Health implications of smoke from prescribed fires and wildfires

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[Starting text from NASA proposal, need to differentiate from PM2.5 surface paper]

Wildfires in the western US are increasing both in terms of acres burned and economic impact. Prescribed fires are used as a management tool to reduce fuel loads and the risk of large uncontrolled wildfires while allowing ecological benefits of fire. Previous research indicates that prescribed fires impact air quality less than wildfires on a per-fire basis. To our knowledge, previous studies have not considered if air pollution from prescribed fires and wildfires pose differential risks to public health. Air quality managers and public health professionals in the western US want empirical evidence of the health impacts associated with prescribed fires to inform their smoke management plans and public health interventions and messaging. Prescribed fires often occur in more rural areas, thus large datasets over broad geographic areas for many years are needed for statistical power, and studies cannot rely solely on monitoring data for air pollution exposure estimation as these monitors are often far from fire-impacted areas. Increasingly, researchers are statistically blending information from remotely-sensed Earth observations, atmospheric models, and air quality monitoring data to obtain improved spatiotemporal air pollution exposure surfaces for health studies. Our proposal directly fits within the NASA Health and Air Quality Area objectives of incorporating Earth observations into air quality management and public health. Our project has three aims.

We will use surface PM2.5 estimates obtained from machine learning algorithms to analyze the associations of fire-attributed $PM_{2.5}$ levels with cardiorespiratory health endpoints to determine if the health impacts associated with prescribed fire smoke are different from those of wildfire smoke. To our knowledge, our work will be the first to (1) assess health impacts associated with prescribed fire smoke and (2) analyze cardiorespiratory impacts of repeated smoke exposures.

Introduction

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Knowledge about the health impacts associated with fine particulate matter ($PM_{2.5}$) from fires is important for air quality managers and public health departments, particularly in western US states where fire can often cause public health and air quality emergencies. We have therefore partnered with the Western States Air Resources (WESTAR) Council, and the Centers for Disease Control and Preparednesss Environmental Public Health Tracking Network (EPHTN), as the results of our proposed work would be useful to their state partners.

Air quality is managed at the state and local levels to conform to air quality standards set by state and federal policy. Decisions about when to set prescribed fires involve air quality management agencies for states, tribal, and sometimes local areas in order to mitigate impacts that are both regulated and of concern for public health. State and local land management agencies are tasked with writing smoke management plans whenever they put fire on the ground [1]. Smoke plans involve planning burns that produce minimal smoke with maximum ecological benefit and fit within specific land management plans that consider the benefits of fire while minimizing

risks related to both fire and smoke. Prescribed fire planning involves modeling both the quantity and trajectories of emissions from the proposed prescribed fire with smoke prediction tools. When projected emission levels are lower than the air quality standard for fine particulate matter ($PM_{2.5}$), it is assumed that there are no health impacts, however, it is possible that health impacts could occur at that level or lower. Furthermore, sometimes air pollution levels from prescribed fires reach levels higher than smoke planning tools predict.

Fire is a necessary part of many ecosystems in the western US, and complete fire suppression is not feasible. To help minimize risk of often catastrophic unplanned wildfires, prescribed burning is used to reduce fuels and create desired ecosystem conditions. There are tensions among various stakeholders involved in land, fire, air quality, and public health management with some wanting to do more prescribed burning and some wanting to do less. In different states, the public can be on either side of this issue. State air quality managers have impressed upon us that they are incredibly supportive of this project because it will provide them with data on the health impacts of prescribed fires and wildfires that they can present to various stakeholders to base these discussions on science more than on the presumed benefits of more or less prescribed fire. Our project is timely as the state of Oregon is undergoing review of their smoke management plan, and other states will be reviewing their smoke management plans in the near future. The results of our proposed project can inform these processes. Better understanding of health impacts associated with exposure to smoke from wildfires and prescribed fires could allow better planning for future prescribed burning and targeted mitigation strategies in the face of unplanned wildfire events.

Our partners at WESTAR have indicated to us that their organization, and particularly the state air quality managers who form their organization, are interested in understanding the concentration-response functions for $PM_{2.5}$ from various types of fire. They are especially interested in understanding if there is a difference in the health impacts of $PM_{2.5}$ from prescribed fires versus unplanned wildfires. They will use this information as part of their smoke management planning, which many of our state partners are updating in the next few years.

EPHTNs mandate is to collect, integrate, and analyze non-infectious disease and environmental data for empowering environmental and public health practitioners, health-care

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Reserved for Publication Footnotes

providers, community members, policy-makers, and others to make information-driven decisions that affect health [10]. We have partnered with EPHTN because their partners, state public health departments, are interested in knowing more about air pollution exposures attributable to various types of fires and understanding the health risks associated with those exposures.

The current advice for public health departments on how to protect the public from wildfire smoke does not refer to prescribed fires [38]. The reason for no differentiated communication to the public is because there is currently no information on the association between smoke from prescribed fires and health, so it is assumed to be the same as that from wildfires, and only impacted by the level of $PM_{2.5}$. Public health officials are encouraged to use the Air Quality Index (AQI) (a tool to communicate air pollution levels to the public) to recommend health protective actions such as using an air filter and staying indoors. If differential health impacts of $PM_{2.5}$ associated with prescribed fire or wildfire smoke at levels below (the current 24-hour $PM_{2.5}$ standard set by the US EPA) are found to occur, then more targeted messages could be made that may help protect the public from an exposure that is a part of our ecosystem and cannot be removed.

Our state public health partners have indicated to us that they will use the results of our study to provide information to the public to increase the understanding of wildfire (or prescribed fire) and how it can impact health, in general. They will use the information to more effectively target their public health messages should a differential health effect between wildfire smoke and prescribed fire smoke be found. In communities in which there is a lot of opposition to prescribed burns, they would like to quantify the impact of wildfires versus prescribed fires using the results from our study. This may increase their ability to get the publics support in targeted communities while also motivating them to take steps to reduce exposure when a prescribed burn is scheduled. The state public health departments measure baseline performance as the daily $PM_{2.5}$ from monitoring stations as well as the number of respiratory and cardiovascular hospitalizations, emergency department visits, and deaths on days with wildfire smoke. Ultimately, their goal is to reduce emergency department and hospitalization visits for respiratory and cardiovascular conditions on these days.

In addition to information about the associations between cardiovascular and respiratory health and $PM_{2.5}$ from wildfires and prescribed fires, we will provide fire-type source-apportioned annual estimates of $PM_{2.5}$ concentrations at the county level for the western US to EPHTN. The state partners of EPHTN can use these annual estimates for further investigations of the health impacts of smoke from wildland fires in their own communities, using more local information on health that cannot be provided to outside researchers. This will continually enhance the decision-making of public health departments in the western US related to communicating about health interventions for high smoke events from wildfires and prescribed fires.

Both the annual estimates and the daily ZIP code-level $PM_{2.5}$ estimates will be made publicly available via the EPHTN national portal as well as state EPHTN portals to enable members of the public, including environmental and public health practitioners, healthcare providers, community members, policy-makers, and others to make connections between the environments where they live and their health.

The increase in frequency and severity of landscape fires occurring in the western US [7, 34] and the decrease in other sources of air pollution fraction of total air pollution. The in-

crease in wildfires has prompted increasing pressure to engage in more prescribed burning [35]. Therefore, understanding (1) the exposure of the public to air pollution from wildfires and prescribed fires and (2) the impacts of smoke exposure from both prescribed fires and wildfires on health are important and timely topics, which are addressed in this project.

Increasingly, in the wildfire-health literature, researchers are 'blending' satellite AOD data and air quality models together to estimate air quality exposures in locations far from monitoring sites, (e.g., [27, 26, 39, 12]) as these two data sources have different strengths and weaknesses but merged together can better estimate exposures. Satellite AOD data is a measurement but of the full atmospheric column rather than at ground level, whereas ground-level $PM_{2.5}$ estimates can be extracted from air quality models, but there are uncertainties inherent in the models. Blending these data sources over large geographic areas and long periods of time, including many fires in different locations, can provide the statistical power needed to detect if there are differential health impacts from smoke from prescribed fires and unplanned wildfires.

Air quality managers and public health departments work together to protect public health from air pollution due to prescribed burns, but that proves difficult without knowing if the health impacts for this fire type are different from those for wildfires. Therefore, we are partnering with the Western States Air Resources Council (WESTAR) and the Environmental Public Health Tracking Network (EPHTN) of the Centers for Disease Control and Prevention to operationalize our research to support decision-making by states about how to minimize health impacts from prescribed fires and wildfires.

Our proposal aims to address this gap in knowledge by addressing the following objectives:

1. Estimate the proportion of total $PM_{2.5}$ per day attributed to all sources, and then specifically for wildfires and prescribed fires. This will entail the following steps:

   (a) Create a multi-year daily spatiotemporal total $PM_{2.5}$ exposure surface for an 11-state area in the western US for the years 2008-2014

   (b) Model the transport of air pollutant emissions from each fire type (wildfire and prescribed fire), daily for the study area

   (c) Calculate daily estimates of wildfire-attributed and prescribed fire-attributed $PM_{2.5}$ for all ZIP codes in the study area for all 7 years

2. Calculate annual average $PM_{2.5}$ concentrations for each fire type and total for each county in the 11-state area for use by EPHTN

3. Analyze the associations of $PM_{2.5}$ from each fire type on respiratory and cardiovascular hospitalizations and mortality

4. Disseminate results about the differential health impacts of wildfire $PM_{2.5}$ and prescribed fire $PM_{2.5}$ on respiratory and cardiovascular health to WESTAR and EPHTN for use in their decision-making related to air quality and health impacts of prescribed fires and wildfires

Fire is an integral part of many ecosystems, yet many fires are suppressed to protect human populations, property, and infrastructure [3]. This suppression can lead to a build-up of fuels that contribute to the increased intensity of wildfires in the western US [30]. Prescribed fires are used as a management tool to decrease fuel loads and risk of large uncontrolled wildfires while allowing for the ecological benefits of fire [30]. Previous research indicates that prescribed fires may impact

air quality less than wildfires on a per-fire basis [21]. In planning prescribed fire, air quality managers are obligated to understand and plan for the impacts of smoke on air quality and to minimize the impact of smoke on populations (see more from the National Interagency Fire Center at). Prescribed fires, therefore, are intended to last for short durations and under ideal weather conditions for allowing smoke to be transported away from settlements, making it less of a concern than wildfires which often burn under adverse conditions for smoke management. Currently, there is tension between entities that want more prescribed fires and those who oppose them, who often cite air quality and health concerns as their primary opposition to prescribed fires. Air quality managers are often caught in the middle. Empirical information on the health impacts of historical prescribed fires, which is not currently available, could help quantify the benefits of prescribed burning and scientifically inform the ongoing debate about whether it is prudent to increase prescribed burning in the western US.

A differential risk for health for prescribed fires is plausible because prescribed fires (1) typically burn at lower temperatures with more smoldering than high intensity wildfires which can lead to differences in chemical composition of emissions, (2) tend to occur during different times of the year than wildfires, and this could lead to burning wetter fuels, affecting particle chemistry and quantity, (3) are lower intensity which can lead to lower atmospheric injection height and therefore more air quality impacts where people breathe, and (4) have to be repeatedly set to have an impact on controlling larger fires, potentially leading to more chronic exposure to smoke [40, 36]. Thus, although studies have documented lower air pollution levels from prescribed fires [21], it is not clear that the health impacts would be less than those caused by wildfires.

To understand if there are differential health impacts of smoke from prescribed fires and wildfires on population health, a very large dataset needs to be created and analyzed. We therefore propose to create estimates of $PM_{2.5}$ source-apportioned to each fire type for a 7-year period (2008-2014) over an 11-state region of the western US (see Figure 1). To date, there have been no empirical studies of the health effects of prescribed fires compared to wildfires, despite some theoretical publications [14, 32] on the important considerations related to these two sources of air pollution that are increasing in importance in the western US. Therefore, our study will be ground-breaking in its ability to attribute fine particulate matter, both emitted (primary $PM_{2.5}$) and chemically-created (secondary $PM_{2.5}$), to wildfires and prescribed fires in the historical record and then to estimate the health impacts from these fire types on cardiovascular and respiratory health outcomes among the elderly, a particularly sensitive subpopulation about which we have a consistent national dataset.

The results from these studies will be important not just for furthering the science of the health implications of wildfire and prescribed fire smoke, but will also be used by decision makers in both air quality management and public health, as evidenced by our letters of support from WESTAR and EPHTN. The state partners of these groups have expressed enthusiastic support for our project with intent to use our results for current and future smoke and public health preparedness planning.

We will also pilot the first, to our knowledge, investigation into the health impacts of repeated exposures to smoke from prescribed fires and wildfires.

Results

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quam pretium luctus leo quis congue. Morbi vel felis mi. Referencing Table 1. Referencing Figure 2.

Simulations.

Simulation 1

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Real Data.

Discussion

general reference for health effects of PM2.5 and O3 (non-wildfire) [5]... see references #42-47 therein about health effects of wildfire smoke and compare those to our study

[text from NASA grant as starting point:]

This work directly addresses NASA's desire to "discover and demonstrate innovative and practical uses of Earth observations" by using several Earth observations, including several MODIS, Landsat, and VIIRS products, to spatiotemporally estimate ground-level $PM_{2.5}$ concentrations and combine this information with Medicare data so that we may better understand the health impacts of smoke from both prescribed fires and wildfires in the western US. Using satellite data and other Earth observations allows us to estimate air quality in locations without air quality monitors. **Our results will be used by both state air quality managers in updating their smoke management plans and state health departments for targeted communication related to health-protective measures during prescribed fires and wildfires.** All of this work is directly applicable to NASA's Health and Air Quality Application area's interest in the use of Earth observations in air quality management and public health. By working with the NASA Earth Science Division (ESD)/Applied Sciences socioeconomic consortium to coordinate our research and results, the work proposed could be of interest to other NASA Applied Sciences activities.

Our work falls under NASA's Second Strategic Goal in the 2014 Strategic Plan to "advance understanding of Earth and develop technologies to improve the quality of life on our home planet" within the realm of Objective 2.2 to "advance knowledge of Earth as a system to meet the challenges of environmental change, and to improve life on our planet." Wildfires are a significant source of air pollution that impacts the health of human populations, particularly in the western US. Prescribed fires are one way to decrease high-intensity catastrophic fires, but without empirical knowledge of the health impacts of prescribed fires compared to wildfires, it is difficult for all stakeholders to come to consensus about the use of prescribed fires. Our work will inform how the western US decides to manage its forests to minimize health harms from ecologically necessary fires on the landscape.

The relevance of our work to decision-makers in both air quality and public health is apparent by the **incredible outpouring of support we have received from WESTAR and EPHTN as well as their state partners**. This is exemplified in the letters of support that are part of our proposal submission. We had more letters of support than we were allowed to submit with this application, thus EPHTN and WESTAR leaders offered to compile one letter of support from all of their state partners who were interested. The WESTAR letter of support implies that all state air quality managers provide their support, even though they are not enumerated. We also received individual letters of support from some air quality managers before they knew about the combined WESTAR letter. We have included the letter from Colorado as an example of these letters that we also received from New Mexico and Washington.

Anticipated Results and Improvements

Many state smoke management programs were put into place to assist states with implementing measures to reduce regional haze. Smoke management and difficulties communicating across agencies are often seen as impediments to more prescribed fires in the US [33]. In addition to this, decisions about when and where to set prescribed burns are made based on air quality, but without information related to the health impacts associated with smoke from wildfires and prescribed fires. Since these decisions are being made without complete information, the baseline performance of these decisions is based on a presumption that if the air quality impacts of the prescribed fire are low, then the health impacts will also be low. According to our state partner collaborators, no information on health impacts associated with smoke from prescribed fires is known but just assumed because no one has yet done an analysis such as the one presented here.

The state partners are enthusiastic about this project because it will provide them with information to influence their smoke management planning and public health messaging. For example, if we find that there are significant health impacts of prescribed fires at levels below the national ambient air quality standard, this could cause smoke management plans to modify the use of prescribed fires to have lower impacts on air quality. On the other hand, if we find that there are no significant health impacts from prescribed fires, or that they begin to occur at higher levels of $PM_{2.5}$, then smoke management plans may be modified to allow more burning. Similarly in regards to public health decision-making, more targeted messaging for how to protect oneself during fires could be employed for different types of fires if there are indeed dif-

ferential health impacts. Currently, messaging is the same regardless of fire type [38].

Our project can provide information that will help at the state air program/state health department interface. In years 2 and 3, we have budgeted funds for members of the research team (a to-be-determined subset of Drs. Reid, Maestas, and French) to travel to conferences/meetings attended by the state air quality managers and by the state public health departments to update them on progress in the grant and disseminate results that can influence their decision-making.

Given that **the decision-making we aim to influence is done through combined intersections of air quality managers and public health professionals, our partnering with both groups is essential.** We have received enthusiastic support from all state air quality managers in our region who are part of WESTAR and all state public health departments who are part of EPHTN. By having support from both agencies in most states in our region (not all western states are part of EPHTN), we hope that we will have the most success in those states (Arizona, California, Colorado, New Mexico, Oregon, Utah, and Washington) for using empirical evidence of the health impacts of smoke from prescribed fires and wildfires. Through our collaboration with air quality managers in the other states (Idaho, Montana, Nevada, and Wyoming), we hope to make connections to their public health departments and provide them with data and results from our analyses. We recognize that this endeavor will be a long-term process that may not occur for all states within the three years of this project. As we learn more about the decision-making related to prescribed fires and the challenges each state has with effective communication, we will be able to identify ways forward through further projects and grants.

Transition & Sustainability Plan

Research translation to decision-making will be an on-going activity during our three-year project, and will proceed based on consultation with our state-level partners. The information that is co-developed between the research team and state decision-making partners will be the most impactful. We will have regular meetings with the research team and collaborators to ensure that we all understand the goals of the project and to update our decision-makers about our progress.

We will begin with a project kick-off in Boulder, Colorado at the beginning of the grant in summer 2018. We have budgeted funds for travel for many of our participants and will additionally have web-cast capabilities through Earth Lab at CU Boulder to involve those who cannot attend in person. Each spring, the researchers will travel to a conference attended by the WESTAR state partners, such as the WESTAR business meeting, and one attended by the EPHTN states, such as the Environmental Public Health Tracking Workshop. To ensure effective adoption of the information, it is essential for us to start the project on the same page of what the intended methods, outcomes, and uses of the data are by all parties.

Throughout the tenure of the grant, we will be meeting in person (at conferences the decision-makers attend) annually and by phone/internet biannually, with the state air quality managers and public health professionals. These meetings will be ways to update our partners on our progress and hear from them about ways that we could better meet their informational needs related to decision making for prescribed fires and wildfires.

In the last year of the grant, we will survey our state partners about how they intend to use the information we have provided, whether they will continue to use this information, and what information they still need for continued use of the

information in prescribed fire decision making. Sustained development and transition of the products will depend on the needs identified through this process. Since data on health impacts from prescribed fire has not been available before this project, we anticipate our project to be just the beginning of a long-term exchange of how valuable science-based information can be made useful for decision-making.

Materials and Methods

Study Population

We will use Medicare hospital discharge data accessed through the Dartmouth Institute for Health Policy and Clinical Practice. We will be able to use a virtual private network (VPN) to access these data in the Dartmouth servers. We will import our spatiotemporal air pollution surfaces and other covariates to link them by date and ZIP code to counts of Medicare hospitalizations with ZIP code of residence (). Respiratory and cardiovascular outcomes that are hypothesized to be related to acute particulate matter and ozone exposures (and their associated ICD-9 codes) include: asthma (493), COPD (496, 491492), pneumonia (480486), ischemic heart disease (IHD) (410414), cardiac dysrhythmias and conduction disorders (426427), heart failure (428), cerebrovascular disease (430435, 437), and hypertension (401405).

Using Medicare data has a number of benefits for this type of analysis: (1) Medicare enrollees are a population that is particularly sensitive to air quality, (2) a growing literature documents the health impacts of air pollution exposures, including air pollution from wildfires, on cardiovascular and respiratory health outcomes among this population [20], to which we can compare our results as a first pass at validating our findings, (3) the Medicare dataset is a national dataset that allows us to not lose many individuals to follow-up if they move within the US, and (4) provides individual-level information that is often not available in state-level administrative health datasets.

The Medicare database does not have information on socio-economic status (SES) of individuals, which can be an important confounder in our chronic exposure analyses, but is inherently adjusted for in the case-crossover methodology we will use for assessment of acute health outcomes from smoke exposures. Additionally there is growing evidence that SES indicators from one's neighborhood can influence health regardless of their own individual-level SES [8, 9]. We will obtain information on community-level SES variables, such as ZIP code poverty rates and median income, from the American Community Survey five-year rolling averages for the years ending in 2009-2014 for all ZIP Code Tabulation Areas (ZCTAs) in the analysis [37]. ZCTAs are spatial areas created by the US Census to approximate ZIP code boundaries used by the postal service. We will control for confounding by ozone by using output for that pollutant from CAMx.

In our repeated exposures analysis that does not control for individual-level confounders, we will use smoking prevalence estimates derived from Behavioral Risk Factor Surveillance System (BRFSS) data by ZIP code for the 20062010 time period based on the 2000 census ZIP codes [24] as a proxy for smoking status.
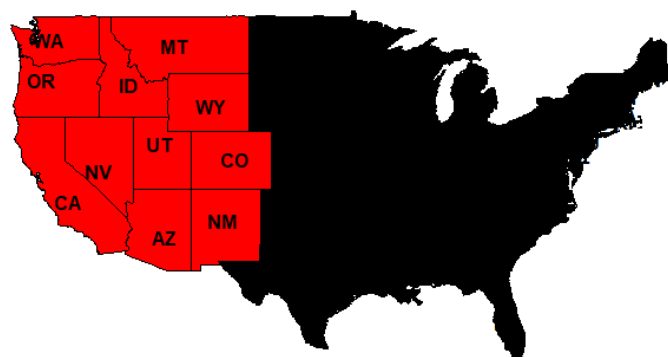

Fig. 1. Map of 11-state study area.

We will conform to all Institutional Review Board requirements for the University of Colorado, Boulder and the Dartmouth Institute for Health Policy and Clinical Practice from which we will obtain health data. No health analysis will be done on the Michigan Technological Research Institute (MTRI) location and therefore, no IRB will be submitted for MTRI.

Acute Impacts of PM2.5 from Prescribed Fires versus Wildfires on Cardiovascular and Respiratory Health Outcomes

example analysis with lags [2]

We will analyze the association between acute exposures to $PM_{2.5}$ attributed to wildfires and prescribed fires and specific respiratory and cardiovascular health outcomes (see (Section **??**) for list of outcomes and ICD-9 codes) among Medicare enrollees using a time-stratified case-crossover design using conditional logistic regression with unconstrained distributed lags [6, 16, 31, 23]. $PM_{2.5}$ exposures will be linked to each Medicare hospital claim by the date of the event (and the corresponding lag days and control days) and home ZIP code of the Medicare enrollee.

In case-crossover design, each individual serves as their own control, which inherently controls for potential confounding variables, such as age, sex, smoking status, and SES, that do not change within an individual over a short period of time [23]. Following the example of [6], we will use a time-stratified approach [19] for choosing control days. A time-stratified approach chooses the control days to be the same days of the week within the same month and year as the case day and the corresponding lag (0-5) days. Choosing control days as the same day of the week, month and year adjusts for day-of-week effects, seasonality, and long-term trends in the data. We will estimate the effects of $PM_{2.5}$ from each fire type, separately and in mutually-adjusted models, on respiratory and cardiovascular hospital admissions at the ZIP code-level across the western US for a seven-year time frame (2008-2014). Although the case-crossover design inherently controls for individual-level confounders that do not change over a short period of time, and the time-stratified controls adjust for day-of-week effects, seasonality, and long-term trends in the data, we will also adjust for other variables that could be influencing respiratory and cardiovascular outcomes that vary spatially and temporally such as temperature, relative humidity, and ozone.

As stated in the previous section, the emissions estimates during the NEI years of 2008, 2011, and 2014 used a more sophisticated and accurate methodology. As these emissions estimates are used in the CAMx model that is used to estimate $PM_{2.5}$ attributable to each fire type, the fire-attributed exposure estimates in those years may be more accurate than in intervening years. We will therefore additionally run our health analyses for those years with better data (2008, 2011, and 2014) as a sensitivity analysis.

There is growing concern in environmental epidemiology regarding the use of exposure estimates from models rather than measured observations because those models have some error in them that is not accounted for in the epidemiological analysis [29]. Due to the sparseness of the monitoring network, measured observations alone cannot be used to estimate air pollution concentrations, particularly in rural areas, see Figure . A few papers have tried to adjust for exposure measurement error using various techniques, none of which has been proven to be the 'best' way to account for measurement error in epidemiological studies. Although the results of adjustment for measurement error in these studies were mostly similar to unadjusted methods [29], we plan to explore adjustment for exposure measurement error in both the acute and cumulative analyses through the non-parametric bootstrap [17] or regression calibration [15].

Case-crossover designs are considered equivalent to time series methods when they use conditional logistic regression [22]. While they are less statistically powered, the time-stratified approach we will use has greater statistical power and less bias than other designs [4]. There is no formal method of doing power calculations for case-crossover studies, but we anticipate that our estimated sample size for asthma hospitalizations (a very sensitive health outcome associated with wildfire $PM_{2.5}$ [28]) of over 8,700 per year, yielding an estimated 61,000 over the 7-year time period, is large enough to detect an effect because it is a larger sample size than used in many other air pollution - health effects studies that used case-crossover design that observed significant associations. For example, [6] analyzed dust storms in relation to 49,427 mortality records, and [13] found a significant association between out-of-hospital cardiac events and $PM_{2.5}$ during a wildfire event in Australia with 457 observations.

Although there is a recent paper that also investigated the association between wildfire $PM_{2.5}$ and cardiorespiratory health among the Medicare population [20], our

proposed analyses are different from that study because we are: (1) investigating potential differential health effects of smoke due to wildfires versus prescribed fires, (2) attributing the $PM_{2.5}$ to fire with a much more sophisticated exposure modeling strategy that blends Earth observations with air quality models rather than using air quality modeling alone, (3) investigating exposures at the ZIP code rather than county level, and (4) focusing on different years (2008-2014) from their study (2004-2009).

Cumulative Impacts of PM2.5 from Prescribed Fires versus Wildfires on Cardiovascular and Respiratory Health Outcomes

We will use Poisson regression, or if the data is overdispersed, negative binomial regression [25, 18] to estimate the association between repeated exposure to smoke from prescribed fires and wildfires, separately and in mutually-adjusted models, with respiratory and cardiovascular outcomes. The goal of this analysis is to assess if there are higher rates of respiratory and cardiovascular health outcomes for individuals who have been exposed to smoke repeatedly compared to those with less frequent exposures. We will use the Huber-White sandwich estimator to obtain standard errors robust to model misspecification [11]. For each individual in the Medicare data, we will count the number of cardiovascular and respiratory events (hospitalizations) both in aggregate and for each ICD-9 code separately over the 7-year study period (2008-2014). See (Section ??) for list of outcomes and ICD-9 codes included in this study. These counts will be merged with cumulative exposure estimates that take into account both the frequency and intensity of exposure during the study period. Example cumulative exposure estimates are: (1) number of days during the study period with exposure to $PM_{2.5}$ from prescribed fires between half the National Ambient Air Quality Standard (NAAQS) for $PM_{2.5}$ and NAAQS, (2) number of days during study period with exposure to $PM_{2.5}$ from prescribed fires between NAAQS and 1.5*NAAQS, (3) number of days during study period with exposure to $PM_{2.5}$ from prescribed fires greater than 1.5*NAAQS, (4) analogous measures for exposure to wildfire smoke, and (5) analogous measures for exposure to the remainder $PM_{2.5}$ that is not attributed to either prescribed fires or wildfires. We will do sensitivity analyses with a variety of $PM_{2.5}$ concentration cut points.

In the analysis of repeated exposures to prescribed fires and wildfires, we will control for confounding from several variables including age, sex, and race. We will control for loss to follow-up due to death or migration where data is available by adjusting the person-time of those individuals accordingly. As the Medicare dataset does not have information on individual-level SES variables, we will control for community-level SES, such as ZIP code poverty rates or median income, from the American Community Survey five-year rolling averages for the years ending in 2009-2014 for all ZIP Code Tabulation Areas (ZCTA) in the analysis [37]. Similarly, we will not have individual-level information on smoking and will adjust for this through estimates of ZIP code-level smoking prevalence rates [24]. We will also adjust for urban/rural status with an indicator variable by ZIP code from the US Census designations of urban/rural. We will control for potential confounding by ozone using output for that pollutant from CAMx.

According to the Dartmouth Atlas of Healthcare (http://www.dartmouthatlas.org/data/region/) in 2014 there were over 7,600,000 Medicare enrollees in our study region. A previous study of the Medicare population and health outcomes associated with fire had 5 million enrollees and was able to find a statistically significant 7.2% (95% confidence interval: 0.25%, 15%) increase in respiratory hospitalizations associated with days with $PM_{2.5}$ above 35 [fix units][20]. With more enrollees, our study should have the power to detect significant associations should they exist.

Creation of Indicators of Air Quality and Health Burden from Prescribed Fires Versus Wildfires

The results of our analyses will influence decision-making by our state partners that are part of WESTAR and EPHTN. In addition to meeting with them in person to present the findings of our analysis, we will also be providing them with data that will be used in their activities in smoke management and public health interventions and messaging, respectively.

EPHTN has national and state web portals that provide maps and data on environmental and health indicators that can be used by researchers, public health practitioners, and the public to understand the association between environmental exposures and health (see https://ephtracking.cdc.g ov/DataExplorer/ and https://ephtracking.cdc.gov/showStateTracking). We will calculate monthly, sea-

sonal, and annual averages of total $PM_{2.5}$ and $PM_{2.5}$ attributed to each type of fire, for each year, by county. These will be given to each of the seven states in our region who are in EPHTN and also to the other four states in our region if they are interested.

The state air quality managers who are part of WESTAR and the state public health officials of EPHTN plan to use the information about health impacts of prescribed fire $PM_{2.5}$ in their decision-making. We will have regular phone conferences with these stakeholders throughout the duration of the grant, providing them with updates on our progress, and obtaining their feedback. We will also present our results in years 2 and 3 of this grant at conferences to which the partners attend such as the annual business meetings for EPHTN and WESTAR.

Performance Measures.

During our project kick-off meeting, partners from state air quality and public health departments will present about their respective state-specific baseline performance measures on decision-making related to prescribed fires and wildfires. This will allow us to benchmark current decision-making processes, identify difficulties in communicating across state-level bureaucracy, and identify what information is limiting their decision-making. These states have already identified that a lack of information on health impacts associated with prescribed fires means that they are making decisions based on the assumption that the levels of $PM_{2.5}$ denote where health impacts occur, but that empirical evidence for historical fires could help inform or improve those decisions.

Some of the state partners have already provided us with information on how they currently measure performance related to fire smoke. For example, the department of health in Washington measures baseline performance as the levels of $PM_{2.5}$ and the number of deaths, hospitalizations, and emergency department visits for respiratory and cardiovascular health endpoints on days with smoke. New Mexico is trying to allow more prescribed fires in their interagency smoke coordination and communication plan that they review annually, but they get pushback from the public with many complaints about prescribed fire planning and smoke levels. They plan to measure baseline as the number of complaint calls to the department of health and the environment department and then see if those numbers change after providing information to the public from our proposed project about associations between air pollution from prescribed fires and wildfires and respiratory and cardiovascular health.

For our project, we will use the following measures to denote performance: (1) how much does each agency use empirical information of the health impacts of fires for their decision-making, and (2) how well do the public health and air quality managers in a given state collaborate/communicate with each other related to their decision-making related to prescribed and wildfires. We will assess this repeatedly through the project. Therefore, we will be at an ARL 3 (detailed characterization of the user decision-making process completed) by the end of the first quarter of the grant, having started at ARL 2 (decision-making activity to be enhanced by the application identified).

In each annual meeting with the state partners, we will assess the extent to which they are using health-based information in their smoke decision-making and that the results from our investigations are influencing those decisions. We hope to be at ARL 4 by the end of year 1 of the grant, and getting to ARL 7 by the end of the project. This will be demonstrated by states proving that they are using information on the health impacts of prescribed fires in their smoke management plans and in their public health messaging during such fires. To get beyond ARL 7 we recognize will require further funding, which our group hopes to pursue during the third year of this grant such that the decision-making activity can be further enhanced with more health information. By engaging with our state-level health partners, we expect to learn more about their needs in order to contribute to a sustained decision-making process.

Measurement error

[Consider accounting for measurement error via a nonparametric bootstrap, see [17]. Also consider spatial compatibility - "monitor and cohort locations are sampled from identical, or at least very similar, spatial distributions"]

Appendix
An appendix without a title.

Appendix: Appendix title
An appendix with a title.

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Fig. 2. Figure caption

Table 1. Table caption

Treatments	Response 1	Response 2
Treatment 1	0.0003262	0.562
Treatment 2	0.0015681	0.910
Treatment 3	0.0009271	0.296

Ideas and Notes for paper

See this paper for discussion of changes in toxicity of smoke between smoldering/open flame: Kim YH, Tong H, Daniels M, Boykin E, Krantz QT, McGee J, et al. Cardiopulmonary toxicity of peat wildfire particulate matter and the predictive utility of precision cut lung slices. Part Fibre Toxicol. 2014;11(1):117.