$_{2.5}$ and surrounding prescribed fire into context, it is compared to the influence of important meteorological drivers of air quality (temperature, precipitation, relative humidity, wind speed, and wind direction). When comparing the relative weights of permitted burning and weather data as predictors of PM$_{2.5}$ in a generalized linear model, at most locations (>60%) the explanatory power of nearby permitted fire is greater.
than that of the meteorological predictors, suggesting that prescribed fire has stronger influence on PM$_{2.5}$. This is particularly true at Georgia sites, where the average variability in 24-hour PM$_{2.5}$ concentrations explained by burning is over 4 times larger than that explained by the meteorological variables. In contrast, at most monitoring sites near the coast or large metropolitan areas, including most Florida locations, the weight of fire-related explanatory variables relative to meteorology is substantially lower.

The observational network is sparse in places where prescribed fire has an impact on air quality.

We have conducted a detailed analysis of the prescribed fire impacts at Georgia’s PM$_{2.5}$ monitors for the 2016 burn season. The first part of the analysis was statistical and determined the days when the daily average PM$_{2.5}$ concentrations were in the 95% percentile of all values for the year. The second part was spatial analysis to determine if there were permitted prescribed burns in the upwind direction of the monitor that might have contributed to high PM$_{2.5}$ observations. For each case that was identified, the PM$_{2.5}$ predictions from Georgia Tech’s forecasting system were compared with observations and the accuracy of modeling prescribed fire impacts were evaluated. This analysis was published in a paper describing the prescribed fire impact forecasting system (Odman et al., 2018).

We analyzed the air quality data that we collected using low-cost sensors (Plantower PMS 3003) deployed at high schools in Southwestern Georgia. The sensors were calibrated using the linear regression between the PM$_{2.5}$ measurements from a beta-attenuation monitor (the reference instrument) and readings from a collocated low-cost sensor. The sensor was not as sensitive to fluctuations in PM$_{2.5}$ concentration as the reference instrument. There were significant differences between the synchronous PM$_{2.5}$ measurements of sensors at different locations suggesting high spatial variability in prescribed fire impacts. Correlation between the low-cost sensors deployed at different schools decreased with increasing distance. This implies that PM$_{2.5}$ concentrations measured at different locations reflect impacts from different fire plumes. Due to the high spatial variation of the fire impacts, a single monitoring instrument is not sufficient to assess the exposures to smoke in the region. We only had 4 sensors and the selected locations of the low cost sensors were not ideal according to a 2018 smoke season simulation, as some major, simulated smoke impacts in Southwestern Georgia were missed (Huang et al., 2020a). A well-designed network of low-cost sensors calibrated with a reference instrument in the area, can be very effective in capturing the spatial variation of the prescribed fire impacts.

We also simulated the air quality impacts of prescribed fires in Southwestern Georgia for comparison with low-cost sensor measurements. Our analysis focused on March 8-15, 2018, a period with high burn activity and an exceedance of the National Ambient Air Quality Standards: the daily average PM$_{2.5}$ concentration was larger than 35 µg/m$^3$ at Albany, Georgia on March 10, 2018. We calculated the prescribed fire emissions using the BlueSky framework along with the information in Georgia Forestry Commission’s burn permit database. We used the Weather Research and Forecasting (WRF) and Community Multiscale Air Quality (CMAQ) models, both at 4 km horizontal resolution, for the simulations. Recall that the simulated air quality impacts of prescribed fires were generated using the Direct Decoupled Method (DDM) embedded into the Community Multiscale Air Quality (CMAQ).

The differences between simulated and measured PM$_{2.5}$ concentrations included absence of some early morning peaks or mismatches in their time of occurrence and underestimation of PM$_{2.5}$ levels, especially at night (Figure 11). Also daily average PM$_{2.5}$ concentration greater than 35 µg/m$^3$ at Albany, Georgia on March 10, 2018
was not reproduced in the simulation. Possible reasons include the uncertainties in ignition times of the burns, a systematic bias in WRF that leads to overestimated nighttime wind speed and the difficulties involved in modeling rapid changes of the boundary layer. Combining model simulations with observations from a dense network of low-cost sensors may be the best approach for accurate estimation of exposures to smoke from prescribed fires.

Figure 11. Comparison between observed and simulated PM$_{2.5}$ concentrations, and the fire impact from March 9 to March 10, 2018 at GA EPD site at Albany.

We applied a data fusion method that combines CMAQ-DDM simulations at 4 km resolution and observations from both reference monitor at Albany EPD site and low-cost sensors to generate hourly spatiotemporal fields of PM$_{2.5}$. In addition, we conducted a location-based data withholding evaluation. Observations from one location (Albany EPD site, Dougherty County High School or Worth County High School) were withheld and data fusion was performed with observations from the two remaining locations. The withheld observations for that iteration were compared with the simulated values to evaluate the performance of the data fusion method and assess whether low-cost sensors could provide spatial and temporal information to improve the data fusion results. In all cases, data fusion improved the agreement between the simulation and observations, even when one station’s data were withheld (Figure 12). A manuscript describing our analysis has been submitted to Environmental Science & Technology (Huang et al., 2020a).
Comprehensive Simulation of Regional Air Quality Impacts and Data Fusion for Exposure Assessments

Exposure fields at 4-km resolution were created for Georgia between January-April of 2015-2018.

We created daily average fields of PM$_{2.5}$ concentrations associated with prescribed burning in Georgia at 4 km spatial resolution for 120 days spanning the first four months in the year, 1 January through 30 April 2018 (Huang et al., 2019). This time period encompasses the majority of the state’s prescribed burning activity in any given year. Our method followed the data fusion approach developed by Friberg et al. (2016) that combines: 1) observations at ambient monitors and 2) pollutant concentration fields simulated by an air quality model. First, we simulated total PM$_{2.5}$ concentrations using the CMAQ model and fused the available PM$_{2.5}$ observations to the simulated PM$_{2.5}$ fields. Then, we estimated the impacts associated with prescribed burning using the Direct Decoupled Method (DDM) embedded in the CMAQ model. Finally, we took the results of data fusion and scaled them with the ratios of simulated prescribed fire impact to pollutant concentration. The monthly averages of the resulting data-fused prescribed fire impact fields are shown in Figure 13.
Figure 13. January – April monthly averages of prescribed fire impacts on PM$_{2.5}$ concentrations after fusing observations to CMAQ-DDM simulated fields for the years: a) 2015, b) 2016, c) 2017 and d) 2018.

The data fusion technique is designed to produce fields that blend the spatiotemporal information from the air quality model with the temporal variations from the pollutant observations. As a result, the model bias and errors are expected to decrease. To see if that is indeed the case, we performed a 10% data withholding evaluation as follows. First, we constructed ten groups of observational data, with each group having 10% of the data randomly withheld. We fused the remaining 90% of the data with the CMAQ simulated PM$_{2.5}$. Then, we compared the withheld 10% of the observations to the data-fused simulated values. The results of 90% data fusion had larger correlation with observations (Figure 14) compared to the raw CMAQ results (not shown). They also had smaller normalized biases and errors. Hence, as expected, the results agreed better with observations.
when data fusion was applied. More details about the results of the air quality impact simulations and data fusion can be found in Huang et al. (2019) and its supplement.

**Figure 14.** Comparison of daily total PM$_{2.5}$ concentrations between observations (OBS) and 10% data withheld fusion for the first four months (January–April) of: a) 2015, b) 2016, c) 2017 and d) 2018.

In addition to the 4-km resolution gridded dataset, we prepared prescribed fire related PM$_{2.5}$ fields at census tract level. These datasets are easily transferrable and have already been shared with researchers for use in health impact assessment and other studies in environmental justice, fire liability and health economics.
Human exposure, Health Impacts and Affected Communities

Asthma-related emergency room visits increase because of prescribed fire smoke in Georgia.

Using the PM$_{2.5}$ concentration fields that we generated for the first four months (January–April) of 2015–2018 as described above, we estimated the health impacts of prescribed fires in Georgia. We used health effect estimates derived from a wildfire smoke exposure epidemiological study (Alman et al., 2016). We calculated the health impacts of prescribed fire, $\Delta Y$, as:

$$ \Delta Y = Y_0 \left( 1 - e^{-\beta \Delta PM} \right) \times Pop $$

where $Y_0$ is the baseline incidence rate, $\beta$ is the effect estimate coefficient obtained from Alman et al. (2016), $\Delta PM$ is the change in PM$_{2.5}$ concentration due to prescribed fire, and Pop is the exposed population. We focused our analysis to the calculation of the excess numbers of asthma-related emergency-room (ER) visits (Figure 15) and hospitalizations in Georgia. A manuscript describing our analysis was published in the International Journal of Environmental Research and Public Health (Huang et al., 2019). In addition, a health effects layer has been added to the SIPFIS information system, and coupled with the prescribed fire information and the air-quality data layers.

![Figure 15. Estimated asthma-related ER visits by county in Georgia from 2015 to 2018, first four months.](image)

Recall that southwestern Georgia had the greatest prescribed burning activity and consequently the highest PM$_{2.5}$ levels in the state (Figure 13). However, the largest health impacts, in terms of absolute number of asthma-related ER visits, with an average of about 66 people in the burn months during the reporting years, were found in the Atlanta metropolitan area due to the much larger population exposed to moderate levels of prescribed burning emissions. This corresponds to approximately a 0.6% increase in asthma-related ER visits. In the less populated county of Dougherty in southeastern Georgia, the number of asthma-related ER visits was limited to 4, although the prescribed fire impact on PM$_{2.5}$ levels was highest there.
Burn-intensive areas tend to have more socially vulnerable populations

In addition, we used prescribed fire data, demographic data and reduced form modeling to characterize the communities exposed to the high levels of burning and related air pollution. To characterize social vulnerability, we use the Centers for Disease Control and Prevention’s (CDC) 2016 social vulnerability index (SVI). To investigate the local level spatial autocorrelation of burn activity and SVI, we used the Local Indicators of Spatial Association (LISA) statistic. LISA statistics provide the distribution and strength of spatial association or pattern for each feature. In addition to identifying the pattern (clustered, dispersed, and random) of a feature, LISA statistic also separates high-high clusters from low-low clusters, which are called ‘hot spots’ and ‘cold spots’, respectively. For health risks assessments, we used the CO-Benefits Risk Assessment (COBRA) screening tool managed by U.S. EPA’s Office of Atmospheric Programs’ Climate Protection Partnerships Division. We updated the model’s prescribed fire emission using emissions derived from GFC burn permits records and provided by the Georgia Environment Protection Division (EPD). We also updated the model’s wildfire emissions based on the EPD’s wildfire emissions inventory. We assessed the impact of PM$_{2.5}$ from prescribed fires and other major emission sources using health impacts (concentration-response) functions compiled in COBRA for different health outcomes. We also consider a recent response function from a U.S. cohort study (Wang et al. 2018; doi: 10.1097/EDE.0000000000000614) focused on older adults in the Southeastern U.S. and included in U.S. EPA’s recent 2019 Integrated Science Assessment for Particulate Matter. Specifically, we predict impacts on the annual incidence of all-cause respiratory hospital admissions, asthma hospital admissions, asthma emergency room visits, and all-cause premature mortality, health outcomes that have been found to have a causal or likely-causal relationship with PM$_{2.5}$ exposure. We anticipate submitting these results for publication in August 2020.

We identified that burn-intensive areas have more socially vulnerable populations compared to those with less burn activity. Figure 16 shows the extent and distribution of local spatial association identified using LISA statistics at a significance level $p < 0.05$. LISA statistics distinguish hot spots (the clusters with higher estimates than average surrounded by neighbors with higher estimates than average) from cold spots (the clusters with lower estimates surrounded by neighbors with lower estimates). Burn activity hot spots represent 20% of the state’s total area, while for social vulnerability ~19% of the area is considered as hot spots. Clusters of burning hot spots are mostly observed in Southwest Georgia. Vulnerability hot spots are mostly located in the southern portion of the state. The mean SVI for the tracts in burn activity hot spots is 34% higher than the state average and approximately 50% higher than mean SVI at burning cold spots. This finding illustrates that high burning activity and its associated impacts could disproportionately affect populations with lower socioeconomic status, high elderly or young populations, disabilities, and with less access to housing and transportation.
Health risks associated with prescribed fire smoke are larger in social vulnerability hot spots.

To compare health impacts attributed to prescribed fire PM$_{2.5}$ within different clusters of burn activity and social vulnerability, we categorized incidence rates across all Georgia census tracts (Figure 17). Average census-tract-level incidence rates related to prescribed fire smoke for all health endpoints considered are higher within burning hot spots and compared to the complete state and cold spots. For example, the average impact on older adult mortality incidence rate in burn activity hot spots is 3.3 times higher than the state average impact. Incidence rates are also higher at the SVI hot spots, revealing that socially vulnerable people are also at risk of higher health impacts associated with prescribed burning smoke. In contrast, incidence rates associated with smoke at the burn activity and vulnerability cold spots are less than a third of the state average. For all health endpoints considered, similar patterns of health incidence rates are observed across clusters, even though their magnitude varies depending on health endpoint and selection of concentration response function or epidemiological study.
Figure 17. Prescribed fire smoke health impacts within spatial clusters of burn activity (BA) and SVI in Georgia. Results show incidence per million for a) asthma emergency room visits, b) asthma hospital admission, c) respiratory hospital admission, d) adult mortality, e) adult mortality, and f) older adult mortality. Mean estimates are shown as diamond markers.

African-American population in southwest Georgia may be less likely to conduct prescribed burns but more likely to live close to others that do.

We also examined the association between percent African Americans and prescribed fire related PM$_{2.5}$ in Georgia. African Americans constitute 32.4% of Georgia’s population, making it the largest racial/ethnic minority group in the state. In Georgia, racial and ethnic minorities and lower wealth groups are more likely to live in urban areas. On the other hand, prescribed fire smoke typically emanates from fires occurring in rural or peri-urban areas. We analyzed burn permit and PM$_{2.5}$ data for the first four months of 2018 to answer two questions: 1) Is there an association between percent African American and PM$_{2.5}$ concentrations at the census tract level in Georgia, and 2) Who are the emitters of prescribed fire smoke resulting in 24-hour average PM$_{2.5}$ larger than 35 µg/m$^3$, which constitutes an exceedance of the national ambient air quality standard (NAAQS). To answer the first question, we regressed our PM$_{2.5}$ estimates on the percent of the population that is African American; Hispanic; lives in mobile homes; employed in agriculture and related occupations; percent evergreen forest; percent evergreen/deciduous forest; and other variables, respectively. For the second question, we merged parcel and prescribed burn permit data to identify landowners who conduct prescribed fires that produce smoke exceeding the NAAQS. In terms of direct effects, percent African American population and mobile home dwellers were positively related to PM$_{2.5}$ concentrations. Government and non-industrial private landowners (NIPLs) were the greatest contributors to exceedance levels. The parcel data did not include a racial identifier, so we could not determine the racial identity of the NIPLs. However, land values for these parcels might suggest that African Americans are less likely to be among the NIPLs contributing to exceedance levels because the average assessed
values of properties associated with exceedance were higher than the overall average of NIPLs. Black landowners are less likely to own the parcels with the higher land values in the state. However, the data did indicate higher proportions of African Americans near prescribed burn activity in southwest Georgia. Our findings suggest that in this part of the state, blacks are not likely to be the primary contributors to prescribed burn smoke but rather tend to live proximate to entities, both public and private, that are (Johnson Gaither et al., 2019).

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 burn permit records are the most reliable tool for estimating prescribed fire emissions. The permitted burn areas differ from actual burn areas by only 15 to 20%. Meanwhile, compared to the permit records, the satellites underestimate the burned areas by large factors ranging from 6 to 10. It should be noted however that this was the situation prior to the availability of GOES 16 for fire detection, which may have improved significantly. Unfortunately, burn permit records are not always available everywhere; satellite-based burned areas may be the only resource when such records are unavailable.

2) One of our objectives was to develop a uniform prescribed fire database for the South. However, not all states responded to our data requests; some states indicated privacy concerns. In the end, we could achieve this objective only partially, as there were spatial and temporal gaps in the resulting database. This is another reason for relying on satellite-based data in the future especially if new satellites (e.g., GOES 16) provide more accurate fire data.

3) The current analysis and visualization technologies are ripe for developing a regional or even national prescribed fire information system that can be used for cohesive fire and air quality management. We have shown this by developing SIPFIS using MySQL, webGIS and other peripheral, mostly open source, technologies. SIPFIS is operational, serving as the primary dynamic fire, air quality and health management tool in the Southeast.

4) There is a significant positive correlation between prescribed fire and PM$_{2.5}$ air quality in the Southeast. We have demonstrated this by linearly regressing the observed 24-hour PM$_{2.5}$ concentrations at monitoring sites throughout the Southeast versus the permitted burn area near each site. In fact, the permitted burn area can explain most of the variation in observed PM$_{2.5}$ concentrations at several sites in Georgia and Florida.

5) The prescribed fire impacts on PM$_{2.5}$ concentrations are persistent for 1-2 days. Among the different types of prescribed fire, silvicultural burns generally have a greater impact on PM$_{2.5}$ concentrations than agricultural, land clearing or pile burns.

6) The association of air quality with burn permits is stronger than the association with satellite derived burned areas as well as the associations with key meteorological parameters. Hence, accurate forecasting of PM$_{2.5}$ concentrations in the Southeast requires prediction of prescribed fire impacts particularly during the burn season.
Unfortunately, the PM$_{2.5}$ monitoring network is too sparse in the Southeast for an accurate assessment of prescribed fire impacts on air quality and health. Model simulations show large areas under prescribed fire smoke impacts where no monitoring is conducted due to small population density. Establishing low-cost sensor networks may be one way of measuring the air quality impacts of smoke in those areas.

We have created prescribed-fire originated PM$_{2.5}$ fields by combining model simulations with observations in Georgia for the years 2015-2018. The models employed estimates of fire emissions derived from burn permit databases. The fusion of observations significantly improved the accuracy of the model simulated fields. These fields can be used in health impact assessment and other studies in environmental justice, fire liability and health economics.

For example, we used these fields to assess the excess numbers of asthma-related emergency-room (ER) visits and hospitalizations in Georgia. While prescribed-fire originated PM$_{2.5}$ levels were largest in Southwest Georgia, the increase in the number of asthma-related ER visits was greater in Atlanta metropolitan area due to its much higher population density.

A demographic study of the burn-intensive areas revealed that the population in those areas are more socially vulnerable compared to areas with less burn activity. Hence, prescribed fire and its associated impacts could disproportionately affect populations with lower socioeconomic status, high elderly or young populations, disabilities, and with less access to housing and transportation.

As a result, the health effects attributable to prescribed fire are much higher for the socially vulnerable populations. For example, the average impact on older adult mortality incidence rate is 3.3 times higher in burn activity hot spots.

Finally, percent African American population is higher in southwest Georgia where prescribed-fire originated PM$_{2.5}$ concentrations are higher, but blacks may be less likely to own lands where prescribed fires are routinely conducted. These preliminary results suggest, but certainly do not confirm, the disproportionate exposure of socially vulnerable populations to prescribed fire smoke, resulting from economic activities with little benefit to them.

Future Research

Florida and Georgia have detailed prescribed burning permit records; however, other southeastern states either do not have the necessary infrastructure to collect and archive prescribed fire activity data needed for air quality and health assessments or have various concerns with sharing such data. On the other hand, the permit records are not a perfect source of information since the records do not contain actual fire data. The difference between permitted and burned acreage is around 15-20%. New satellites such as GOES 16 may already be providing better fire information that might reduce the uncertainties we identified in data from earlier satellites and future satellites are expected to further improve the accuracy of fire information. Therefore, in future studies, it would be better to expand the use of satellite data, particularly in areas that do not have systems as extensive or as accessible as Florida and Georgia.

Statistical- and machine-learning methods can be used to calibrate satellite-derived fire products with permit records. Current satellite products are calibrated with wildfires and are likely biased for long burning, large fires; therefore, they cannot detect the smaller, shorter duration prescribed fires as well as they could. Using the burn permit records for Florida and/or Georgia a statistical- or machine-learning model can be trained to align the burned area from satellite-derived products with permitted burn areas. The calibrated results can be useful for
more accurate emission estimation and improving model simulations on quantifying the impact of prescribed fire. This type of calibration can also be useful in improving, refining, and further developing small fire detection with satellite products.

A dense network of low-cost sensors can be built in southwestern Georgia and other pockets of the southeastern US where there is no current air quality monitoring to detect and investigate the impact of prescribed fire on air quality. The spatial variation provided by the dense network of low-cost sensors network could benefit the health studies to better estimate the exposure fields and minimize the uncertainty in model simulations using the data fusion method.

There are many new methods developed and applied to provide the spatiotemporal exposure fields for health studies such as satellite-retrieved AOD included methods, improved Land Use Regression model, hybrid methods that incorporate AOD data, monitor observations, land use variables and CTM simulations in the last decade. All those methods have their pros and cons and should be evaluated by inter-comparison for the same domain at the same spatial resolution. Those methods should also be assessed in applications to health studies to see how the results may change with different methods, especially at different resolutions, and to answer the question of how fine the scale of exposure fields should be for different type of health studies considering the time and effort spent in such studies, to find the balance between appropriate resolution of exposure fields and accuracy of health results. Finally, in terms of further environmental justice analyses, research concentrating on rural, southwest Georgia counties where prescribed burning is typical, is needed to assess African American contributions to these activities and their exposure to the same.

7. Literature Cited


Johnson Gaither, C.J., Goodrick, S., Murphy, B.E., Poudyal, N., 2015. An Exploratory Spatial Analysis of Social Vulnerability and Smoke Plume Dispersion in the U.S. South. Forests 6, 1397-1421.


8. Appendix A: Contact Information for Key Project Personnel

Mehmet Talat Odman
School of Civil and Environmental Engineering
Georgia Institute of Technology
311 Ferst Drive
Atlanta, GA 30332-0512
404-894-2783
odman@gatech.edu

Fernando Garcia Menendez
North Carolina State University
Campus Box 7908
Raleigh, NC 27695
919-513-7778
f_garcia@ncsu.edu

Cassandra Johnson Gaither
U.S. Forest Service
Southern Research Station
Forestry Sciences Laboratory
320 Green Street
Athens, GA 30602
706-559-4270
cassandra.johnson@usda.gov
9. Appendix B: List of Completed/Planned Scientific/Technical Publications/Science Delivery Products:

Detailed List of Deliverables

Articles in Peer-reviewed Journals

Text Books or Book Chapters
Graduate Theses

Conference or Symposium Abstracts

(2) “Burned Area Comparisons between Prescribed Burning Permits in Southeastern USA and two Satellite-derived Products” R. Huang and M. T. Odman, 16th Annual Community Modeling and Analysis System (CMAS) Conference, October 23-25, 2017, Chapel Hill, NC.


(10) Afrin, S., F. Garcia-Menendez, “Public Health Impacts of Intense Prescribed Burn Activity in Socially Vulnerable Communities of the Southeastern U.S.”, NC BREATHE Conference, Wilmington, NC, April 11, 2019

(11) Garcia-Menendez, F. and S. Afrin, “Connections between prescribed fire, air quality, and communities in the Southeastern U.S.”, Air and Waste Management Association Annual Conference, Quebec, Canada, June 26, 2019

(12) Garcia-Menendez, F., “Wildland fire, air quality, and public health in the Southeastern U.S.”, Colombian Congress and International Conference on Air Quality and Public Health, Barranquilla, Colombia, August 15, 2019

**Posters**


(5) Afrin, S., Koplitz, S., Baker, K., and F. Garcia-Menendez, “Evaluating the air quality impacts of an operational prescribed burning program”, 2019 CMAS Conference, Chapel Hill, NC, October 23, 2019


**Workshop Materials and Outcome Reports**

(1) The SIPFIS workshop was held at Georgia Tech on August 8, 2017 as a forum to provide input to the development of a unified prescribed fire record for the South and participate in the design of an integrated information system for fire and air quality management decision support. SFE helped us increase the audience of the SIPFIS workshop and recommended members to the panels. The participants were fire and air quality managers in southern states and federal agencies and scientists interested in smoke and its impacts on air quality and health. During the workshop, challenges associated with keeping prescribed fire records and information related to smoke emissions and dispersion were identified. Issues and opportunities in generating a unified prescribed fire database were discussed. Data and modeling needs related to prescribed fire and air quality were identified. Prototypes of the database and information system were introduced to the community. Input was sought to guide the development of a community-driven system that can be sustained beyond the end of this project.

**Website Development**

(1) A website created earlier for the Smoke Impact Prediction Center (SIPC) at Georgia Institute of Technology (http://sipc.ce.gatech.edu) was updated to disseminate the data sets and documents created during this project. Currently, the website contains links to the presentations and recordings of the SIPFIS workshop. Data, reports and project related information was also posted to the website.

(2) A new website was created at Georgia Institute of Technology (https://sipc.ce.gatech.edu/SIPFIS/map/) to serve as the front end of the Southern Integrated Prescribed Fire Information System (SIPFIS).
Presentations / Webinars / Other Outreach / Science Delivery Materials

(1) “Prescribed Fire and Air Quality Integrated Information System (SIPFIS),” M. T. Odman, Southern Fire Chiefs’ Winter Meeting, 7 February 2017, Gatlinburg, TN.

(2) “Southern Integrated Prescribed Fire Information System (SIPFIS) for Air Quality and Health Impacts,” M. T. Odman, F. Garcia Menendez, C. Johnson Gathier, presented online to the Southeast Prescribed Fire and Air Quality Workgroup, 3 October 2017.

(3) “Southern Integrated Prescribed Fire Information System (SIPFIS) for Air Quality and Health Impacts,” M. T. Odman, F. Garcia Menendez, C. Johnson Gathier, presented online to the National Wildfire Coordinating Group, Smoke Committee, 5 October 2017.

(4) “Southern Integrated Prescribed Fire Information System (SIPFIS) for Air Quality and Health Impacts,” M. T. Odman, F. Garcia Menendez, presented at the Smoke Summit III, 10-11 April 2017, Jones Ecological Center, Newton, GA.

10. Appendix C: Metadata

Southern Integrated Prescribed Fire Information System (SIPFIS) Data

We developed a web-based application to provide access to the data and facilitate visual analyses. The data can be accessed and analyzed interactively through user-friendly tools and online visualizations. The current focus of the website is mostly on the impacts of prescribed fire smoke on air quality. The impacts on human health is also being addressed. At present, the following data are available on the SIPFIS Website (https://sipc.ce.gatech.edu/SIPFIS/map/).

**Air Quality Observations:** Ozone and PM$_{2.5}$ observations from the national air quality monitoring network (https://www.airnow.gov); nationally, from January 1, 2015 to present; updated daily.

**Air Quality Predictions:** Ozone and PM$_{2.5}$ predictions from the Georgia Tech’s HiRes-2 forecasting system (https://forecast.ce.gatech.edu); Contiguous U.S., from January 1, 2015 to present; updated daily.

**HMS Detections:** Locations of satellite fire detections from the Hazard Mapping System Fire and Smoke Product (http://www.ospo.noaa.gov/Products/land/hms.html); North America, from January 1, 2015 to present; updated daily.

**Permits:** Burn locations and areas from Florida’s open burn authorization records and Georgia’s burn permit records; Florida and Georgia, from January 1, 2015 to December 31, 2016; updated annually.

**Burn, Air Quality (with burns) and Burn Impact Predictions:** Prescribed burn activity, air quality with burns and burn impact from the Georgia Tech’s HiRes-2 forecasting system (https://forecast.ce.gatech.edu); Southeastern U.S., from January 1, 2015 to April 30, 2015; January 1, 2016 to April 30 2016; and January 1, 2017 to present; updated daily.

**Burn Impact on Social Vulnerability and Human Health:** SVI weighted smoke exposure forecasts and forecasts of increased relative health rates due to smoke exposure, derived from the Georgia Tech’s HiRes-2 forecasting system, available from 1 January 2019 to present; updated daily.

**Geocoded Fire Data**

Geocoded fire data compiled for the analyses described in Section 5 (pages 17–28) are available as a spreadsheet at: https://drive.google.com/file/d/106MS_75rc0X_Ctm4uOSgedxq0Y2EJHKV/view?usp=sharing. This spreadsheet includes geocoded Georgia and Florida burn permits for the period from 2013 to 2016, under three tabs: GA, FL_acres, and FL_pile.

**GA:** Includes all Georgia burn permits during the 2013 to 2016 period. The permits contain the following fields: a unique fire identification number, burn date, geographic location as latitude and longitude, burned area in acres, and burn type or purpose for each fire reported during the period.

**FL_acres:** Includes all Florida burn permits for acreage burns during the 2013 to 2016 period. The data fields are the same as the GA tab above.
**FL_piles**: Includes all Florida burn permits for pile burns during the 2013 to 2016 period. This tab contains “Id”, “Date of Burn”, “Latitude”, “Longitude”, and “Burn Type” for each pile burn. Here the size (“Size of Pile”) is reported as the number, length, and width of the piles.