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Developing an online tool for identifying at-risk populations to wildfire smoke hazards☆

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Abstract

Wildfire episodes pose a significant public health threat in the United States. Adverse health impacts associated with wildfires occur near the burn area as well as in places far downwind due to wildfire smoke exposures. Health effects associated with exposure to particulate matter arising from wildfires can range from mild eye and respiratory tract irritation to more serious outcomes such as asthma exacerbation, bronchitis, and decreased lung function. Real-time operational forecasts of wildfire smoke concentrations are available but they are not readily integrated with information on vulnerable populations necessary to identify at-risk communities during wildfire smoke episodes. Efforts are currently underway at the Centers for Disease Control and Prevention (CDC) to develop an online tool that utilizes short-term predictions and forecasts of smoke concentrations and integrates them with measures of population-level vulnerability for identifying at-risk populations to wildfire smoke hazards. The tool will be operationalized on a national scale, seeking input and assistance from several academic, federal, state, local, Tribal, and Territorial partners. The final product will then be incorporated into CDC's National Environmental Public Health Tracking Network (http://ephtracking.cdc.gov), providing users with access to a suite of mapping and display functionalities. A real-time vulnerability assessment tool incorporating standardized health and exposure datasets, and prevention guidelines related to wildfire smoke hazards is currently unavailable for public health practitioners and emergency responders. This tool could strengthen existing situational awareness competencies, and expedite future response and recovery efforts during wildfire episodes.

Keywords

Wildfire smoke; Particulate matter; Vulnerable populations; Online tool

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Appendix A. Supplementary data
Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2017.10.270.

1. Introduction

Wildfire episodes pose a significant public health threat in the United States. The potential impact on health, arising from the flame activity near active fires as well as exposures to surface smoke concentrations downwind of the burn area, represent several far-reaching consequences of wildfires (Williamson et al., 2016). Smoke plumes from wildfires represent a complex mixture of pollutants and its composition depends on several factors, including the fuel type and prevailing meteorological conditions (Urbanski et al., 2008). As a result, plume composition can vary over time and space (Lassman et al., 2017) and can consist of several air pollutants, including high concentrations of fine particulate matter ($PM_{2.5}$) and ozone (Jaffe et al., 2008; Pfister et al., 2008). Health effects associated with wildfire smoke can range from eye, nose, and throat irritations to more serious disorders, such as asthma exacerbation, bronchitis, decreased lung function, and premature death (Reid et al., 2016).

A comprehensive strategy to mitigate adverse health impacts associated wildfire disasters necessitates a thorough understanding of population-level exposures to surface smoke $PM_{2.5}$ concentrations. Additionally, identifying vulnerable populations and places, and quantifying the disease burden associated with surface smoke exposures are critical to strengthening public health preparedness capabilities for wildfires. Accordingly, to support preparedness efforts, a need emphasized by state, local, territorial, and tribal (SLTT) health departments (HDs), is access to smoke forecast data, visualization tools, and communication documents, as well as surveillance data on population health- and on vulnerable populations, — all of which can be made available on one information system and on a real-time basis. Unfortunately, such a health information system does not currently exist. However, CDC's Environmental Public Health Tracking Network (Tracking Network), which is a surveillance platform with a well-designed repository of environmental health data and user-friendly visualization capabilities, has the necessary information technology infrastructure and expertise to undertake such tool development efforts (CDC 2010).

In this manuscript, we describe CDC's efforts to develop an online tool, which can assist SLTT HDs with conducting a real-time vulnerability assessment and identify at-risk populations to wildfire smoke impacts.

2. Materials and methods

CDC's National Environmental Public Health Tracking Program (Tracking Program) has been collaborating with a multi-disciplinary team of experts from several academic, state, and federal agencies to support this effort. In this section, we describe the different phases involved in the tool-building effort. Fig. 1 describes our tool-building framework with specific tasks, which can be classified under the substantive areas of environmental epidemiology, health informatics, and risk communication.

2.1. Assessment of data sources and selection of historical wildfires

Exposure to wildfire smoke is a growing national concern, especially with an ever expanding wildland-urban interface (Theobald and Romme, 2007). There are several databases online that offer invaluable information on historical wildfire occurrence and burn severity; however, considerable effort is required to consolidate such information, which often resides in disparate databases. We conducted an assessment of major databases for obtaining environmental and health data as well as those providing information on vulnerable populations. In addition, we conducted a pilot study assessing the feasibility of bringing together data from several of these datasets into one information system, as well as abstracting health risk information from extant scientific literature.

2.2. Social vulnerability assessment

Social vulnerability or social capital is a construct measured by the prevailing levels of certain socioeconomic and demographic factors. Social vulnerability is a key factor that determines the resilience of communities when under stress from natural and human-made disasters (Flanagan et al., 2011). Social vulnerability metrics (SVMs) assist our understanding of the differential capacity that exists in communities including the ability to carry out preparedness, response, and recovery efforts. As part of our tool-building effort, we conducted a social vulnerability assessment, using an overall social vulnerability index for fires that occurred in the Western U.S. The overall social vulnerability index ranks each community based on the degree of vulnerability; a detailed description and formulation of this index are available from the following website (https://svi.cdc.gov/index.html).

We conducted a simplistic exercise, i.e., without any air quality information but with information on location of fires, to delineate the spatial extent of potential wildfire impacts on nearby population. This rudimentary analysis was our attempt to simulate a “first-stage” vulnerability analysis that our SLTT partners can conduct in the absence of historical smoke $PM_{2.5}$ concentration, which are not systematically archived for public access. Based on satellite imagery and GIS processing, we initially delineated the spatial extent of each wildfire and classified the impacted state based on three proximity categories. The first category consisted of counties that were directly impacted by wildfires. We executed a spatial query, using a nearest neighbor approach, to classify remaining counties in the state as either surrounding areas to those directly impacted by fire (second category) or other areas in the state not covered by the first two categories (third category). The results for each fire were stored in a spatially indexed GIS database. Subsequently, we created a separate database that contains a suite of SVMs, at the census tract and county level. The extracted variables address several aspects of social vulnerability, including socioeconomic status, household and demographic composition, minority status, and transportation/access to care. Finally, we conducted a spatial linkage between the two databases to explore the levels of social vulnerability in the above-mentioned three categories.

2.3. Health burden risk assessment/literature review

We partnered with researchers from Colorado State University to conduct a health risk assessment, based on the 2012 fires in the state of Washington, for generating Concentration–Response (C-R) relationships (Gan et al., 2017). We also conducted a literature search to abstract C-R relationships for various health outcomes associated with smoke exposure, particularly for some of the wildfires identified in the Western U.S. In addition to C-R relationships, we also acquired information on baseline health rates and population information, for estimating health burden resulting from smoke $PM_{2.5}$ exposure. The formula for health burden calculation is provided in the supplemental information.

2.4. Surveillance indicators development

CDC's Tracking Program funds health departments in 25 states and 1 city, and they collectively support the National Tracking Network by providing guidance on advancing surveillance priorities that are common across multiple jurisdictions. As part of the Tracking Program, a group of experts and public health practitioners from CDC and SLTT HDs collaborated to evaluate available wildfire related data sources, and identified datasets and consistent protocols for creating surveillance indicators.

3. Results

Databases that are necessary to identify at-risk populations and advance our understanding of the health impacts associated with wildfire smoke are highlighted in Table 1.

We selected 11 major wildfires in multiple western states during 2008–2013 to conduct a pilot study. The selection criteria for these fires was based on the estimated potential adverse health impacts as well as availability of data to carry out tasks related to social vulnerability and health burden assessments. The data availability for these fires are explained in Table 2.

Our assessment of the 11 wildfires (Fig. 2) indicates that, areas directly impacted by fires (denoted by the area highlighted in red in Fig. 2), have communities that rank poorly for social vulnerability. Surrounding areas to those directly impacted by fires, which are denoted by a cross-hatched pattern, do not directly bear the brunt of wildfire damage but may still be impacted by wildfire smoke. While, using a proximity relationship to identify vulnerable populations to wildfire smoke may overlook transport issues due to meteorology, terrain, and chemistry, it provides an overview of areas likely to be impacted by wildfire smoke.

Predictions from air quality models are used to understand transport of smoke during major wildfire episodes, but information from these historical model runs are not systematically archived for public access. Toward this end, we relied on historical model- and monitor-based air quality data from academic and federal partners. The model building strategy, including an ensemble approach using satellite-based aerosol optical depth and an evaluation of various smoke estimation methods was conducted by Colorado State University (Lassman et al., 2017). The health risk assessment that was conducted for Washington 2012 fires evaluated the health risk estimates generated from various $PM_{2.5}$ estimation methods (Gan et al., 2017). After comparing results, we selected C-R relationships generated using a geographically weighted ridge regression — an ensemble approach using multiple air quality inputs.

Research is being conducted evaluating the impact of wildfire smoke on human health in the context of varying population cohorts and geographical locations (Liu et al., 2015). However, health risk assessments exploring adverse health effects associated with wildfire smoke in the U.S. are limited to a few wildfires. A critical review (Liu et al., 2015; Reid et al., 2016) of available evidence related to health effects associated with wildfire smoke demonstrated that there is a robust association between wildfire smoke and respiratory morbidity, including exacerbations of asthma and chronic obstructive pulmonary disease (COPD). Reid et al., 2016 noted that the evidence for all-cause mortality is growing while associations for other outcomes, particularly cardiovascular morbidity, remain unclear. We were able to compile a database of estimated effect sizes for various health end points, using C-R relationships based on 2012 Washington fires and those abstracted from literature. In Table 3, we provide a summary of effect estimates from U.S. based studies for asthma exacerbations and COPD associated with smoke $PM_{2.5}$.

Lastly, based on input from tracking funded partners and HDs, we have identified GIS databases from the Active Fire Mapping Program to summarize state- and county-specific information on the number of fires, acreage burned, and duration of major wildfire episodes. We used SAS v9.4 and ArcGIS 10.3, for data processing and for creating map displays.

4. Discussion

CDC's Tracking Network satisfies a wide array of users by providing reliable environmental and health information via an online platform. The IT platform, upon which the Tracking Network is built, is interoperable and supports integration of real-time feeds from reliable external sources. Currently, we use base map layers from external sources to accomplish our visualization needs. Our real-time tool development efforts will tap into web services for real-time wildfire smoke predictions and forecasts available from NOAA/NWS. Specifically, we have successfully piloted protocols to import NWS' web feature services for smoke and expose smoke concentrations as a map layer on the Tracking Network's web portal (https://ephtracking.cdc.gov/DataExplorer/). A description of wildfire smoke model that NOAA/NWS uses is provided in the attached supplemental information (Fig. S1). We also have created a process to integrate real-time smoke information with static measures of vulnerability and other indicators of baseline health information. Fig. 3 provides a snapshot on how a user will query smoke predictions and forecasts along with measures of vulnerability; the graphic is based on smoke predictions for the recent CA wildfires (July 2017).

The tool-building effort helped us gain insights on several knowledge gaps related to reducing public health impacts associated with wildfire smoke exposure. Firstly, epidemiologic studies that have explored the relationship between exposure to smoke and adverse health outcomes are limited to a few fires in the U.S. A systematic assessment presenting evidence from multiple fires across multiple jurisdictions is needed to help generate a nationally representative C-R relationship. In addition, population-level exposure assessment methods rely on a combination of monitor-based measurements and model-based predictions. Absence of a central repository with data collection standards for historical and near-real-time smoke predictions affects our ability to conduct routine health investigations. Further, extant literature sheds little light on the differential toxicity of smoke constituents—smoke is a complex mixture and particulate matter is a marker for many toxic components in smoke. These scientific and data access limitations collectively shaped our decision-making, especially with respect to conducting the vulnerability assessment and selection of C-R functions.

The design and development process has been complicated and resource-intensive. Accordingly, we have leveraged existing partnerships and fostered new ones, especially with agencies and institutions whose priorities related to reducing wildfire smoke exposure complemented or aligned with ours. For example, we partnered with USFS on identifying the right databases on location of fires and burn severity, and worked with Colorado State University on comparing various methods to generate smoke exposure and their implications for conducting health risk assessment. We also plan to enhance existing risk communication documents and synthesize key messages that cater to specific audiences. Recently, a multi-agency consortium of experts updated the Wildfire Smoke Guide—a communication tool for public health officials (https://www3.epa.gov/airnow/wildfire_may2016.pdf). This guide consists of information including an introduction to wildfire smoke and its health effects, information on sensitive populations, specific strategies to reduce smoke exposure, and recommendations for public health action during wildfire emergencies. Our plan is to abstract relevant prevention guidelines from this resource guide and disseminate them along with smoke forecasts and measures of vulnerability.

In addition, we received input from various stakeholders to refine the design of this online tool. A majority of these stakeholders are funded by the Tracking Program or through other programs within CDC, providing a pool of potential end users with interests in reducing public health impact associated with wildfires. As soon as a beta-version of this online tool is ready for testing, we plan on gaining feedback from these knowledgeable end users to resolve any potential inconsistencies in visualization and reporting of information and to improve user experience.

After the initial launch, we will add functionalities to this online tool such as projecting health burden on a real-time basis by using smoke predictions and forecasts, or possibly providing additional information for decision making, including the location of the nearest shelter or hospital. Dissemination of smoke forecasts and identifying vulnerable populations can help emergency responders and public health practitioners, but a unified response is incomplete without engaging the public and providing them with effective messaging to reduce smoke exposure. Once the tool is launched, it will be important to design an evaluation plan in partnership with interested stakeholders to examine the impact of this online tool in reducing the health burden associated with wildfire smoke.

5. Conclusions

A primary motivation for developing an online tool is to assist public health practitioners and emergency responders in making informed decisions before, during, and after wildfire emergencies. Toward that end, CDC is developing an online tool that utilizes short-term predictions and forecasts of smoke concentrations and integrates them with measures of population-level vulnerability to help identify at-risk populations to wildfire smoke hazards. The tool will be operationalized on a national scale, seeking input and assistance from several academic, federal, and SLTT Partners. We foresee that this tool will decrease the time to identify impacted communities, help to identify and enumerate vulnerable populations, better characterize population-level exposure, and inform implementation of appropriate interventions for those areas affected by wildfire smoke hazards.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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HIGHLIGHTS

- Wildfire episodes pose a significant public health threat in the United States;
- Real-time forecasts of wildfire smoke are available but they are not integrated with information on vulnerable populations;
- This tool could strengthen existing situational awareness, and future response and recovery efforts during wildfire episodes.

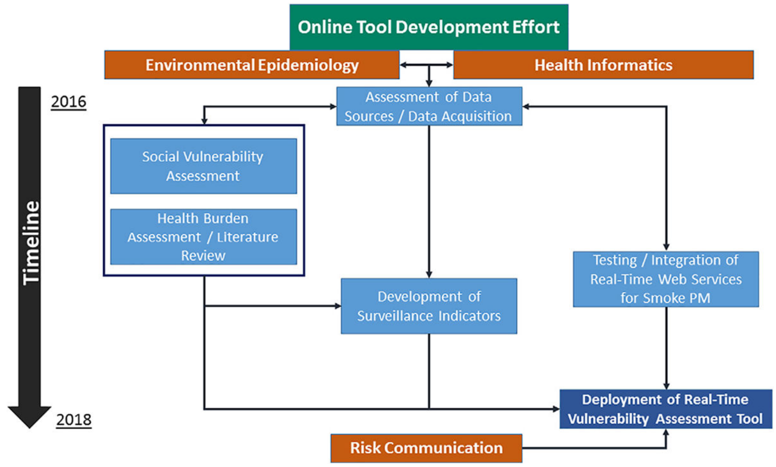

Fig. 1.
Tool-building framework with specific tasks.

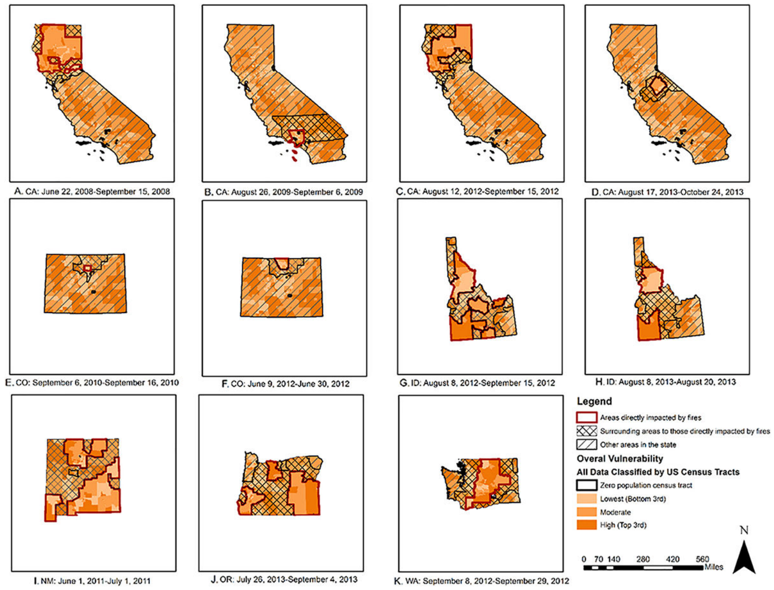

Fig. 2.

Distribution of Overall Vulnerability, as measured by Social Vulnerability Index, for the selected fires.

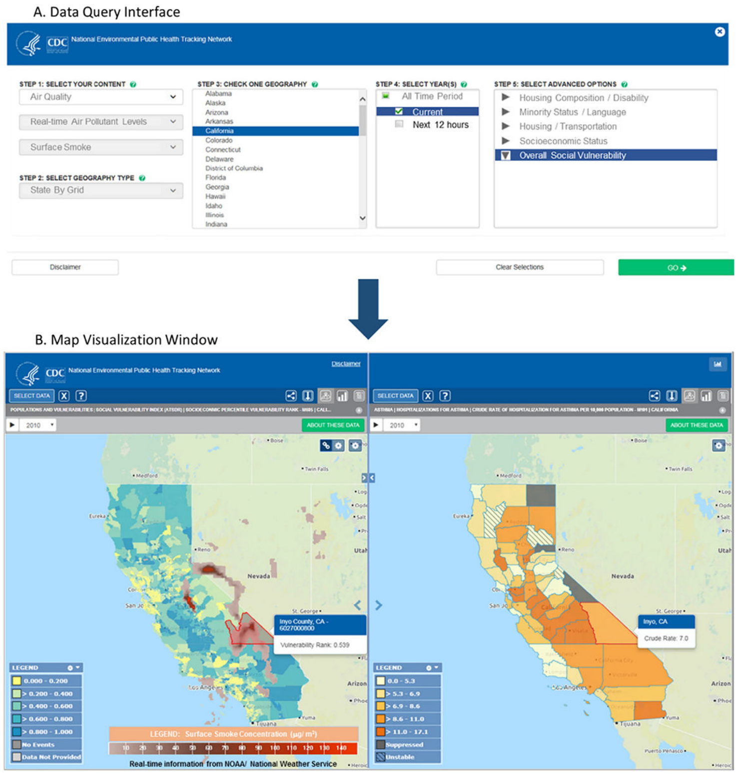

Fig. 3.

Integration of web service for smoke into the Tracking Network; A. Data Query Interface, and B. Map visualization Window showing smoke predictions integrated with social vulnerability metrics and baseline asthma rates on the right hand side.

Table 1

Assessment of existing databases to support the development of an online tool.

Type of information	Major databases	Description	Data steward and partners	Data accessibility
Location of fires/burn severity	Monitoring Trends in Burn Severity (MTBS)	Information available on burn severity and perimeters of fires across the United States.	MTBS is sponsored by the Wildland Fire Leadership Council (WFLC), a multiagency oversight group. U.S. Department of Agriculture (USDA) and U.S. Geological Survey (USGS) are responsible for the development and maintenance of MTBS products.	Data access is free and there is a data query interface to download data.
	Active Fire Mapping Program	Satellite based active fire mapping program provides a near real-time spatial context to wildland fire situation at regional and national scales.	This program is managed by USDA Forest Service Remote Sensing Applications Center.	Data access is free and various datasets, including satellite and Geographic Information Systems (GIS) data, can be downloaded by accessing the program website.
Air quality data	Air Quality System (AQS) Data Mart	This database houses all historical air quality data for several air pollutants.	U.S. Environmental Protection Agency (EPA) manages this database. For $PM_{2.5}$, which is a criteria pollutant and a primary pollutant of interest in measuring impacts of wildfire smoke on health, data are available from monitors that are part of several networks.	Data access is free and can be downloaded as either text files or accessed via a web service.
	AirNow	This system provides real-time and forecast air quality data for the U.S., and parts of Canada and Mexico	EPA developed this system in partnership with National Oceanic and Atmospheric Administration (NOAA), National Park Service (NPS), and other local, state, and tribal agencies.	Images of Air Quality Index (AQ) from this system can be downloaded as maps or through web services.
	National Digital Guidance Database	This system provides real-time and forecasts for smoke-related data products	NOAA/National Weather Service (NWS) maintains this system.	Real-time and forecast maps are available through a website.
Health data	National Vital Statistics System Databases	This system provides information on vital events, including births and deaths	CDC's National Center for Health Statistics manages these databases through contracts with vital registration systems operated in various jurisdictions.	A data use agreement is needed to access highly resolved vital statistics data. When given access, end-user must comply with data steward's confidentiality and privacy protection rules and policies.
	Medicaid Beneficiaries and Children's Health Insurance Program	These databases are the basic source of state-submitted eligibility and claims data, their characteristics, utilization, and payments.	Centers for Medicare and Medicaid Services (CMS) manages these databases by collecting data from states through multiple reporting vehicles.	CMS has developed a public use file for the Medicare fee-for-service population. However, a data use agreement must be established to access highly resolved spatiotemporal datasets.
	Healthcare Cost and Utilization Project (HCUP)	This program is a comprehensive source of hospital care data	Agency for Healthcare Research and Quality (AHRQ) manages the HCUP in partnership with several local and state hospital data organizations. HCUP is a family of databases that provides hospital care data, including but not limited to information on in-patient stays and emergency department encounters.	Access to HCUP databases depends on the nature of end-user's data request. While summary data are available online, daily data at fine-scale geographies (e.g., zip code and county) requires permission from data stewards and participating states.
	Tracking network	Tracking Network is a system of integrated health, exposure, and hazard information and data from a variety of national, state, and city sources.	CDC funds health departments in 25 states and 1 city to build and implement local tracking networks. These state and local data systems feed into the national Tracking Network.	Access to baseline health data are available for download from the Tracking website. However, access to data that are highly resolved in both space and time require permission from original data stewards.

Type of information	Major databases	Description	Data steward and partners	Data accessibility
Information on vulnerable populations	U.S. Census Bureau Databases	U.S. Census Bureau provides several metrics to assess population level vulnerability to various extreme events.	Data are collected by U.S. Census through several surveys, including decennial census, American Community Survey, American Housing Survey. These survey data are processed to create indicators at various geographic scales.	Data access is free and can be downloaded in multiple data formats.

Table 2

Data availability for 11 selected wildfires.

Time period	Location(s) of wildfire	Location and burn severity information data	Air quality data ($PM_{2.5}$, ozone)		Health data availability from primary data steward			Information on vulnerable populations
			Station-based	Model-based	Mortality	Hospital admissions	Emergency department visits	
6/22/08–9/15/08	Northern California	✓	✓		✓	✓	✓	✓
8/26/09–9/6/09	Southern California	✓	✓	✓	✓	✓	✓	✓
9/6/10–9/16/10	Four Mile Canyon Fire, Boulder, Colorado	✓	✓		✓	✓	✓	✓
6/1/11–7/1/11	Eastern Arizona, New Mexico	✓	✓		✓	✓	✓	✓
6/9/12–6/30/12	High-Park Fire, Northern Colorado	✓	✓		✓	✓	✓	✓
8/8/12–9/15/12	Idaho	✓	✓		✓			✓
8/12/12–9/15/12	Northern California	✓	✓		✓	✓	✓	✓
9/8/12–9/29/12	Washington Fires	✓	✓	✓	✓	✓		✓
7/26/13–9/4/13	Douglas Complex Fires, Western Oregon	✓	✓	✓	✓			✓
8/8/13–8/20/2013	Central Idaho	✓	✓		✓			✓
8/17/13–10/24/13	Rim Fire near Yosemite, California	✓	✓		✓			✓

Table 3

Effect sizes from U.S. based studies for asthma exacerbations and COPD associated with smoke $PM_{2.5}$ (for all ages).

Health outcome	Disposition type	Study id	Primary exposure measure	Exposure offset	Mean effect estimate (β) with 95% confidence interval[a]
Asthma exacerbations	Emergency department visits	Rappold et al., 2011	Smoke period vs. reference period	Lag 0–5	0.501 (0.223, 0.775)
		Resnick et al., 2015	Smoke period vs. reference period	N/A	0.548 (0.030, 1.019)
		Alman et al. 2016	$PM_{2.5}$	Lag 0	0.008 (0.004, 0.012)
		Alman et al. 2016	$PM_{2.5}$	Lag 0–2	0.014 (0.008, 0.019)
	Hospitalizations	Delfino et al., 2008	$PM_{2.5}$	2-day moving average	0.005 (0.002, 0.008)
		Rappold et al., 2011	$PM_{2.5}$	Lag 0	0.008 (0.002, 0.013)
COPD	Emergency department visits		Smoke period vs. reference period	Lag 0–5	0.548 (0.058, 1.040)
		Alman et al. 2016	$PM_{2.5}$	Lag 0	0.010 (0.004, 0.015)
		Alman et al. 2016	$PM_{2.5}$	Lag 0–2	0.014 (0.004, 0.023)
	Hospitalizations	Delfino et al., 2008	$PM_{2.5}$	2-day moving average	0.004 (0.000, 0.077)
		Gan et al., 2017	$PM_{2.5}$	Lag 0	0.008 (0.003, 0.014)

[a] Effect estimates reported for 1 μg/m^3 increase in continuous $PM_{2.5}$ or for a change in $PM_{2.5}$ levels as observed during smoke period vs. reference period.