INTEGRATING GEOSCIENCE AND HEALTH DATA FOCUSING ON WILDFIRES

A Report by the

SCIENCE FOR DISASTER REDUCTION INTERAGENCY WORKING GROUP

About the Science for Disaster Reduction Interagency Working Group

The Science for Disaster Reduction Interagency Working Group (SDR), under the National Science and Technology Council's Subcommittee for Resilience Science and Technology (SRST), brings together the civilian and defense agencies that develop and apply science and technology to reduce the impacts of natural and technological hazard events. By building a community of interested Federal agency partners, the SDR works to enhance cross-agency collaboration in disaster-related science and technology. This collaboration takes many forms including identifying best practices in data delivery and communication; enhancing awareness of science and technology products and tools across the Federal government; working with SRST to develop science and technology-based guidance for policy makers and advance informed strategies for managing disaster risks. More information is available at https://www.sdr.gov/index.html

About this Document

This document was developed by the members of the Integrating Geoscience and Health Data in Disasters Working Group (GHDWG), a sub-working group of the SDR. To identify areas for improvement in data collection, integration, and sharing across the geosciences, atmospheric sciences, and human health fields, the GHDWG conducted a detailed examination of the existing landscape of data using wildland urban interface (WUI) fires as a case study. WUI fires were selected as the context for this data exploration because of the growing threat of wildfires that affect areas where homes and other structures meet vegetative fuels, which generates the potential for a wide range of exposures that may negatively impact health. This report summarizes several activities performed by the GHDWG to explore how data being collected by federal agencies can more effectively be used to inform and reduce the health impacts associated with disasters, specifically WUI fires.

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Abbreviations and Acronyms

AAI	Absorbing Aerosol Index
AHRQ	Agency for Healthcare Research and Quality
AOD	Aerosol Optical Depth
AQI	Air Quality Index
AQM	Air Quality Monitoring
AQS	Air Quality System
ARI	Acute Respiratory Infection
BC	British Columbia
BenMAP-CE	Benefits Mapping and Analysis Program—Community Edition
BRFSS	Behavioral Risk Factor Surveillance System
CAL FIRE	California Department of Forestry and Fire Protection
CARB	California Air Resources Board
CAP	California Air Pollution
CDC	Centers for Disease Control and Prevention
CHHS	California Health & Human Services Agency
CMAQ	Community Multiscale Air Quality Modeling System
CMS	Centers for Medicare & Medicaid Services
COPD	Chronic Obstructive Pulmonary Disease
CSL	Chemical Sciences Laboratory
ED	Emergency Department
EHR	Electronic Health Record
EMS	Emergency Medical Services
EPA	Environmental Protection Agency
FAM-WEB	Fire and Aviation Management Web Applications
FEM	Federally Equivalent Monitor
FEMA	Federal Emergency Management Agency
FIRMS	Fire Information for Resource Management System

FRAP	Fire Resource Assessment Program
FRM	Federal Reference Monitor
GEOS-Chem	Goddard Earth Observing System - Global 3-D Chemical Transport Model
GFED	Global Fire Emissions Database
GHDWG	Integrating GEO and Health Data in Disasters Working Group
GIS	Geographic Information System
GOES	Geostationary Operational Environmental Satellite
HAP	Hazardous Air Pollutants
HCUP	Healthcare Cost and Utilization Project
HHS	Department of Health and Human Services
HMS	Hazard Mapping System
HRSA	Health Resources and Services Administration
HYSPLIT	Hybrid Single-Particle Lagrangian Integrated Trajectory
ICD-CM	International Classification of Diseases – Clinical Modification
IHS	Indian Health Service
IMPROVE	Interagency Monitoring of Protected Visual Environments
IWFAQRP	The Interagency Wildland Fire Air Quality Response Program
MODIS	Moderate Resolution Imaging Spectroradiometer
MOZART-4	Model for Ozone and Related Chemical Tracers, version 4
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCEI	National Centers for Environmental Information
NCEP/NAM	National Center for Environmental Protection's North American Mesoscale Forecast System
NCHS	National Center for Health Statistics
NHANES	National Health and Nutrition Examination Survey
NIFC	National Interagency Fire Center

NIH	National Institutes of Health
NIEHS	National Institute of Environmental Health Sciences
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Association
NOHM	Naturally Occurring Hazardous Materials
NREL	National Renewable Energy Laboratory
NWCG	National Wildfire Coordinating Group
NWS	National Weather Service
OAR	Office of Oceanic and Atmospheric Research
OC/EC	Organic Carbon/Elemental Carbon
OSHPD	Office of Statewide Health Planning and Development
PAH	Polycyclic Aromatic Hydrocarbons
PFDFs	Post-Fire Debris Flows
PM	Particulate Matter
PM_{10}	Coarse particulate matter; Particles with diameters of 10 micrometers or less
$PM_{2.5}$	Fine particulate matter; Particles with diameters of 2.5 micrometers or less
PTSD	Post-Traumatic Stress Disorder
SAMHSA	Substance Abuse and Mental Health Services Administration
SAWRI	Santa Ana Winds Regional Index
SDOH	Social Determinants of Health
SDR	Science for Disaster Reduction
SVI	Social Vulnerability Index
TE	Trace Elements
TEOM	Tapered-Element Oscillating Microbalance
THI	Temperature Humidity Index
UC	Urgent Care
UDS	Uniform Data System
USAID	United States Agency for International Development
USDA	United States Department of Agriculture

USFS	United States Forest Service
USGS	United States Geological Survey
VABS	Victorian Adult Burns Service
VIIRS	Visible Infrared Imaging Radiometer Suite
VOC	Volatile Organic Compounds
WRF	Weather Research and Forecasting
WUI	Wildland Urban Interface
ZCTA	Zip Code Tabulation Area

CHEMICAL FORMULAS

CH_4	Methane
CO	Carbon Monoxide
NO	Nitric Oxide
NO_2	Nitrogen Dioxide
NO_x	Nitrogen Oxides
O_3	Ozone
SO_2	Sulfur Dioxide

Executive Summary

The Science for Disaster Reduction (SDR) Interagency Working Group of the National Science and Technology Council's Subcommittee for Resilience Science and Technology is a community of Federal agency partners working toward reducing the adverse impacts of natural and technological hazard events. One of the main goals of the SDR is to address gaps in science and technology related to disaster risk reduction and building community resilience to disasters.

The Integrating Geoscience and Health Data in Disasters Working Group (GHDWG), a working group of the SDR, conducted a detailed examination of the existing landscape of geoscience, atmospheric, and human health data sources, using wildland urban interface (WUI) fires as a case study, to identify areas for improvement in data collection, integration, and sharing. WUI fires were selected as the context for this data exploration because of the growing threat of wildfires that affect areas where homes and other structures meet vegetative fuels, which generates the potential for a wide range of exposures that may negatively impact health. This report is a snapshot that summarizes several GHDWG activities conducted between August 2021 and June 2022 to explore how data being collected by federal agencies can more effectively be used to inform and reduce the health impacts associated with disasters, specifically WUI fires. Although new data streams, resources, and technology have evolved since then, this summary report is not intended to be comprehensive but rather aims to inspire collaboration and spur deeper work around this topic.

The first activity was to use the 2020 Walbridge Fire in Sonoma County, California, as a scenario to frame priority questions related to data needs from different agency perspectives. These questions helped to identify data availability and gaps, particularly in the published literature on wildfires and health effects, and informed subsequent activities, including creating a table of existing data streams of environmental and exposure data, health, and social determinants of health data (SDOH) at the state and national levels. Next, the GHDWG created a conceptual model to visualize the life cycle of the WUI fire scenario from pre-event through post-event timeframes, characterizing data into main categories of modifiers, exposure sources and pathways, exposure media and routes of exposure, receptors, health outcomes, and mitigation strategies.

Furthermore, to better understand how data were being used by the research community to evaluate the health impacts of wildfires, a scoping review of published literature from January 1, 2016 through July 31, 2022 was conducted to identify the specific environmental, exposure, SDOH, and health data sources. Finally, as proof of concept, the GHDWG used a pilot exercise to develop a GHDWG web map, hosted on the National Aeronautics and Space Administration (NASA) Disasters Mapping Portal, integrating high-priority data streams into a Geographic Information System (GIS) that facilitated data visualization and analysis.

Key takeaways include: 1) There is a need for accurate and comprehensive observational and modeled exposure data, collection of real-time health data, and improved access to and integration of federal data sources. 2) Despite the focus on a WUI fire scenario as the basis for mapping the landscape of geospatial and health data systems, this approach provides a generalizable foundation for future applications to other natural and human-caused disasters, ranging from hurricanes to earthquakes to chemical releases. 3) Identifying the data needs and understanding the types, time frames, and scale of exposure and health data being collected, as well as improving access to these data resources, will strengthen opportunities for improving the timely use of available data for informed decision-making,

risk communication, and efforts to improve response, recovery, and future preparedness related to wildfires and other disasters.

Introduction

In August 2021, agency representatives within the Science for Disaster Reduction (SDR) Interagency Working Group formed a new sub-working group “Integrating Geoscience and Health Data in Disasters Working Group” (GHDWG). The goal of the GHDWG was to explore the integration of federal agency geoscience and health data systems to rapidly respond to the acute and longitudinal scientific data and informational needs associated with wildfires, and more specifically, wildland urban interface (WUI) fires (Glickman and Babbitt, 2001). This effort was undertaken in light of ongoing and overarching SDR goals to address existing gaps in science and technology related to disaster reduction and community resilience, including a specific Grand Challenge to “provide hazard and disaster information where and when it is needed” (Marburger, 2005).

In recent years, wildfires have increased across the Western United States, and in the coming decades, wildfires could become more frequent and severe (Dennison et al., 2014; Parks and Abatzoglou, 2020; Jain et al., 2022) with an estimated 82 million Americans experiencing a 57% increase in the frequency of wildfire-related smoke (J. C. Liu et al., 2016). Wildfires emit large amounts of smoke that contains fine particulate matter and other pollutants, volatile organic compounds, nitrogen dioxide and metals, that pose a risk to human health. Exposure to wildfire smoke has been shown to significantly increase the risk of asthma exacerbations (J. C. Liu et al., 2017; Reid and Maestas, 2019; Xu et al., 2020; Peterson et al., 2022) and other respiratory outcomes (Delfino et al., 2009; Reid et al., 2016; Black et al., 2017; Cascio, 2018; Reid and Maestas, 2019; Xu et al., 2020). Cardiovascular events, birth outcomes (Holstius et al., 2012), and mortality (Magzamen et al., 2021) have also been linked to wildfire smoke exposure, but findings from these studies have been less consistent (Black et al., 2017; Cascio, 2018; Xu et al., 2020).

WUI fires are of particular concern because they occur where homes and other structures meet vegetative fuels and have the potential to damage property and emit a broad range of chemicals and pollutants that may negatively impact health. For example, though most exposure assessments have used fine particulate matter ($PM_{2.5}$) – inhalable particulate matter with aerodynamic diameter less than or equal to 2.5 micrometers – the mixture of native and built environment fuels in WUI fires create a mixture of other toxic compounds that may pose additional risk to health. Therefore, there is a growing need to understand the complex exposures associated with wildland and WUI fires and associated physical and mental health impacts on our communities (National Academies of Sciences, Engineering, and Medicine, 2022; US Fire Administration, n.d., Wildland Fire Mitigation and Management Commission, 2023).

Recognizing the severity of these impacts, recent actions have been taken establishing multiple strategies to combat wildfires and protect communities, including actions to advance air quality coordination (USDA, 2023) and to improve the speed and accuracy of wildfire detection through the Bipartisan Infrastructure Law and the Inflation Reduction Law (USDA, 2024). Multiple reports, including the Congressionally-mandated Wildland Fire Mitigation and Management Commission report (Wildland Fire Mitigation and Management Commission, 2023), have also called out the need for additional research and data collection to better understand and mitigate the public health impacts of wildfires.

Integrating Geoscience and Health Data in Disasters Working Group (GHDWG)

The GHDWG was started in August 2021 to assess how agencies can more effectively combine earth and atmospheric observations, stationary monitoring, personal monitoring, and health data to improve response, recovery, and future preparedness for WUI fires. The GHDWG chose WUI fires as the focus for this effort given the growing number of federal resources, data, and agency attention to these situations and the direct human health implications at multiple levels.

The co-chairs invited interested members of the SDR to participate in monthly meetings to design the goals and objectives of the GHDWG, as well as to identify other experts from federal and state agencies and academia to participate in meetings and contribute to the workflows and products. Given the broad range of interests and expertise of the group, a sub-working group was formed focus on the more technical aspects of the identified deliverables, including a pilot effort to integrate different data sources using the 2020 Walbridge Fire as a model.

The GHDWG and sub-working group members worked through June 2022 and engaged 48 participants from 16 different organizations. A subset of participants developed this report to summarize completed GHDWG activities that explored the challenges and opportunities related to data collected by federal agencies used to inform and reduce the health impacts associated with disasters, specifically WUI fires. A collection of literature and data resources were identified over the course of the working group convenings, which are also included with this report.

GHDWG Workflow and Products

The GHDWG selected a specific WUI fire scenario to highlight important questions from different agency perspectives and improve data integration efforts. This exercise allowed for a more detailed evaluation of existing data sources and resources relevant to the scenario. Collaborators at the United States Geological Survey (USGS) identified the Walbridge Fire for a scenario based in Sonoma County, California, that focused on wildfire behavior as it spread to a WUI area and impacted the local population. The Walbridge Fire started on August 17, 2020, and quickly grew in size, joining other fires in the area to form the Lake Napa Unit Lightning Complex Fire. The Walbridge Fire was located solely in Sonoma County, CA, and was responsible for the destruction of 55,209 acres (CAL Fire, 2020). The Lake Napa Unit Lightning Complex Fire had a total burn area of 363,220 acres and spanned five counties (California Department of Forestry and Fire Protection, 2020; CAL Fire, 2020, 2022;). As the fire occurred in 2020, most methods currently used to obtain geospatial data were operational when the GHDWG convened, making this wildfire an appropriate test case.

Starting with discussions about the data needs and concerns about the Walbridge Fire, and other WUI fires in general, the group explored priority research questions of concern from multiple perspectives. A list of questions was developed and organized into categories for consideration. Subsequently, additional discussions followed from this list of research questions and included what data sources were available that could be useful to answer these questions; how the group could organize and map the questions and data sources to better understand data availability, gaps, and needs; and what data sources have historically been used in published research studies to explore the health effects associated with wildfires. Additionally, the group undertook a pilot effort to integrate some of the identified data sources using the Walbridge Fire as a model. This activity helped the group to better understand the issues and challenges associated with timely data integration to understand health effects and inform protective measures.

Ultimately, the discussions and activities resulted in five GHDWG products: 1) Questions List, 2) Data Streams, 3) Conceptual Model for Wildfire Data, 4) Review of Published Literature for Data Used in Wildfire Health Studies, and 5) Pilot Data Integration, as described in detail below.

1. Questions List

The GHDWG developed a list of questions to identify and address high-priority research areas. The purpose of this work product was to improve understanding of each agency's priority areas in order to optimize federal data sources and guide future data collection. During monthly meetings, GHDWG members proposed questions through a collaborative process. Then the group reviewed and discussed these questions to identify common priority areas. The final set of questions included a total of 60 questions that were organized by topic area, metric, and lifespan of the WUI fire event (see Appendix A).

The group identified a subset of agency-related questions that addressed common priorities. For example, *"How do we address cascading concerns as they relate to population disbursement, infrastructure, and water and food contamination?"* addressed multiple agency priorities. The remaining questions were grouped by topic areas. For example, health metric questions captured the impacts on people who are at higher risk of both short- and long-term health outcomes such as *"Are there groups at higher risk of experiencing adverse health outcomes (individuals/communities experiencing health disparities, pregnant people, infants/children, older adults, those with pre-existing conditions)?"*. Exposure metric questions addressed specific exposure sources such as *"What are the soil and surface contamination risks of exposure through ingestion, dermal, and airborne pathways?"*, as well as non-specific exposures and mitigation strategies. Priority questions associated with the WUI fire scenario were ordered by time periods spanning from pre- to post-event. For example, *"How can we assess damage to human life, structures, buildings etc.?"* addressed post-event priorities. These questions served as a guide for addressing priority areas and were used to inform subsequent work products produced by the GHDWG.

2. Data Streams

GHDWG members identified the data streams cataloged in Appendix B. Data sources include currently available state and federal data identified by the GHDWG subject matter experts (SMEs), as well as data sources identified through the scoping review of published literature (below). Additionally, the GHDWG explored comparisons of differing exposure, health, and post-event data streams, as follows.

Comparisons of Exposure Data Streams: Wildfire Smoke

Surface monitors: Surface monitors provide direct measurements of air pollutants in outdoor air and in smoke plumes. Smoke plumes often have tight spatial gradients, especially near burn areas where smokey and clean areas may just be kilometers apart and may vary over hours. Most studies of smoke exposure have focused on $PM_{2.5}$ mass concentration and have used regulatory monitors that provide accurate, reliable measurements. These monitors tend to be sparse in various parts of the US, particularly in many regions of the western and central US, where there may be just a single monitor per county. Air sensors, sometimes referred to as low-cost air pollution monitors, such as the PurpleAir network, now have many more locations and thus more spatial coverage than regulatory monitors and are starting to be employed for assessing wildfire smoke exposure. For example, the EPA incorporates data from air sensors that have undergone extensive testing and development of data correction and data quality check approaches in their AirNow Fire and Smoke Map. While these air sensors are not as accurate or reliable as regulatory monitors, the correlation of air sensors with more reference instruments can be more readily checked when they exist near regulatory monitors. A limitation of surface monitors for estimating smoke exposure is that most monitors do not collect data that allows for analysis of speciation and hence cannot separate smoke from non-smoke $PM_{2.5}$. However, under moderate-to-thick smoke concentrations, the majority of $PM_{2.5}$ mass concentration can be attributed to wildfire smoke, so there is less uncertainty about the smoke contribution.

Satellite-based observations: Satellite remote sensing data have been used for both quantitative and qualitative estimates of wildfire burn areas, emissions, and smoke exposure. Quantitative estimates have relied on aerosol optical depth (AOD) - the amount of scattering and absorption of sunlight by aerosol particles in the atmospheric column - measured by several satellites to approximate column concentrations of particulate matter. Active fire data products are available from the Visible Infrared Imaging Radiometer Suite (VIIRS) sensor aboard the NASA/NOAA Suomi NPP and NOAA-20 satellites (VIIRS, 2021). The VIIRS sensor detects thermal anomalies at high resolution and provides data on active fires (location, area) in high resolution and near real-time. Qualitative estimates have generally been used by the National Oceanic and Atmospheric Administration's (NOAA) Hazard Mapping System (HMS) smoke polygons. Trained analysts draw polygons around spatial regions with visibly "light", "medium", and "heavy" smoke density. Generally these analysts do not have clarity in terms of whether the observed smoke is at the ground level or lofted, and this uncertainty is important when considering exposure. Satellite data are advantageous because of the potential to "see" the entire US, although not always concurrently. However, satellite data have several limitations: (1) most satellite-based estimates of smoke occur only during the day and during cloud-free conditions, and dense wildfire smoke can sometimes be flagged as clouds or confused with clouds and thus removed from the calculations; (2) most satellite-based AOD observations are column integrated and thus cannot determine the altitude or vertical distribution of the smoke, including whether or not the smoke is at the surface or aloft in the atmosphere; (3) even when smoke is at the surface, translating AOD or HMS polygons to surface $PM_{2.5}$ concentrations attributed to wildfire smoke requires additional modeling to derive accurate, quantitative source contributions in space and time; (4) similar to surface monitors, it is challenging to separate the smoke and non-smoke contributions to PM from satellite data except when smoke concentrations are moderate to high; and (5) high AOD days when wildfires might be at play can also be flagged as outliers or excluded from subsequent modeling in many applications, thus missing the wildfire signal.

3D modeling and forecasts: Source dispersion and three-dimensional (3D) chemical transport models can be employed for both retrospective analysis and forecasts of smoke pollutant concentrations. Based on fundamental atmospheric chemistry and physics principles, these deterministic models incorporate emission rates, physical processes such as dispersion, and may include chemical reactions to predict concentrations of PM mass, several chemical species in $PM_{2.5}$ and other size fractions, and gases directly emitted from wildfires or formed through secondary reactions from wildfire emissions. Additionally, estimates can predict smoke concentrations for several days into the future and as a function of height, where the surface layer is usually selected to represent ground-level concentrations that are more closely representative of human population exposures. In particular, these chemical transport models, for example, the Community Multiscale Air Quality Modeling System, or "CMAQ", are commonly used for separating the smoke and non-smoke $PM_{2.5}$ contributions. This is sometimes done with a first order approach by calculating the difference in estimated pollutant concentrations, such as $PM_{2.5}$ mass, with and without the wildfire emissions terms; however, this approach oversimplifies the chemistry involved. Scientists can also directly model the emissions, transport, and dispersion patterns of wildfire-related $PM_{2.5}$ using frameworks like BlueSky. These models require each of the following factors to be known with high accuracy: (1) 3D meteorology that transports smoke, including mountain and valley flows that may be at finer spatial resolution than the model; (2) plume injection height, which is highly dependent on burn intensity, plume buoyancy, and the atmospheric thermodynamic vertical profile; and (3) smoke emission rates for multiple species depending on burn area land cover and material. Despite their advances, modeled estimates often benefit from post-calibration or adjustment to ground-based measurements to more accurately reflect surface concentrations of wildfire smoke related pollutants given uncertainties in each of these inputs.

There are complementary strengths and limitations of the above three data streams for assessing wildfire smoke exposures. The GHDWG members reviewed an analysis of the Walbridge fire using NOAA satellite products and discussed different strategies to integrate georeferenced information from multiple source types, including statistical or machine learning-based models for prediction of wildfire smoke impacted $PM_{2.5}$ or other pollutants. These methods are further described in the "Future Directions" section of this report.

Comparisons of Health Data Streams

For near real-time health data needs, syndromic surveillance provides an opportunity to identify wildfire-related health conditions of interest. Policies for syndromic surveillance data collection vary from jurisdiction to jurisdiction. The National Syndromic Surveillance Program (NSSP) is a network of public health partners that includes the Centers for Disease Control and Prevention (CDC), other federal agencies, state and local departments, academic institutions, and private sector organizations. Electronic health records (EHR) from emergency departments, urgent and ambulatory care centers, inpatient healthcare settings, and laboratories are integrated into the cloud-based BioSense Platform (Gould et al., 2017). The NSSP receives data from 73% of the nation's emergency departments, covering 50 states, the District of Columbia, and Guam (CDC, 2022). Health outcomes of interest can be captured from chief complaints and specific diagnosis codes.

For less time-sensitive health data needs, administrative data, including records from emergency department visits, inpatient hospitalizations, emergency medical services (EMS) dispatches, clinic visits, pharmaceutical databases, and insurance claims, are available. Medical diagnoses for morbidities are based on diagnosis codes from the International Classification of Diseases – Clinical Modification (ICD-CM). After October 1, 2015, all US health systems covered by the Health Insurance Portability and Accountability Act (HIPAA) transitioned from the 9th Revision (ICD-9-CM) to the 10th Revision (ICD-10-CM). Health outcomes are identified by specific codes. Diagnosis codes for asthma, for example, are defined as: 493.00 – 493.99 in ICD-9-CM and J45.0 – J45.998 in ICD-10-CM. For mortalities, causes of death are based on the ICD-10 coding system.

National, public data platforms exist that provide and display health information based on administrative data. These repositories typically present health data aggregated to a particular geographic area, such as a census tract or county. The CDC Environmental Public Health Tracking Network and CDC WONDER are two examples. A few federal agencies offer publicly available health datasets that can be directly downloaded for analysis: Agency for Healthcare Research and Quality (AHRQ) Healthcare Cost and Utilization Project (HCUP) and CDC National Center for Health Statistics National Vital Statistics System (NVSS).

Primary data collection from surveys and questionnaires are another potential source of health data. These forms of information gathering rely on respondent-reported symptoms or conditions. Surveys can be administered at a small scale for a particular community or cohort or at a larger population scale with appropriate informed consent and human subjects protections. A few population-based surveys with health data include the CDC National Health and Nutrition Examination Survey (NHANES) and Behavioral Risk Factor Surveillance System (BRFSS). Another resource for survey data is the CDC Community Assessment for Public Health Emergency Response (CASPER) toolkit, which is designed to quickly and inexpensively gather household-level information on health and community needs in both disaster and non-disaster settings.

Crowdsourced data may also be used to assess health outcomes. Both public and private entities offer platforms for citizens to submit health-related information. The U.S. Environmental Protection Agency (EPA) offers Smoke Sense, a mobile application that uses a questionnaire individuals can use to share symptoms and behavior changes on a daily basis and provides real-time smoke and air quality information based on location.

Comparisons of Post-Wildfire Data Streams

Wildfires have a significant impact on watershed hydrology that can lead to increased rates of surface erosion and flooding. For instance, suspended sediment yields in rivers draining burned areas can increase from one to three orders of magnitude (Smith et al., 2011a). During high-intensity rainfall, commonly occurring cascading hazards following wildfire include post-fire debris flows (PFDFs). Loose sediment and water from these fast-moving flows are capable of destroying infrastructure and taking human life (Meyer and Wells, 1997; Cannon, 2001; Cannon et al., 2008). Data related to burned area mapping may be especially helpful for identifying areas where water quality may be significantly affected, as the increased sedimentation and pollution of waterways after wildfire remains a continued area of study (Smith et al., 2011b; Bladon et al., 2014; Reale et al., 2015; Langhans et al., 2016).

Data related to post-fire processes include the short-term impacts of wildfire on watershed and landscape processes after the termination of burning as well as the longitudinal impacts related to burned areas. Short-term impacts on human health and safety include exposure to the heightened risk of PFDFs and the effect of increased sediment and pollutant mobilization in waterways. Typically, these impacts to watershed hydrology are temporary and vary based on local environmental factors. In their review, Pacheco and Sanches Fernandes (2021) report that watersheds can return to pre-fire conditions in four to six years, even as the full recovery of vegetation in an area may take longer (Storey et al., 2016; Bright et al., 2019). For specific events such as PFDFs, the risk of runoff-induced debris flows decreases significantly two years following the fire (Cannon et al., 2011; Santi and Morandi, 2013; DeGraff et al., 2015).

To understand the spatial extent and potential likelihood of exposure to these hazards, knowledge of burned areas and their severities is essential. Burn area and severity mapping products are primarily available by the United States Forest Service (USFS) Geospatial Technology and Applications Center (GTAC). A suite of products are available depending on their use case, including the rapid burn area assessments made available shortly after fire conclusion by the Burn Area Emergency Response program (BAER) and the extended assessments of burn severity by the Monitoring Trends in Burn Severity (MTBS) program (Eidenshink et al., 2007). Despite some overlap, these two data products have differing goals: BAER data are generated for the purposes of emergency disaster response and focus on the degree to which soil is affected by fire; MTBS data are generated to quantify the degree to which an area is disrupted by fire – usually highlighting the disturbance to vegetation – and provide long-term guidance for policy and land management decisions (Eidenshink et al., 2007). A third program, Rapid Assessment of Vegetation Condition After Wildfire (RAVG), provides data to quantify the impact of wildfire on National Forest System land. The program delivers data related to changes in basal area, canopy cover, and burn severity to assist with post-fire vegetation management within the National Forest System. RAVG products are typically made available within 45 days of fire containment.

USGS provides probabilistic estimates of PFDF hazards for recently burned watersheds via the PFDF Dashboard. These estimates are based on the statistical models detailed in Staley et al. (2016), which relate storm intensity and burned catchment properties to observed PFDF activity and include potential debris flow volume estimates based on work by Gartner et al. (2014). Available data are organized by fire name and include fires from 2013-present day at the time of publication.

In addition to the detailed burn severity mapping and subsequent hazard assessment products made available by USFS and USGS, several satellite-derived products exist for global-scale burned area mapping. These products do not document burn severity; rather, they provide a global-scale assessment of burn perimeters. One popular product is the 500m Moderate-resolution Imaging Spectroradiometer (MODIS) Monthly Burned Area Product, which is regularly released each month and provides an extensive record of historic burned perimeters at the global scale (Giglio, 2015). However, for the purposes of burn severity mapping and its related hazards, we refer to products provided by USFS and USGS, as global burned perimeter products are not generated for this explicit use case.

3. Conceptual Model for Wildfire Data

GHDWG created a conceptual model to visualize the life cycle of the WUI fire scenario and to serve as a tool for identifying relevant data sources and potential data gaps (see Figure 1). In this report we have referred to this model as a conceptual model because our approach was adapted from EPA Conceptual Site Models (CSM) such as the Project Life Cycle CSM (US EPA, 2011) and is a working model that can be expanded for other wildland or WUI fire events and downstream impacts and health consequences that are broader than one specific site. The GHDWG conceptual model includes over forty different exposure sources, modifiers, pathways, receptors, health outcomes, and mitigation strategies that could exist before, during, and after a wildfire such as the Walbridge Fire that occurred in 2020. The model was organized along a typical environmental health-based source-to-receptor model starting with the source of a WUI fire event and ending with health endpoints and mitigation strategies. Each of these inputs exists as separate boxes in the conceptual model, and they are organized by timescale (pre-event, event, post-event) so the reader can visualize the WUI fire scenario. Information is grouped into nine categories to capture specific aspects of the WUI event. Starting from left to right, the first six categories describe fire event forecasting and modeling (i.e., pre-event modifiers and event), fate and transport modeling of event-related contaminants/pollutants/stressors (i.e., source modifiers and exposure sources and pathways), exposure modeling (i.e., exposure media and exposure routes) and health modeling ((i.e., receptors, health outcomes, and mitigation strategies).

In Figure 2 below, we highlight an example pathway using the GHDWG conceptual model, focusing on a single pathway starting with the WUI fire event through smoke exposures and associated health outcomes.

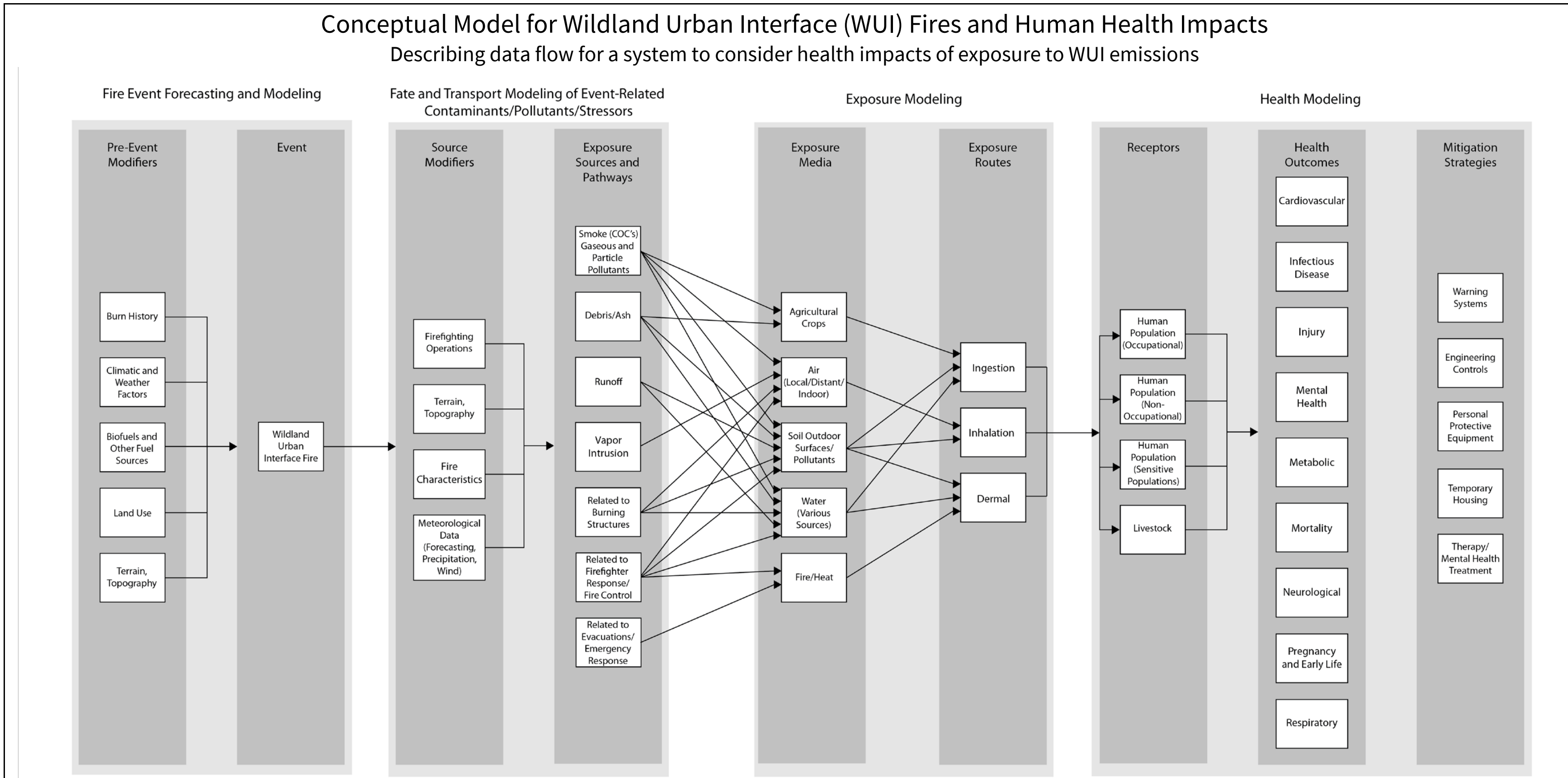

Figure 1. *This conceptual model describes a method to connect data for estimating exposure pathways to health outcomes for a WUI fire. The model is organized along a typical environmental health-based source to receptor model starting with the WUI fire and reaching health endpoints and mitigation strategies.*

Legend by Column Categories: *Fire Event Forecasting Modeling*: This grouping encompasses pre-event modifiers, possible ignition sources, and the WUI fire event. The GHDWG focused on WUI fires, but this model could be modified and applied to other wildfire events. *Fate and Transport Modeling of Event-Related Contaminants/Pollutants/Stressors*: This grouping captures exposure sources from the WUI fire event including physical, chemical, biological, and social agents. Then exposure pathways describe how a person may encounter these agents. *Exposure Modeling*: Exposure modeling encompasses the media in which individuals are exposed to hazardous substances (e.g., air, soil, water, etc.) as well as the routes by which they are exposed (e.g., ingestion, inhalation, dermal). *Health Modeling:* This grouping includes receptors, health outcomes and mitigation strategies. Receptors depicted in this model were informed by the data streams and literature review for this scenario and include human populations and non-human receptors such as livestock. Wildfire exposures have been studied in relation to various health outcomes (e.g., cardiovascular, injury, mental health, respiratory, etc.) described in the second to last column. Mitigation Strategies (e.g., warning systems, personal protective equipment, temporary housing, etc.) that could impact health outcomes of WUI fires are listed in the final column starting with the most immediate. COC's = chemicals of concern

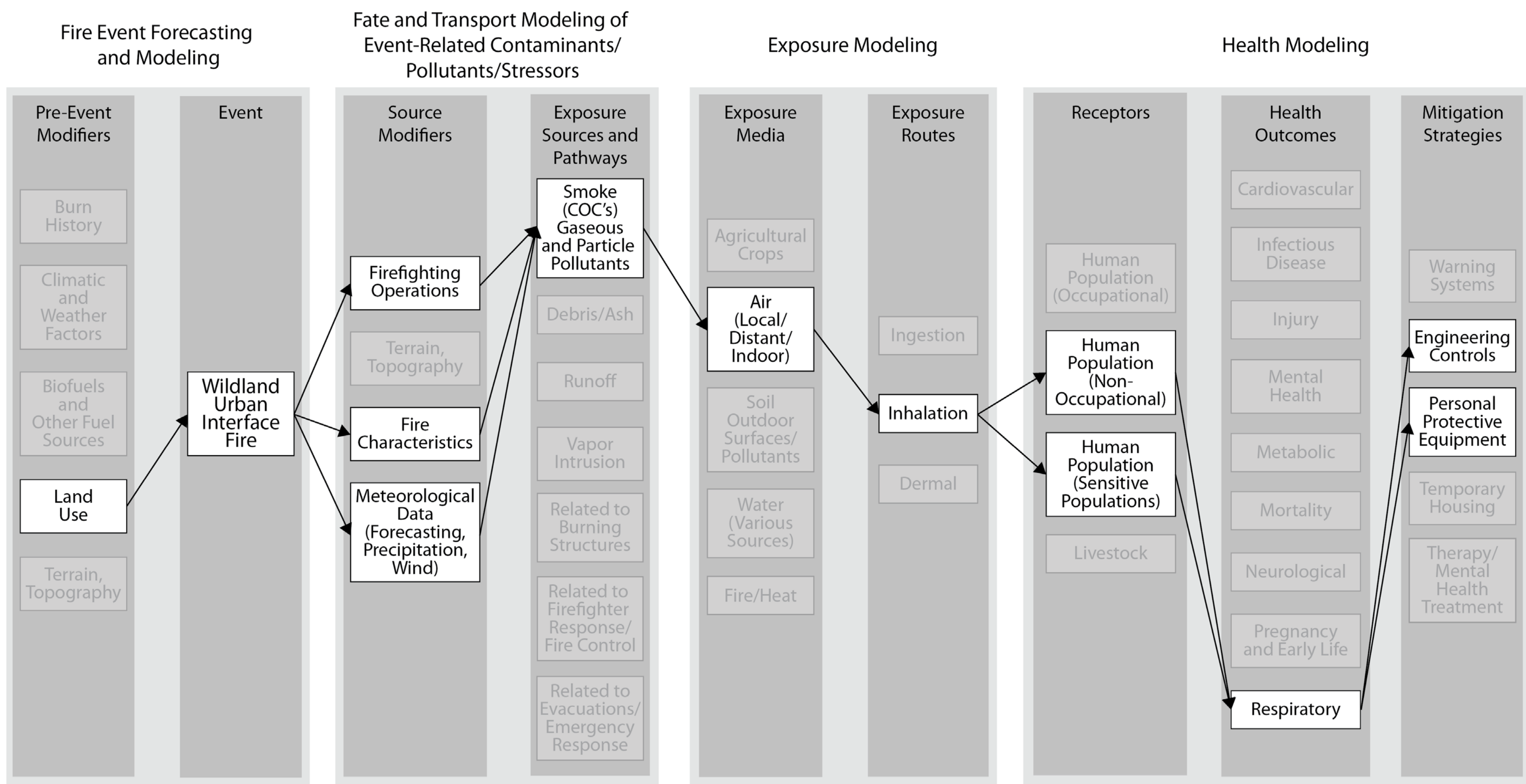

Figure 2. GHDWG conceptual model illustrating an example exposure pathway for respiratory health outcomes.

- **Pre-event** land use and land cover characteristics (e.g., industrial uses, residential density, and types of vegetation) can provide information on the type of material burned and are usually considered for estimating emission rates of potential airborne pollutants that may be released during a WUI fire event.
- With respect to the **event** itself, fire hazard reporting systems such as the California Department of Forestry and Fire Protection (CAL FIRE) can provide information on fire locations, burn dates, and perimeters. NOAA/NASA satellite-based observations of thermal anomalies from Visible Infrared Imaging Radiometer Suite (VIIRS) can be used to determine the size and areas affected by major, active fires near real-time or retrospectively.
- Once the WUI fire has started, there are several factors to consider as **source modifiers**, such as the intensity and duration of the fire, as well as certain meteorological factors that can impact the fire. Fire duration and intensity can be assessed by measures such as fire radiative power, venting index, and emissions estimates from satellite instruments, which rely on a variety of modeling assumptions. Researchers use meteorological forecasting data from sources, such as NOAA's National Climatic Data Center, to determine how meteorological factors, such as humidity, wind speed/direction, and precipitation, impact the event.
- Each of these elements can impact contaminants that are transported through different **exposure media**. The most commonly assessed **source of exposure** is smoke, specifically pollutants like $PM_{2.5}$. Data on $PM_{2.5}$ can be obtained from the US EPA's regulatory database, the Air Quality System (AQS) that contains ambient air pollution data from over thousands of monitors.
- **Exposure routes** vary. Here, the pollutants are inhaled by humans and can cause or exacerbate asthma-related symptoms and cardiovascular events.
- Asthma **outcomes** can be studied by analyzing emergency department visits and hospitalizations from local hospital data, medication dispensations from pharmaceutical databases, and self-reported symptoms from survey data.
- Strategies to **mitigate** inhalation impacts like asthma include use of an N95 respirator and indoor air filtration.

4. Review of Published Literature for Data Used in Wildfire Health Studies

The GHDWG recognized the need to better understand the types of adverse health effects associated with wildfires, and to identify environmental, exposure, and health data sources that have been used by the research community to study wildfire related health effects. In response, NIEHS performed a scoping review of the available literature published between January 1, 2016 – July 31, 2022 focused on identifying underlying data streams used in research studies. A literature search was conducted in PubMed using search terms related to wildfires, wildfire exposures, and human health outcomes, and broader search terms were used to capture additional exposure metrics (e.g., water, ash, and soil). Initially, three recent review articles on wildfire smoke exposure (Liu et al., 2015; Reid et al., 2016; Holm et al., 2021;) were identified and literature cited in these papers were included for review. Because the primary purpose of this scoping review was to identify data sources to address the objectives set forth by GHDWG, metrics from the US and North America were prioritized, and research conducted in other geographical regions was included when relevant to GHDWG objectives. A total of 77 papers were included in this review (see Appendix C).

Results of the scoping literature review showed that research has focused on respiratory and/or cardiovascular health outcomes with fewer studies investigating perinatal health outcomes, mental health outcomes, injuries, and cancer. Administrative data (e.g., emergency department visits, clinic visits, hospitalizations, EMS dispatches, and insurance claims) were the most common health data sources, followed by national data (e.g., CDC WONDER, AHRQ HCUP, EPA BenMap, and Medicare claims). For example, Aguilera et al. (2021) examined associations between wildfire smoke exposures and pediatric visits for respiratory outcomes from 2011 – 2017 in San Diego County, California. Pediatric emergency department and urgent care respiratory visit data were obtained from a hospital network which provided medical care for 91% of the County's hospitalized children. Primary health outcomes were assessed using chief complaints (difficulty breathing, respiratory distress, wheezing, asthma, or cough). These health data were linked with wildfire-specific fine $PM_{2.5}$ and studied using modeled daily concentrations at the zip code level over a longer study period (7 years) and larger area compared to previous studies (Aguilera et al., 2021). Lastly, research articles using primary data collection were sparse; however, a few studies administered surveys during evacuations or soon after a wildfire event. See Appendix C for the list of specific health metrics examined in these studies.

Health outcome data were commonly linked with exposure estimates obtained from surface monitors, modeling approaches, and wildfire event data. Researchers largely focused on wildfire smoke pollutants (e.g., $PM_{2.5}$, PM_{10}, NO_2) and of these pollutants, $PM_{2.5}$ was the most studied. Metrics were obtained from a variety of air quality monitoring data sources such as the EPA's AQS and AirNow databases, state-, local- and Tribal-managed ground monitors, and air sensors (e.g., PurpleAir). Other exposure data sources included satellite remote sensing data (e.g., AOD obtained from MODIS satellite instruments) models and forecasting systems (e.g., CMAQ, BlueSky Framework, and the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model), and wildfire event data (e.g., California Fire Resource Assessment Program (FRAP), NOAA Hazard Mapping System (HMS), USGS Geospatial Multi-Agency Coordination (GeoMAC), Global Fire Emissions Database, and National Center for Atmospheric Research (NCAR) Fire Inventory (FINN)). For example, O'Neill et al. conducted a simulation of air quality conditions using a suite of remotely-sensed data, surface observational data, chemical transport modeling, data fusion and machine learning methods to estimate $PM_{2.5}$ concentrations from five major Northern California wildfires that occurred in October 2017. Resulting $PM_{2.5}$ exposure estimates were then linked with the CDC WONDER database to conduct a health impact analysis (O'Neill et al., 2021). Appendix C contains the list of specific exposure metrics assessed in these studies.

Examining the specific data resources used in these research studies provided valuable information concerning what our current understanding of health concerns related to wildfires is based upon. Notably, this scoping review indicated numerous gaps with respect to the data sources used to understand health effects. Health data were not available in real-time or near real-time, and these data sources lacked geospatial and temporal coverage to study the effects of repeated exposures or health outcomes with longer latency periods. Exposure data did not capture the complex mixture of hazardous wildfire smoke pollutants, nor exposures from other sources such as soil and water. Additionally, the lack of harmonization of different data streams and collection of exposure and health data that are spatially and temporally aligned are barriers to the use of currently available data streams, which impedes timely and robust research. Results from this scoping review were used to inform subsequent work products developed by the GHDWG.

5. Pilot Data Integration

As a proof of concept, the GHDWG conducted a pilot exercise to help agencies learn how they could effectively identify and integrate data. With this exploratory proof of concept, the GHWG created a Geographic Information Systems (GIS) web map hosted on the NASA Disasters Mapping Portal that allowed for integration of high0priority data streams. The NASA Disasters Mapping Portal is an ArcGIS Enterprise Portal used by the NASA Earth Science Applied Sciences Disasters Program to disseminate NASA Earth Science data, maps, and applications to partners.

The GHDWG identified several high-priority data streams: air quality measurements from the US EPA's AQS, historical and scenario-specific optical imagery and wildfire data products from multiple NOAA and NASA satellites, de-identified human health data from the California Department of Health Care Access and Information, and Social Vulnerability Index (SVI) data from the CDC. All of these data were available for Sonoma County, California, where the Walbridge Fire occurred in 2020.

Health data included ICD-CM codes for emergency department visits related to respiratory outcomes aggregated by health facility. EPA AQS data provided information on current and historical monitoring of air quality at each surface-based air quality station in the US. The satellite imagery included True Color and Burn Scar Corrected Reflectance band combinations to provide different views of the movement of the fire and smoke during the Walbridge Fire. This imagery was collected by the MODIS sensor aboard NASA Terra and Aqua satellites and the VIIRS sensor aboard NOAA-20 and NASA Suomi National Polar-orbiting Partnership (Suomi-NPP) satellites. By using these two satellite-based sensors together, the area of interest is captured eight times daily with four overpasses during the day and four during the night. To detect and monitor the active fire perimeter, Fire Information for Resource Management System (FIRMS) Active Fire Points were used. FIRMS distributes near real-time active fire data within three hours of satellite overpass from both the MODIS and VIIRS sensors through NASA's Land, Atmosphere Near Real-time Capability for EOS (LANCE). These publicly available data can provide information about where new fires may have formed and how they evolve during their life cycle. The SVI data from the CDC provided information about how vulnerable an area's population is aggregated by census tract or county.

Using the NASA Disasters Mapping Portal, the group successfully integrated these existing human health data, satellite imagery, geospatial data products, and demographic vulnerability data into a singular web map that can be used for data visualization and analysis. This product serves as the foundation for future data integration efforts from the GHDWG.

Lessons Learned

1. Data Limitations and Needs: Exposure

There are still important data gaps and needs to be able to accurately measure or model wildfire-related physical and chemical exposures, assess their impacts on clinical and population health, and develop interventions to improve public health for individuals and communities. Reliable and accurate data are needed to guide acute care and population health protective measures, to inform prospective risk assessment exercises, such as scenario simulation, and to support retrospective health impact assessments and epidemiological studies that examine exposure-response relationships. Taken together, these data gaps pose significant challenges for researchers and policymakers to fully characterize and understand the health impacts of wildfires.

Wildfire smoke itself is a mixture composed of thousands of chemical species not limited to the $PM_{2.5}$ size fraction or to the aerosol phase but can include gases, volatiles, semi-volatiles. Some components of the wildfire smoke mixture include ultrafine particles (UFP), PM_{10}, black and brown carbon, polycyclic aromatic hydrocarbons (PAH), other organics like formaldehyde, benzene, benzo-a-pyrene, and other acids, alcohols, terpenoids, phenols, sugars, etc., ions, metals (Andreae, 2019; O'Dell et al., 2020;

National Academies of Sciences, Engineering, and Medicine, 2022). Many of these components are considered hazardous air pollutants (HAPs), toxic air pollutants known to or suspected to cause cancer or other serious adverse health effects. This mixture is strongly dependent on the nature of the material being burned, whether natural or manmade, especially at the WUI. Changes in humidity and temperature that occur downwind of fires may lead to some semi-volatile chemicals in this mixture shifting equilibrium and partitioning into the aerosol phase or volatilizing into the gas phase, and vice versa, which could also influence deposition potential out of the air onto surfaces and into water bodies and systems. The mixture also changes drastically as the plume ages and gets transported downwind, with many of these components oxidizing, leading to secondary aerosol formation and secondary ozone through photochemistry (Diapouli et al., 2014; Wu et al., 2018; Hodshire et al., 2019). As such, size distribution of aerosols, chemical composition of the plume, and spatial gradients in 3D can vary substantially as the plume evolves and gets transported. Vertical profile is especially important and challenging to accurately assess, where plumes can be very elevated aloft in the atmosphere and can take some time, over hours to days, to mix downwards and enter the mixing height, eventually reaching ground level where human population exposures occur (Val Martin et al., 2018; US EPA, 2021; Wu et al., 2021; National Academies of Sciences, Engineering, and Medicine, 2022). Very few readily available and current data exist on these types of fire and smoke-related exposure metrics.

Other exposure data needs include detailed, high resolution and ideally real-time human data related to residential mobility, time-activity patterns, household characteristics, and personal behaviors that affect personal exposures to wildfire-related smoke and other air pollutants. During wildfire events, and especially in areas close to significant wildfire damage or disruption, communities and individuals are very likely to relocate temporarily or permanently, depending on the scale of the fire. This means that residential address location on its own may not be sufficiently resolved to assess exposure if it does not reflect actual location during or soon after a wildfire. However, even if residential location did not change, time-activity and mobility patterns may change drastically during wildfires compared to non-wildfire days as part of or in addition to exposure-averting behaviors. For example, individuals might spend increased amounts of time indoors and may limit their time outdoors; however, they might also be more likely to close windows and doors, seal homes, minimize ventilation of air from outside and increase indoor filtration and cooling. These changes in behaviors and activities together, potentially captured through surveys, can lead to outdoor measures of wildfire smoke and related air pollutants becoming more erroneous or less representative of true personal exposures during wildfires and may introduce important sources of exposure measurement error and bias in the health analysis (Liang et al., 2021).

Additionally, data involving other relevant exposure pathways such as ingestion and dermal exposures are also important for understanding various health outcomes. Understanding wildfire impacts on water (e.g., water contamination of wells, drinking water systems, recreational waters), food sources (e.g., home gardens, area crops), and soils and dusts such as contamination of children's playgrounds and yards, which may be carried back into home and school environments, are vital to understanding the full dimensions of wildfire exposures and resultant health impacts on at-risk populations. The Conceptual Model (Figure 1) developed as part of this activity demonstrates the various exposure pathways and the need for additional areas of data to inform our understanding of exposures and health impacts. Recent advances in personal monitoring and geolocation technologies (e.g., wearables, GPS), mobile health and smartphone applications (e.g., EPA's Smoke Sense), crowdsourced and network data collection (e.g., apps, air sensor networks) are all advancing researchers' ability to fill in some of these exposure data gaps at high resolution. However, important data privacy and ethical considerations, as well as issues related to data ownership, quality, latency, and generalizability remain.

Other less-developed data topics include naturally occurring hazardous materials (NOHMs), which include asbestos, erionite, heavy metals (Niewendorp, 2011). Ground disturbance activities in geologic areas that contain NOHMs may release them into airborne and waterborne pathways and result in potential risks to public health and safety (Van Gosen, 2007; Niewendorp, 2011). In particular, naturally occurring asbestos (NOA) occurs in ultramafic geologic areas (Van Gosen, 2007). NOAs occur across areas such as California and in the Appalachian Mountains (ATSDR, 2007). Erionite, a similar health threat to asbestos, occurs in altered volcanic ash in southwestern Montana, the western Dakotas, and other parts of the country (Meeker et al., 2012; North Dakota Department of Environmental Quality, n.d.). Areas that may be disturbed need a geological evaluation prepared by a qualified geologist to describe the geographic distribution of potential NOHM-bearing areas, the site geology where proposed actions overlap potential NOHM-bearing terrain, and the NOHM hazards and risks (Clinkenbeard et al., 2002).

2. Data Limitations and Needs: Health

The available sources of health data compared to exposure data are relatively limited and more difficult to access. Privacy and confidentiality concerns related to protecting individual-level data are the main obstacles. A considerable challenge to using administrative data is that the process to obtain data directly from the data stewards depends on establishing data use agreements that typically require annual renewal. Moreover, each data steward may place restrictions on the use, sharing, and display of the data depending on the organization's specific policies and regulatory obligations. For example, there may be a requirement for aggregation of data in calculating rates or presenting counts of a particular health outcome.

Administrative data are collected for purposes other than public health surveillance, generally for billing purposes. Therefore, health outcomes are based on diagnosis codes as proxies for clinical diagnoses. Administrative data also have spatial and temporal limitations. The location of a "case" of a health outcome of interest is the patient's residential or billing address, not necessarily the place of exposure. Records are generally provided on a yearly basis due to the nature of data collection, management, and quality evaluation, so timeliness is a factor.

For near real-time health data needs, syndromic surveillance provides an opportunity to study wildfire-related health conditions of interest, but there are limitations in terms of coverage, and policies for syndromic surveillance data collection vary from jurisdiction to jurisdiction. Currently, there is patchwork reporting of syndromic surveillance across the country. Expanding the jurisdictions that share near real-time health data to the CDC would greatly increase the ability for public health officials and emergency planners and responders to more quickly identify and protect populations at risk of health impacts from wildfires. It would also provide a more complete population upon which to conduct epidemiological studies of wildfires and health. In addition to expanding the geography of the current syndromic surveillance database system, increasing the types of data elements collected would bridge information gaps in prescription drugs, school absenteeism, and transit, for example. Moreover, though syndromic surveillance can provide near real-time information, there are still important lag times depending on the data provider and the need for data processing to prepare, clean, and publish data for end-users.

Crowdsourcing data may be a useful way to supplement traditional health data sources by capturing health data directly from individuals. For example, the EPA Smoke Sense tool, a mobile phone application, allows citizen scientists to record their health symptoms and behaviors in addition to exploring current and forecast maps of air quality. Though crowdsourcing offers an additional source of health data that may capture cases outside official clinical settings, the quality of information may be more questionable. Data contributions are also limited and self-selected and may not be representative of all affected populations. Another way to acquire health data can be through partnerships with private vendors that curate health insurance claims and EHR in a standardized format. However, data access is not free and can require a contractual agreement where the agency purchases “seats,” or role-based access, for users to mine private vendor data.

3. Challenges of Data Integration

Numerous data sources are available on air, water, soil, and built environment exposures as well as health impacts and population vulnerabilities in the context of wildfires. Different agencies have different goals driving the data collection, however, resulting in data that tend to vary considerably and are often difficult to integrate for analysis.

There are important issues with data accessibility, particularly in relation to health data, that impede large-scale and timely research of wildfire events. A major hurdle to accessing health data lies in the need to establish separate data use and data sharing agreements with each data steward, such as individual hospitals, public health agencies, or private data vendors. These agreements vary in specificity depending on the requirements of the data steward and outline the instructions users must agree to adhere to in order to access, analyze, and display patient-level data. Getting each data use and data sharing agreement in place, however, can be a lengthy, time-consuming process. Therefore, having standardized, long-term agreements would greatly simplify and expedite the process and help reduce a substantial burden for researchers.

Similarly, another impediment to data access and timely studies of the health impacts of wildfires is the amount of time and effort required to obtain approval for human subjects research. In a disaster scenario, research activities must minimize participant and community trauma but must not interfere with any public health and environmental response efforts. Having validated study protocols specific to catastrophic wildfire events and pre-approved Institutional Review Board (IRB) templates would help facilitate the process. For example, the NIH Disaster Research Response program offers Rapid Acquisition of Pre- and Post-Incident Disaster Data (RAPIDD), a protocol containing surveys, checklists, and other documents to help expedite IRB approval to study disaster response workers. Adapting this set of standardized methodology and instruments for use in wildfire scenarios would reduce the burden on researchers by providing them with established templates and step-by-step guidelines for conducting research on the health implications of wildfires.

There are further challenges once data are obtained. Data vary widely across different sources. Simple discrepancies such as different variable names, formats, or categorizations necessitate significant data management and harmonization prior to any linkage or analysis. For example, one data set may use the label “wildfire smoke” but another names the variable “smoke”; one data set may treat wildfire smoke as a categorical variable with low, medium, and high levels, while another data set may include exact numerical measures.

Data are collected across a spectrum of spatial and temporal scales, ranging from census block groups to states, and hourly to annual measurements, respectively. Selection of the appropriate scale of data relies on the specific research question, yet the data may not be collected at the desired scale or time period to allow the data sets to be linked.

From an analytic standpoint, the ability to link exposure data with relevant health outcomes data has been one of the most substantive challenges of disaster response research. Specifically, the spatial and temporal dynamics of data collection and availability result in lagged responses, often with limited understanding of impact. A complication inherent to spatial data analysis is the modifiable area unit problem, a statistical bias that can arise when aggregation of data into different geographic areas may influence the association being investigated. Because analysis of the same data using different spatial scales may not yield consistent results, having exposure data that exists at only certain geographic levels or needing to aggregate health data to a larger spatial unit to protect confidentiality may introduce bias into studies.

Future Directions for Understanding Exposure and Health Effects of WUI Fires

Groundwork for future applications

Although the GHDWG focused on a WUI fire scenario as the basis for mapping the landscape of geospatial and health data systems, the approaches used in this effort lay the groundwork to be applied widely to other natural as well as human-caused disasters, ranging from hurricanes to earthquakes to chemical releases. The process of 1) identifying and defining a specific disaster scenario, 2) performing a literature review to understand the data available and how they are used to assess exposures and health impacts associated with the disaster in question, 3) developing a conceptual site model of the multiple exposure pathways that may affect human health outcomes, and 4) conducting a landscape analysis of existing data provides a useful approach to help researchers and stakeholders understand the scope of the problem, identify data opportunities and needs, and inform next-steps for enhancing scientific, public health, and emergency response activities.

Refining the conceptual model

A next step following this effort is to continue to expand and refine the conceptual model to account for new data sources and our evolving understanding of relevant exposures and their relationship to both acute (e.g., asthma, hypertension, trauma, pregnancy, anxiety, depression) and longer-term health outcomes (e.g., autoimmune effects, chronic airway disorders, post-traumatic stress disorder, cancer).

Expand public data platforms

An opportunity to facilitate data access and analysis for researchers is to develop disaster-specific dashboards and data integration platforms that house relevant, publicly available data sets to conduct studies on one site. For example, the CDC National Environmental Public Health Tracking platform has a broad range of meteorological, environmental, health, and sociodemographic data at varying geographic and temporal scale for over half of the states in the country. Additionally, the HHS emPOWER Map provides data on Medicare beneficiaries relying on electricity-dependent durable medical equipment and near real-time natural hazard data layers to inform public health emergency activities.

An example specific to extreme heat is the National Integrated Heat Health Information System Extreme Heat Vulnerability Mapping Tool hosted on Heat.gov, a web portal and central repository for heat-related data and tools where users can view and download data on extreme heat. The heat vulnerability mapping tool provides heat event and sociodemographic information and can serve as a model for a data resource that offers multiple data streams.

NASA has an Earth Information System platform focused on fire that offers an open-source, notebook-based dashboard of fire-related satellite data products, including measurements of atmospheric chemistry, ground-based measurements of aerosols, model estimates of near-surface $PM_{2.5}$, and composite indices of meteorological fire risk. Integrating these environmental data with other data such as health and socioeconomic factors would enhance the ability of a platform to meet the needs of researchers investigating the health implications of wildfires.

Using statistical and machine learning approaches to improve exposure estimates

Due to the complementary strengths and limitations of surface monitors including air sensor networks (Wallace et al., 2021; Barkjohn et al., 2022), satellite-based observations, and 3D modeling and forecasts, a growing strategy is to combine or blend georeferenced information from multiple source types using statistical or machine learning based analytical frameworks (Lassman et al., 2017; Y. Li et al., 2021; Childs et al., 2022). Though a concerted effort is needed to validate machine learning models for smoke concentrations, which tend to underpredict measures, the advantages of these approaches include the ability to calibrate remote-sensed observations and deterministic model outputs to ground measurements. These blended estimates also typically have performance that exceeds the individual data sources and allows researchers to generate or estimate exposures in locations that have no in situ surface measurement data. For example, surface monitors and HMS smoke polygons have been combined to separate daily smoke and non-smoke $PM_{2.5}$, and monitors and models have been combined for the same purpose (O'Dell et al., 2019). Geo-weighted regressions and machine learning algorithms have been used to combine information from surface monitors, satellites, and models to estimate spatially continuous, but monitor-constrained estimates of smoke and non-smoke $PM_{2.5}$ (Lassman et al., 2017; Childs et al., 2022). HYSPLIT-modeled wildfire-$PM_{2.5}$ estimates have also been incorporated into California-wide $PM_{2.5}$ machine learning models that incorporate remote sensing, chemical transport model outputs, and geospatial data to predict concentrations (L. Li et al., 2020).

Linking cumulative exposure sources to health outcomes

Wildfire events can lead to chemical, physical, biological, and social exposures directly or through their impacts on the built environment. These exposures can occur over varying timescales such as immediate exposures from wildfire smoke, repeated exposures from multiple wildfire smoke events, or longer-term exposures related to trauma. Chemical exposure routes of concern include inhalation, ingestion, and dermal uptake, where wildfire-related chemicals can be airborne, enter drinking water and food systems, and/or get in direct contact with skin via air and water contamination. The mental health and social impacts of wildfire events are also vitally important and can lead to significant acute and chronic health outcomes, displacement, and loss of social networks. Understanding the true cumulative (i.e., multiple chemicals or agents across multiple routes) or aggregate (i.e., one chemical or agent across multiple exposure routes) health impacts of wildfire-related environmental contaminants and stressors at the population level requires detailed, high resolution data resources on environmental, human behavioral, susceptibility, and toxicological parameters. Some of the key desired features of geospatial and health data sets include timeliness, accuracy, high spatial and temporal resolution, and geographic variety so data are generalizable enough to cover large segments of the population but specific enough to capture important exposure or susceptibility gradients in underrepresented or more vulnerable subgroups of the population.

Health impact assessments

In cases where smoke $PM_{2.5}$ or other smoke-associated pollutants are known or estimated but direct health data are unavailable, health impact assessment (HIA), a commonly used risk assessment approach, can be used to estimate changes to the rates of various health outcomes across large populations. Such HIAs use (1) estimated smoke concentrations, (2) concentration-response functions from existing epidemiological studies, and (3) baseline rates of health outcomes (e.g., daily asthma hospitalization rates) in a given region to estimate the increase in the rate of this health outcome in the region. These HIAs have been used extensively on historical smoke exposure data to estimate the burden of disease associated with smoke (Fann et al., 2018; O'Dell et al., 2021) but may be done using near-real-time smoke exposure data as well. This approach may be particularly useful when applied to forecasted smoke $PM_{2.5}$ concentrations to give health centers guidance on how and when to be prepared.

Concluding remark

As evidenced by the proceedings of the Integrating Geoscience and Health Data in Disasters Working Group (GHDWG), partnerships across the federal agencies are key to addressing identified gaps in data collection, sharing, and integration. Understanding the types and scale of data being collected about air, water, soil, and built environment exposures in combination with population vulnerabilities and health impacts is critical for informed decision-making, risk communication, and related efforts to improve response, recovery, and future preparedness.

There are useful implications for the work conducted by the GHDWG. GHDWG activities directly inspired a new project at NIH funded by the Office of the Secretary Patient-Centered Outcomes Trust Fund in March 2023. With NASA and AHRQ as partners, the NIH initiated the Climate and Health Outcomes Research Data Systems (CHORDS) project based on the information assembled by the GHDWG. CHORDS is building a data ecosystem of meteorological, environment, sociodemographic, and health data – initially focusing on wildfires – to facilitate the linking of these various types of data to advance patient-centered outcomes research. Data streams identified during GHDWG activities are incorporated into the publicly accessible data catalog, and wildfire and health research studies from the literature scan are informing the development of use cases to demonstrate the practical application of CHORDS data resources and tools.

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Appendix A: Questions List

Questions posed by the Integrating Geoscience and Health Data in Disasters Working Group (GHDWG) at the start of working group discussions to identify and address high-priority research areas and improve understanding of each agency's priority areas in order to optimize federal data sources and guide future data collection.

Category	Questions/Issues of Concern
Questions by Receptor and Exposure Metric	
Non-specific: Health (individual)	• What are the short and long-term physical health impacts (lung function, neurologic, cancer, other) that arise from wildfire exposure? • What are the short and long-term mental health impacts (anxiety, PTSD, depression, substance abuse, etc.) that arise from wildfire exposure? • Repeated traumas and health/mental health outcomes • Are there groups at higher risk of experiencing adverse health outcomes (individuals/communities experiencing health disparities, pregnant people, infants/children, older adults, those with pre-existing conditions)? • What are the risks associated with exposures and stress? How do these risk factors compound with things like job loss or repeated traumas? • How is underlying health status impacting outcomes, individual variability? • What are the protective factors for health and resiliency? • What are the differences in health effects between prescribed burns vs active wildfires?
Non-specific: Families	• What is the impact of stress on family health and well-being?
Non-specific: Health (Community)	• What are the impacts on community/social/economic well-being over the short and longer-term? • What are the risk factors that lead to poor outcomes? • What are the protective factors for resilience and recovery? • What are the community level health risks specific to populations of focus?
Non-specific: Exposure	• What are the impacts of air exposures, both local and distant, over time (ozone, $PM_{2.5}$, other)? • What are the soil and surface contamination risks of exposure through ingestion, dermal, airborne pathways? • What are the risks associated with persistent localized airborne exposures due to local activities? • What are the cumulative exposures and health outcomes over the lifespan? • What are the risks associated with the ingestion of locally grown food products? • What are the water exposures to drinking water systems, wells, and surface waters used for recreation or fishing? • What are the differences in exposures in-schools compared to outdoors? • What are the differences in exposures in homes compared to outdoors? • What is the difference between peak vs average exposures on health outcomes (e.g., asthma, infections, etc.)? • Understanding of chronic vs longer-term exposures on health outcomes especially among pregnant persons and kids
Impacts on Domestic Animals/Pets	• What are the exposure-related health impacts on pets? • What are the stress-related health impacts on pets?

Impacts on livestock	● What are the exposure-related health impacts on livestock? ● What are the stress-related health impacts on livestock?
Built Infrastructure	● How do we address cascading concerns as they relate to population disbursement, infrastructure, and water and food contamination? ● What are the risk factors for built infrastructure destruction and occupant injury? ● What are the protective factors for structure survival? ● What are the protective factors for occupant survival?
Mitigation Strategies/ Behavioral Strategies	● What is the value of shelter-in-place? Is there any? ● What is the value of air conditioners/filters? ● What is the value of the use of respirators for children and adults? ● How do we mitigate consequences of wildfire exposures during pregnancy? ● What are the best approaches for treating/mitigating stress, anxiety, and WF related mental health impacts across the lifespan? ● How do we contextualize research and communicate risks that pertain to human health? ● What important aspects of evacuation, emergency notification and fire suppression/structure protection should we look at and how are they currently being addressed? ○ Look at the Campfire Investigation for some details on the above items
Questions by Lifespan of a Wildland Urban Interface Fire	
Pre-event	● How do we forecast fire related items? ● How do we forecast or predict areas of post-fire concern in areas of high fire probability which would impact health status (e.g., map debris flows with high consequence overlaid with high wildfire probability)? ● How do we forecast or predict where most sensitive land uses and populations are located to help plan evacuation routes and immediate emergency response when a wildfire starts? (e.g., daycares, nursing care facilities, urban heat islands, high deprivation neighborhoods, etc.) ● How do we forecast where and when a wildfire might occur, perhaps with confidence limits or probabilities to prioritize resources or plan response needs ahead of time, based on conditions or drivers that increase risk (e.g., local precipitation, drought conditions, available biomass, seasons, weather, thunderstorms, or human activities, etc.)?
Event	● How can technology be applied to smoke and ash particulate-loaded air resulting from wildfires? ● What is the vertical distribution of smoke injected into the atmosphere? ● What are the microphysical properties of smoke particles, and how do they influence smoke lifetime in the atmosphere? ● How do we model actual dispersion or spread of these potential exposures in real time so that we can issue health advisories, and evacuation notices? ● How can we model the chemistry and size distribution of the plume and emissions while looking at the potential toxicity of the mixture? What impacts these measurements, do they lead to more evacuations, and when is the best time to look at these measurements. ● How can limited smoke-plume-height observations from satellites be incorporated into model simulations? ● How can satellite data be used to improve the representation of plume rise and smoke dispersion model simulations? ● How well is the diurnal cycle of air quality/smoke represented in the model?

	• What is the impact of massive wildfires on local weather, fire progression and smoke dispersion? What are the roles played by heat flux, embers and direct flame impingement on WUI fires?
	  ○ More information at WUI Fire Data Collection on Parcel Vulnerabilities Project
	• How is WUI fire behavior driven by the interactions among fuel, weather, and terrain?
	• Below are more specific questions for firefighter response and resources need to respond:
	  ○ City evacuation planning? Issuing health advisories and physical activity guidelines? Risk communication? Anything else that might need quick and urgent information from different agencies' perspectives?

Post-event	• How can we assess damage to human life, structures, buildings etc. (insurance claims, FEMA assistance, etc.)? • How can we assess mental health impacts on first responders or relief needs? • How do we relocate or support impacted populations in the short term if the individuals cannot go back to residential communities? • Can we conduct an environmental impact assessment of wildfire? Water quality, air quality, high ash zones, other concerns that need to be highlighted and mitigated? • What are the acute health effects arising from wildfire exposure? (can also be assessed retrospectively in later phase) • What are the long-term exposure and health effects that can be monitored over longer periods of time (e.g., risk of adverse birth outcomes following exposure to wildfire etc.)? Retrospective analysis would also be acceptable. • As geospatial, mobile health, and sensor technologies advance, along with informatics systems to support them, it's possible we'll be able to answer exposure-health questions in more real time (with little lag time between wildfire occurring and acute effects occurring) - using prescription data, ER data, examples similar to Google flu trends data or COVID19 exposure alerts? • What post-event activities are there and how do we address them? ○ This includes investigating structural failures from hazards. Their portfolio also includes the role to lead post-wind event investigations across NSF, NOAA, FEMA, and NIST. NIST's role post-disaster necessitates shared data sources and would benefit from the working group's products.

Appendix B: Data Streams Tables

Table B1. Environmental/Exposure Data – National Level

Agency/Organization	Resource Name	Scale Level	Data Description	Variable Indicator Examples (But not limited to)	Timeframe	Frequency of Updates	Data Access
CDC	National Environmental Public Health Tracking Network	Census Tracts	Uses a network of people and information systems to deliver a core set of health, exposure, and hazards data, information summaries, and tools to enable analysis, visualization and reporting of insights drawn from data.	Asthma/COPD, Cancer, Developmental Disabilities, Lifestyle factors, Socioeconomic Factors, Environmental Hazards, and Reproductive/Birth Outcomes	Varies	Varies; Dependent on State Reports	Public
EPA	Smoke Sense	ZCTA	Smoke Sense is a crowdsourcing, citizen science research project developed by EPA researchers focused on increasing public awareness and engagement related to wildfire smoke health risks (effect on health and productivity, limit exposure, and develop health risk communication strategies)	N/A	2017-Present	N/A	Public
EPA	Consumer Confidence Reports (Office of Ground Water and Drinking Water)	Census Blocks	Annual water quality reports are a critical piece of the right-to-know rules. The purpose is to provide customers with information on drinking water quality and allow them to make health-based decisions on drinking water consumption.	Water system websites & contact info, Client/population served, drinking water sources, regulated contaminants, potential health effects of contaminants detected	Current	CCR Reports sent annually by July 1st	Public
EPA	BenMAP-Community Edition	County	Open-source computer program that calculates the number and economic value of air pollution-related ($PM_{2.5}$ and O_3) deaths and illnesses. Incorporates a database that includes many concentration-response relationships, population files, and health and economic data to quality impacts. Can also add in EPA Air Quality System data to be used along with BenMAP application.	Baseline death rates (y. 2013) for 4 mortality endpoints (COPD, cerebrovascular disease, ischemic heart disease, lung cancer) stratified by age and sex	Current	N/A	Public
EPA	EJSCREEN	Census Blocks	Environmental justice mapping and screening tool based on nationally consistent data and an approach that combines environmental and demographic indicators in maps and reports.	Demographic (sex, race, language, education, employment), Industrial & environmental variables (hazardous waste, wastewater quality, ozone)	Every Decade ; Dependent on Census Reports	Annual; Reflects Most Recent Census Reports	Public
EPA; USFS	AirNow Fire and Smoke Map	County	Provides information that you can use to help protect your health from wildfire smoke: Current particle pollution air quality information for your location; Fire locations and smoke plumes; Smoke Forecast Outlooks, where available; Recommendations for actions to take to protect yourself from smoke.	Air Quality, Smoke plumes, Wildfire presence, Terrain maps	Current Data	Real Time; Nearly Continuous Updates	Public
FEMA; US Fire Administration	National Fire Incident Reporting (NFIRS)	Incident	Voluntary reporting standard that fire departments use to uniformly report on the full range of their activities: Fire, EMS, severe weather, natural disasters. Includes a Wildland Fire Module that captures data about: 1) The number of acres burned and type of materials involved; 2) Conditions that contribute to ignition and spread; 3) Resources needed to control and/or extinguish fires. (Note: NFIRS data for 2025 and onward will be replaced by data from the new National Emergency Response Information System)	Acres burned, weather information, ignition sources, area type, heat source, fire suppression factors, property impacts, fire behavior	1980-2021	Annual; Lags 1 year	Public/By Request

Agency/Organization	Resource Name	Scale Level	Data Description	Variable Indicator Examples (But not limited to)	Timeframe	Frequency of Updates	Data Access
FEMA; US Fire Administration	National Emergency Response Information System https://www.usfa.fema.gov/nfirs/neris/	Point, 2020 Census Tract, County, State	Voluntary reporting that local fire and EMS departments use to consistently report all local incidents and their full range of response activities, in addition to their community risk reduction activities. Includes reporting on fire service personnel exposures, both physical and psychological exposures. Includes incident details from fires in the wildland-urban interface, urban/community conflagrations, etc.	Acres burned, weather information, ignition sources, area type, heat source, fire suppression and response actions and tactics, property impacts, firefighter health and safety exposures.	2025-Beyond	Daily, automatically refreshes on set frequency	Public
FEMA; US Fire Administration	State Fire Profiles	County	State Fire Profiles provide users with a snapshot of state fire losses reported through NFIRS in 2020. (Note: State Fire Profiles will be replaced by data analytics and dashboards provided through the new NERIS)	Incident Types, Casualties/Fatalities, Fire Department Composition and Specialization	2019-2024	Annual	Public
NASA	NASA FIRMS (fire detection from space)	County	Distributes Near Real-Time (NRT) active fire data from MODIS aboard the Aqua and Terra satellites, and VIIRS aboard S-NPP and NOAA 20 (formally known as JPSS-1). Globally data available within 3 hours of satellite observation; US and Canada active fire detections are available in real-time.	Fire location and intensity (fire radiative power)	2000-Present	Near Real Time; Continuous Updates	Public
NASA	NASA Worldview	N/A; Global Outlook	Open-source code app from NASA's EOSDIS provides the capability to interactively browse over 1000 global, full-resolution satellite imagery layers and then download the underlying data. This supports time-critical application areas such as wildfire management, air quality measurements, and flood monitoring.	Smoke expansion, Smoke optical properties, Atmospheric indicators	2000-Present	Near Real Time; Continuous Updates	Public/Requires DUA
NASA	NASA Disaster Portal	N/A	An interface for latest near real-time and disaster specific data products in GIS format. The Disasters Mapping Portal supports NASAs Earth Applied Sciences Disasters program area in its mission to use Earth-observing data and applied research to improve the prediction of, preparation for, response to and recovery from hazards and disasters around the world.	Fire location, Air quality, plume height, Aerosol optical Depth, Damage proxy maps, Debris flows, Hurricanes, Volcano eruptions, Disasters (general)	Wildfires from 2020 - Present. Other Data dependent on GIS layer	Continuous depending on data layer	Public
NASA	NASA LANCE	N/A	NASA's Land, Atmosphere Near real-time Capability for EOS (LANCE) provides near real-time data and imagery within 3 hours from satellite observation, including MODIS and VIIRS/Suomi NPP Active Fires near real-time data products.	MODIS and VIIRS/NPP: near real-time thermal anomalies/fire products, fire radiative power (FRP), fire pixel attributes (location, background, brightness temperatures (BT), statistics), detection confidence	Current Data; No historical information	3-5 Hour Increments	Public
NASA	Actionable Fire Science Information Hub	N/A	This collaborative portal aims to bring together data from various organizations to allow for informed decision making in the different phases of a wildfire which includes pre- active and post.	N/A; Site is currently in development.	N/A	N/A	N/A
NASA	Global Wildfire Information System	N/A	Joint initiative of the GEO and the Copernicus Work Programs, aims at bringing together existing information sources at regional and national level in order to provide a comprehensive view and evaluation of fire regimes and fire effects at global level and to provide tools to support operational wildfire management from national to global scales.	Historical data, Forecast, Damage assessment	2001-Present	Varies	Public

Agency/Organization	Resource Name	Scale Level	Data Description	Variable Indicator Examples (But not limited to)	Timeframe	Frequency of Updates	Data Access
NOAA	Meteorological Assimilation Data System (MADIS)	N/A	The MADIS Application Program Interface (API) is a library of subroutines, callable from Fortran, which provides access to all of the observation and quality control (QC) information in the MADIS database (referred to as the "FSL database" in the API documentation), and/or other supported meteorological databases (i.e., the NWS AWIPS netCDF database).	N/A	Historical	N/A	Public/Requires DUA
NOAA	VIIRS I-band Active Fire Visual Display	County	RealEarth is a data discovery and visualization platform developed at SSEC/CIMSS at the University of Wisconsin-Madison. The goal: quick and continuous visualization of Earth observation imagery and data in a common and familiar map-based interface. A wide variety of land, oceanic, and atmospheric remote sensing imagery and related data are available to be layered, compared, and animated in time-series loops.	Fire radiative power	Current	Real Time (<30 minutes).	Public
NOAA	Global Biomass Burning Emissions Product eXtended (GBBEPx)	N/A	The product contains daily global biomass burning emissions, blended fire observations from MODIS Quick Fire Emission Dataset (QFED), VIIRS fire emissions, and Global Biomass Burning Emission Product from Geostationary satellites (GBBEP-Geo), which are in a grid cell of 0.25 x 0.3125 degree and 0.1 x 0.1 degree.	Air Quality ($PM_{2.5}$, emissions, GBBEP, biomass burning)	Current	Near Real Time (Once a Day)	Public
NOAA	HourlySurface $PM_{2.5}$	N/A	EPA plans to ingest the near real time surface $PM_{2.5}$ estimates into its AirNow system. Data has been collected since 2021.	Air Quality ($PM_{2.5}$, emissions, cloud cover), Satellite Imagery, Wildfires	Current	Hourly	Public
NOAA	AerosolWatch	State	The data is provided to the NWS for model verification. The data is also provided to the public in near real time via AerosolWatch website.	Air/Wind patterns and currents	48 Hrs	10 Minutes Increments	Public
NOAA	GOES-R Fire Alerts	County	This website prototypes the usage of VOLCAT Thermal Anomaly detection and characterization applied to wildfires over CONUS. This project is a collaboration between the VOLCAT team and NOAA Wildfire teams and allows for the rapid detection of wildfire events.	Thermal anomaly detection	Current	Continuous (1 to 5 Minutes)	Public
NOAA	Hazard Mapping System (HMS)	State	The system combines near real-time polar and geostationary satellite observations into a common framework in which expert image analysts perform quality control of automated fire products and digitization of smoke plumes. First implemented in 2003 in response to high demand for active fire and smoke information over North America.	Wildfires and smoke presence	2003-Present	Daily	Public
NOAA	National Integrate Drought Information System	County	Shows the location and intensity of drought across the country. This data is available for every state and county. The measurements are tracked using a 5 items scale ranging from D0, abnormally dry, to D4, Exceptional Drought.	Drought conditions, Precipitation levels	2000-Present	Weekly (Thursday)	Public
NOAA	Wildfire Air Quality Impacts	State	Rapid Refresh is the continental-scale NOAA hourly-updated assimilation numerical forecast modeling system operational at NCEP. Complemented by the higher-resolution 3km High-Resolution Rapid Refresh (HRRR) model.	Air quality prediction	2020 - Present	Hourly	Public

Agency/Organization	Resource Name	Scale Level	Data Description	Variable Indicator Examples (But not limited to)	Timeframe	Frequency of Updates	Data Access
NOAA; NASA	Satellite in HMS: G16/17, VIIRS NOAA20/JPSS, MODIS/Terra	N/A	To detect active fire pixels and the extent of smoke plumes. Data collected is based on Mission.	Smoke plumes, Cloud cover, Haze, Sea surface heights, GOES satellite measurements	2011 - Present	Real Time and Archival	Public
NOAA; NWS	National Digital Forecast Database	County	The goal of the NWS is to provide weather and water data, forecasts, warnings, and impact-based decision support services for the protection of life and property and enhancement of the national economy.	General weather, wind, temp, precipitation etc.	Real-Time; Forecasting	Future Forecast Data	Public
NOAA; NWS	National Weather Service Spot Forecast	N/A	Site specific NWS spot forecast requests for wildfires or prescribed burns which provides a 48-hour forecast.	Spot weather forecasts (forecasts issued to fit time, topography, and weather of specific incidents)	Current	Future Forecast Data	Restricted Access
NOAA; NWS	NOAA Operational Model Archive and Distribution System (NOMADS)	N/A	NCEP delivers national and global weather, water, and space weather guidance, forecasts, warnings and analyses to its Partners and External User Communities. These products and services are based on a service-science legacy and respond to user needs to protect life and property, enhance the nation's economy, and support the nation's growing need for environmental information.	Weather forecasting data	2016-Present	Hourly to Daily	Public
NOAA; OAR; CSL	Wildfire Emission Factors	Local - Varies by instrument	A coordinated effort based at the USDA Fire Sciences Lab in Missoula, Montana. The focus is on measuring fuels or combustion conditions that are characteristic of the western U.S. that may be under-sampled by the fire research community. Developed from FIREX (Fire Influence on Regional and Global Environments Experiment, which evolved into FIREX-AQ).	Air pollutants/quality	2016	N/A	Public/Requires DUA
NREL	Geospatial Data Science Applications and Visualizations	N/A; Dependent on Resource Used	The Geospatial Data Science (GDS) group in NRELs Strategic Energy Analysis Center leads modeling and visualization research at the intersection of renewable energy deployment, geospatial technologies, big data science, and application development.	Wind, Solar, Biofuels	Current Data	N/A	Public
NWCG	InciWeb	County	InciWeb is an interagency all-risk incident information management system. The system was developed with two primary missions: 1) Provide the public a single source of incident related information; 2) Provide a standardized reporting tool for the Public Affairs community.	Fire location, Cause, Date of origin, Coordinates, Size, Fuels, # of personnel, Closures (includes post-fire information as well)	Current	Near-real time	Public
NWCG	National Interagency Fire Enterprise Geospatial Portal (EGP)	N/A	Authoritative source of standardized geospatial information for the full range of wildfire activities ranging from response to planning. A central source of spatial data for mapping, decision support, business intelligence, and situational awareness through multiple tools to view and analyze wildland fire data: the Fire Globe, SituationAnalyst, and a GIS data repository.	Fire location, incident information, estimated cost	N/A	N/A	Public/Restricted Access
OpenAQ	OpenAQ	N/A	Open-source air quality data from a range of reference monitors and air sensors. Includes data on the following pollutant types: PM_{10}, $PM_{2.5}$, Sulfur dioxide (SO_2), Carbon monoxide (CO), Nitrogen dioxide (NO_2), Ozone (O_3), or Black carbon (BC).	Air Quality	Current	real-time	Public

Agency/Organization	Resource Name	Scale Level	Data Description	Variable Indicator Examples (But not limited to)	Timeframe	Frequency of Updates	Data Access
Purple Air	Purple Air	Neighborhood	PurpleAir's industry-leading sensors measure particle pollution ($PM_{2.5}$) and are priced at a fraction of what you pay for a commercial sensor. This data is available to view for free, but data availability is dependent on presence of PurpleAir sensors.	Air Quality (Indoor and Outdoor), $PM_{2.5}$	Real-Time	Continuous	Public
USDA	Web Soil Survey	County	Provides soil data and information produced by the National Cooperative Soil Survey. Operated by the USDA Natural Resources Conservation Service (NRCS) and provides access to the largest natural resource information system in the world. NRCS has soil maps and data available online for more than 95 percent of the nation's counties and anticipates having 100 percent in the near future.	Soil quality	Unspecified; Appears Current	Annual	Public
USDA; USFS	ArcGIS WUI Layer	State	This joint USDA/USFS GIS platform allows users to identify Wildland Urban Interface (WUI) areas. WUI areas are areas where houses/structures meet or interface with undeveloped vegetation. The primary concern are fires burning in the WUI might emit more toxic mixtures than wildland fires.	Wildland Urban Interface (WUI) locations, topography	2010	N/A	Public/Restricted Access
USGS	LANDFIRE	N/A	Landscape scale geo-spatial products to support cross-boundary planning, management, and operations. LANDFIRE is a real-time tool that screens areas with the highest wildfire risk.	Topographic maps for fuel, vegetation, fire regime, and seasonal	2016-2022	N/A	Public
USGS	Monitoring Trends in Burn Severity (MTBS)	County	MTBS is an interagency program focused on mapping the burn severity and extent of large wildfires.	Fire name, Acreage, Ignition date, Fire type, Fire ID	1984-2020	Annual; Lags 2-3 Years	Public
USGS	Emergency Assessment of Post-Fire Debris-Flow Hazards	State	The USGS conducts post-fire debris-flow hazard assessments for select fires in the Western U.S. The USGS uses geospatial data related to basin morphometry, burn severity, soil properties, and rainfall characteristics to estimate the probability and volume of debris flows that may occur in response to a design storm.	Date of origin, Location, Acreage, Segmented probability	2013-Present	Annual; Potentially Faster	Public
USGS	USGS National Map	N/A	A USGS web application that enables the public to create custom topographic maps on demand. The official name of the application is topoBuilder or OnDemand Topos.	Structures (select medical/emergency response: hospitals/fire/EMS, education, Law enforcement), Geographic Names, Canopy cover, Shrublands (NLCD data), elevation map	Current	Annual	Public

Table B2. Environmental/Exposure Data – State Level

Agency/Organization	Resource Name	Scale Level	Data Description	Variable Indicator Examples (But not limited to)	Timeframe	Frequency of Updates	Data Access
CAL FIRE	Incident Maps	County	Reports of wildfire incidents, acreage burned, and location of wildfires.	Wildfire damage, incident counts, locations etc.	2013-Present	As Events Occur	Public

Agency/Organization	Resource Name	Scale Level	Data Description	Variable Indicator Examples (But not limited to)	Timeframe	Frequency of Updates	Data Access
CAL FIRE	CalFIRE FRAP GIS Data	County	Program assesses the amount and extent of California's forests and rangelands, analyzes their conditions, and identifies alternative management and policy guidelines. Included in FRAP are a variety of measurements included in GIS portals.	Vegetation, Watershed, Fire characteristics, Erosion, WUI, County Boundaries, Fire Threat, Fire Severity, Land Ownership	Dependent on Data Requested	N/A	Public
CARB	CARB Air Quality and Meteorological Information System	County	CARBs AQMIS system provides users with a variety of air quality measurements that can be overlayed with google maps.	Ozone, Air Quality, Meteorological, Greenhouse Gases	2012-Present	Daily	Public
Colorado State University	Gridded Surface Smoke and Non-Smoke $PM_{2.5}$	National	This dataset contains spatially interpolated daily $PM_{2.5}$ concentrations observed by monitors in the EPA AQS and non-smoke seasonal background $PM_{2.5}$ estimates for 2006-2015.	Looks at wildfire smoke epidemiology, Health-impact assessments, Economics, etc.	2006-2015	Retrospective	Public
Sonoma County	Sonoma County Evacuation Zones	County	Sonoma County has put together a GIS map that allows users to identify evacuation zones, where to go in response to an evacuation notice, and when a notice is given.	Evacuation Zones	Current	Continuous	Public
Sonoma County Permit Sonoma	Sonoma County Zoning and Land Use Map	N/A; Zones	This map provides information about land use in the unincorporate area of Sonoma County including zoning, zoning overly, land use, land development and density. The map is updated based on Sonoma Counties General Plan.	Land Use	2020	Varies	Public

Table B3. Health Data – National Level

Agency/Organization	Resource Name	Scale Level	Data Description	Variable Indicator Examples (But not limited to)	Timeframe	Frequency of Updates	Data Access
AHRQ	Healthcare Cost and Utilization Project (HCUP)	N/A	A family of databases, software tools and related products developed through a Federal-State-Industry partnership and sponsored by AHRQ. Derived from administrative data and contain encounter-level, clinical and nonclinical information including all-listed diagnoses and procedures, discharge status, patient demographics, and charges for all patients.	Adult and pediatric ICD-10-CM/PCS diagnosis, procedure, External cause of morbidity codes, and patient characteristics	1988-2019	Varies; 1-3 years	Public/Requires DUA
CDC	National Syndromic Surveillance System (NSSP) Biosense/ESSENCE	N/A	Electronic health surveillance data integration platform. Patient encounter data received from ED, urgent and ambulatory care centers, inpatient healthcare settings, and labs. Secure data system- must request access as data is not publicly available.	Chief Complaint, Diagnosis Discharge, EMR data from disaster medical assistance team (DMAT) operation sites	2003-Present	Within 24 Hrs of Pt Visit	Private
CDC	WONDER	County	Web-based resource that provides state and county level vital statistic data for births, deaths, and infant mortality.	Infant birth weight, Pregnancy characteristics, Mortality, Cancer Incidence and Mortality	1995-2020	Varies	Public/Requires DUA

Agency/Organization	Resource Name	Scale Level	Data Description	Variable Indicator Examples (But not limited to)	Timeframe	Frequency of Updates	Data Access
CDC	National Center for Health Statistics (NCHS) Vital Records - National Vital Statistics System (NVSS)	County	Public use Birth, Period Linked Birth, Infant Death, Birth Cohort Linked Birth, Mortality Multiple Cause, and Fetal Death data files are available for independent research and analyses.	Maternal Behavior and Health Characteristics, Infant Health Characteristics, Medical and Public Services Utilization	1968-2020	Annual	Public
CDC	Web-based Injury Statistics Query and Reporting System (WISQARS)	National	Interactive, online database that provides fatal and nonfatal injury, violent death, and cost of injury data. Data used to learn more about the public health and economic burden associated with unintentional and violence-related injury in the United States.	Injury Fire/Burn	2000-2020	Annual; Lags by Nearly 1 Year	Public
CDC	U.S. Cancer Statistics Public Use Databases	Census Regions	De-identified cancer incidence data reported to CDC's National Program of Cancer Registries (NPCR) and the National Cancer Institutes (NCIs) Surveillance, Epidemiology, and End Results (SEER) Program; can be analyzed using software developed by NCIs SEER Program. Includes cancer incidence and population data for all 50 states, the District of Columbia, and Puerto Rico.	Cancer Incidence (e.g., lung, brain tumors, non-Hodgkin lymphoma, multiple myeloma, and leukemia) using ICD-1O codes, Month of Diagnosis	2005-2019	Annual; In June	Public/Requires DUA
CDC	National Hospital Care Survey (NHCS)	N/A	NHCS collects data on patient care in hospital-based settings to describe patterns of health care delivery and utilization in the United States, including inpatient, emergency (EDs), and outpatient departments (OPDs). Researchers can link these survey data to outside data sources.	Demographics, Diagnoses (ICD-10 codes), Procedures, Laboratory tests, and Medications	2013-2021	Annual	Public/Restricted Access
CDC	National Death Index (NDI)	State	Containing over 100 million death records, the National Death Index (NDI) can help you find out who in your study has died by linking your own research datasets to death certificate information for your study subjects.	ICD-10 Codes	1979-2021	Annual; Lags 11 Months	Public/Requires DUA
CDC	Linked National Hospital Care Survey (NCHS) and National Death Index (NDI) Mortality Data		Data collected from National Hospital Care Survey (NHCS) augmented with mortality data from the National Death Index (NDI). Provides the opportunity to conduct a vast array of outcome studies designed to investigate the association of a wide variety of health factors with mortality.	Day/Month/Year of Birth; Day/Month/Year of Death; ICD-10 Underlying Cause of Death; Other Conditions/Comorbidities	2014-2017	Annual	Public/Restricted Access
CDC	Linked NHCS and CMS Medicare Master Beneficiary Summary File (MBSF) Data and Linked NHCS and CMS Medicare MBSF Claims/Encounters and Assessment Data	N/A	Linkage of NHCS data with the CMS Medicare Data to conduct a vast array of studies on health care utilization and expenditures among the elderly U.S. population and persons receiving Medicare disability benefits. Medicare enrollment and claims/encounters data are available for patient records in the NHCS for which NCHS was able to match with CMS provided Medicare administrative records.	Patient Ambulatory Care and Inpatient Visits, Hospital Characteristics, CMS Data: Beneficiary Demographic, Reason for Medicare Entitlement, Program Enrollment Type	2014-2017	Annual	Public/Restricted Access
CDC	National Health and Nutrition Examination Survey	N/A	Program of studies designed to assess the health and nutritional status of adults and children in the United States. Combines interviews and physical examinations.	Demographics, Dietary, Laboratory Samples, Examination Data etc.	1999-Present	Annual	Public

Agency/Organization	Resource Name	Scale Level	Data Description	Variable Indicator Examples (But not limited to)	Timeframe	Frequency of Updates	Data Access
CDC	Behavioral Risk Factor Surveillance System	State	System of health-related telephone surveys that collect state data about U.S. residents regarding their health-related risk behaviors, chronic health conditions, and use of preventive services.	Demographics, Health Status, Tobacco/Alcohol Use, Chronic Health Conditions etc.	1984-2021	Annual	Public
CMS	Medicare and Medicaid Claims	County	Patient zip-code level data available in the following encounter type datasets: Skilled Nursing Facility, Outpatient, Inpatient, home health agency, and DME. Other datasets include diagnostic codes, discharge status, and other patient demographics.	Diagnostic Codes, Discharge Status, Patient Demographics	2015-Present	Varies; Annually with Lag Possible	Public/Requires DUA; Restricted Access
HRSA	Health Center Program Uniform Data System (UDS)	County	Health Center Program awardees and look-alikes are required to report on a core set of measures each calendar year as defined in the UDS, a standardized reporting system. HRSA uses UDS data to assess the impact and performance of the Health Center Program, and to promote data-driven quality improvement.	Patient characteristics (poverty level, insurance status, race & ethnicity, veterans, Medicare), Clinical (prenatal care, diabetes, cancer), Health outcomes & disparities, medical costs	2017-Present	Annually depending on report type requested	Public
Indian Health Service	National Patient Information Reporting System (NPIRS)	Patient-Level	A database of financial, environmental, engineering, administrative and clinical healthcare information gathered from direct IHS, Tribal and Urban healthcare sites & regional administrative offices throughout the Indian Health systems.	Injury, Clinical services	2006-Present	Annual	Public/Requires DUA
IQVIA	IQVIA Real World Datasets	Varies by dataset	IQVIA proprietary datasets include: EMR, Longitudinal Prescription (LRx), Claims data, Hospital Data, Genomic Data, Oncology Data, and Biomedical Global data.	EMR data, Prescriptions, and Claims	Varies	Varies	Private
Kaiser Permanente	Kaiser Permanente (KP) Research Bank	N/A ; Data is Broken Up into Cohorts	Second largest biobank in the US and provides opportunities to enable research studies related to the prevention, diagnosis and treatment of disease. Resource includes de-identified medical record information, a health survey and biospecimens and is available to scientists who apply to use the information for genetic, epidemiological, and other scientific research.	EMR data, Pregnancy cohort, Cancer cohort	2010-2020	Varies	Public/Requires DUA
Lumosity	Lumosity	N/A	Lumosity hosts a variety of cognitive training "games" from which data is available upon request. Researchers used data to assess cognitive impacts of wildfire.	Cognitive performance, Attention score	Unspecified	N/A	Public/Restricted Access
National Cancer Institute	Surveillance, Epidemiology, and End Results (SEER) Program Incidence Data	Incidence	SEER collects cancer incidence data from population-based cancer registries covering approximately 47.9 percent of the U.S. population. The SEER registries collect data on patient demographics, primary tumor site, tumor morphology, stage at diagnosis, and first course of treatment, and they follow up with patients for vital status.	Demographics, Primary Site, Histology, Size, Extent	1975-2019	Annual	Public/Restricted Access
NIH	Environmental influences on Child Health Outcomes (ECHO) Program	National	The ECHO Program has two major components, the ECHO cohorts for observational research, and the ECHO IDeA States Pediatric Clinical Trials Network (ISPCTN) for intervention research. The core elements addressed across all studies are: demographics, typical early health and development, genetic influences on early childhood health and development, environmental factors, patient/Person (parent and child) Reported Outcomes (PROs).	Varies by cohort	N/A	N/A	Public/Requires DUA

Agency/Organization	Resource Name	Scale Level	Data Description	Variable Indicator Examples (But not limited to)	Timeframe	Frequency of Updates	Data Access
SAMHSA	2020 Uniform Reporting System (URS)	State	State mental health agencies (SMHAs) use the Uniform Reporting Systems (URS) to compile and report annual data as part of SAMHSA's Community Mental Health Services Block Grant. URS is part of an effort to use data in decision support and planning in public mental health systems and in supporting program accountability.	Sociodemographic characteristics, outcomes of care, use of evidence-based practices, client assessment of care, insurance status, employment status	2007-2020	Annual; Lags 1 Year	Public
SAMHSA	Substance Abuse and Mental Health Data Archive (SAMHDA)	Varies; Patient Level and Facility-Level	SAMSHA conducts research on mental health and substance abuse across the United States. The data is collected through several sources and surveys and includes Mental Health Client Level Data (MH-CLD), Treatment Episode Data Sets (TEDS), and the National Mental Health Services Survey	Mental health diagnoses, mental health outcomes, patient demographics, substance use, length of stay, facility characteristics	Varies	Varies; Most are annual	Public

Table B4. Health Data – State Level

Agency/Organization	Resource Name	Scale Level	Data Description	Variable Indicator Examples (But not limited to)	Timeframe	Frequency of Updates	Data Access
California Department of Public Health	Vital Records	County	Birth files include: all state registered births, California residents that occurred out-of-state. Contains demographic and medical information. Death files: in-state California deaths, a combination of in-state deaths and deaths of California residents that occurred in other states or jurisdictions, out-of-state deaths only.	Birth: demographics, medical, place; Death: demographics, birth info, place and cause of death, includes variable indicating whether death was disaster-related	1970-Present	Varies	Public/Requires DUA
California Department of Public Health	California Cancer Registry	Census Tracts	Statewide population-based cancer surveillance system. Collects information about all cancers diagnosed in California (except basal and squamous cell carcinoma of the skin and carcinoma in situ of the cervix).	ICD-1O codes (e.g., lung cancer, brain tumors, non-Hodgkin lymphoma, multiple myeloma, leukemia etc.)	1988-2019	Annual	Public
CHHS	CHHS Open Data	County	439 clinical and administrative datasets available for the state of CA (includes patient discharge data, ED encounters, inpatient characteristics, asthma rates, infectious disease etc.).	Varies by Dataset (e.g., ICD-10 codes, number of ED visits for asthma, confirmed coccidioidomycosis (valley fever) cases, birthweight etc.)	2014-Present	Annual; May Vary	Public
Oregon Health Agency	Oregon State Cancer Registry (OSCaR)	State	Statewide, population-based registry that collects and analyzes information about cancer cases occurring in Oregon. The mission: collect complete, quality cancer data that supports cancer research and public health practices designed to improve efforts in the screening, treatment, and survivorship of all people in Oregon affected by cancer.	ICD-10-CM (e.g., lung cancer, brain tumors, non-Hodgkin lymphoma, multiple myeloma, leukemia etc.)	1995-2019	Annual	Public/Requires DUA
Sonoma County Department of Health Services	Leading Health Indicators - Sonoma County	County	High-level summary data, derived from local and state sources, highlighting major health conditions or events that compromise the health and healthy development of children and contribute most prominently to illness and injury, disability and death for Sonoma County adults and children.	Mortality and Morbidity, Disability by Age, Health Indicators (General), Leading Causes of Death by Age, Hospitalization, Injuries by Age	2007-2010	Not updated beyond 2010	Public

Agency/Organization	Resource Name	Scale Level	Data Description	Variable Indicator Examples (But not limited to)	Timeframe	Frequency of Updates	Data Access
Washington State Department of Health	Data and Statistical Reports	County	Data and reports on a variety of health topics including cancer, infectious diseases, environmental health, health behavior, vital statistics, hospital data, injury and poisoning, material and child health.	Demographics, Birth and death records, Cancer diagnosis, Injury data	Varies	Varies; Primarily Annual	Public/Requires DUA
Washington State Department of Health	Washington Tracking Network	Census Tracts	Public health data are available for download and exploration using five tools (dashboards, data portal, information by location, community reports). Topic areas: health outcomes and surveillance, demographics and community characteristics, weather and the environment.	WA DPH data including BRFS, Cancer incidence, Birth outcomes etc.	2009-2022	Varies; Primarily Annual	Public
Washington State Health Care Authority	Washington State All Payer Claims Database (WA-APCD)	State	A tool used to collect health care claims data for reporting, analytics, and to help the public make their health care decisions. It supports health care and payment reform while addressing the need for cost, quality, and utilization transparency. Using the WA-APCD, Washington State can help to advance medicine and public health	ICD-10 and CPT codes (e.g., asthma, cardiovascular, pregnancy and birth outcomes etc.)	2014-Present	Annual	Public/Requires DUA

Table B5. Social Determinants of Health Data – National Level

Agency/Organization	Resource Name	Scale Level	Data Description	Variable Indicator Examples (But not limited to)	Timeframe	Frequency of Updates	Data Access
AHRQ	Social Determinants of Health Database	Census Tracts	These SDOH beta data files are curated from existing Federal datasets and other publicly available data sources. The purpose of the files is to make it easier to find a range of well documented, readily linkable SDOH variables across domains.	Social demographics, employment, income, education, physical infrastructure (housing, food, transportation), healthcare access/ use	2009-2020	Annual; Lags by about 2 years	Public
CDC	The Community Assessment for Public Health Emergency Response (CASPER)	State	A type of Rapid Needs Assessment (RNA) that provides household-level information to public health leaders and emergency managers. Used to initiate public health action, identify information gaps; facilitate disaster planning, response, and recovery activities; allocate resources, and assess new or changing needs in the community. It is a cross-sectional epidemiologic design; it is not surveillance.	Public Health Perceptions, Estimating Needs of Community, Assist in Planning	Varies; Dependent on State Use	Varies; Dependent on State Use	Public
U.S. Census Bureau	American Community Survey (ACS)	Census Tracts	ACS helps local officials, community leaders, and businesses understand the changes taking place in their communities. It is the premier source for detailed population and housing information about our nation.	Demographics, Socio-economic Factors, Population Distributions, Population Vulnerabilities, Emergency Response and Evacuation Planning	2007-Present	Annual; Lags 1 Year	Public
U.S. Census Bureau	Community Resilience Estimates	Census Tracts	Examines how at-risk every single neighborhood is to the impact of a disaster. The Community Resilience Estimates use single year microdata.	Social Vulnerability and equity gaps	2018-2019	N/A	Public

Table B6. Social Determinants of Health Data – State Level

Agency/Organization	Resource Name	Scale Level	Data Description	Variable Indicator Examples (But not limited to)	Timeframe	Frequency of Updates	Data Access
CalMatters	Disaster Days	School Site	A school-site level database of reported school closures for the state of California. Reported closures were manually coded into five categories: wildfires, natural disasters and weather, student safety, infrastructure and other. State enrollment data for the year of each reported closure was matched with each school site to quantify the student impact.	Closure days, reasons for closures, number of schools impacted, number of students impacted	2002-2019	Not indicated	Public
Washington Office of Financial Management	Population and Demographics	Census Tracts	The Forecasting division conducts research on a variety of issues related to the state budget, public policy, and demographics. The Population unit develops official state and local population estimates and projections for use in the allocation of certain state revenues, growth management, and other planning functions.	Household income, Demographics, Demographics Forecasting, Housing, Population density,	2000-2020	Every Decade	Public

Table B7. Other Data Sources

Agency/Organization	Resource Name	Scale Level	Data Description	Variable Indicator Examples (But not limited to)	Timeframe	Frequency of Updates	Data Access
Google	Google Trends	State	Used as a proxy for health outcomes/exposures. Publicly available data that can be used to analyze location-specific variation in search query behavior.	Search term popularity; Behavior; Future purchasing (of protective equipment)	Current Data	Weekly	Public
SafeGraph	SafeGraph	Census Blocks	Used as proxy for health outcome. These data measure the aggregate activity of anonymized device signals, or pings, at the census block group level. Signals are collected from smartphones, not all cell phones.	Mobility, Migration	Current Data	Monthly	Private
Twitter	Twitter	Neighborhood	Used as a proxy for health outcomes/exposures. Geolocated tweets can be downloaded using Twitter's API.	Sentiment; Behavior	Current Data	Near Real Time	Public/Requires DUA

Appendix C: Scoping Literature Review Table

Citation	Title	Exposure Metric	Health Metric
Abdo, 2019	Impact of wildfire smoke on adverse pregnancy outcomes in Colorado, 2007-2015	NOAA HMS (smoke plume); EPA AQS ($PM_{2.5}$); ambient temperature; PM_{10}; Ozone	Colorado Vital Records Registry (Birth Certificates)
Ademu, 2022	Impact of short-term air pollution on respiratory infections: A time-series analysis of COVID-19 cases in California during the 2020 wildfire season	EPA open-source data ($PM_{2.5}$, CO, NO_2, AQI); NCEI/NOAA (mean temperature, mean precipitation, average wind speed)	California Dept of Public Health (COVID-19 Confirmed Cases)
Aguilera, 2020	Respiratory hospitalizations and wildfire smoke: a spatiotemporal analysis of an extreme firestorm in San Diego County, California	CA FRAP (fire perimeters); MODIS Rapid Response system (smoke plumes); NOAA HMS (smoke plumes)	California OSHPD database (respiratory hospitalizations/patient discharges)
Aguilera, 2021a	Fine particles in wildfire smoke and pediatric respiratory health in California	EPA AQS ($PM_{2.5}$); NOAA HMS (smoke plume)	Rady's Children Hospital Network in San Diego County, CA (date of visit, date of birth, residence ZIP code, respiratory or non-respiratory visit)
Aguilera, 2021b	Wildfire smoke impacts respiratory health more than fine particles from other sources: observational evidence from Southern California	EPA AQS ($PM_{2.5}$); NOAA HMS (smoke plumes); CA FRAP (fire perimeters); NCEI/NOAA (mean wind speed, mean temperature, mean humidity); SAWRI (dailywinds)	California OSHPD database (respiratory hospitalizations/patient discharges)
Alman, 2016	The association of wildfire smoke with respiratory and cardiovascular emergency department visits in Colorado in 2012: a case crossover study	Weather Research and Forecasting Model with Chemistry (WRF-Chem)($PM_{2.5}$, Ozone); MOZART-4 (chemical boundary conditions); NCEP/NAM (meteorological boundary conditions); NCAR fire inventory - FINN with burned area product from SMARTFIRE framework (wildfire emission estimates); EPA surface network (CO, AOD, $PM_{2.5}$); NLDAS (mean temperature)	Colorado Dept of Public Health and Environment (hospitalizations and ED visits for cardiorespiratory disease)
Beaupied, 2022	Cows as canaries: The effects of ambient air pollution exposure on milk production and somatic cell count in dairy cows	EPA AQS ($PM_{2.5}$, Ozone); THI from NOAA regional monitors; CO from local ground monitors; NOAA HMS (Smoke Plume)	Average daily milk production (metabolic output); average daily bulk tank somatic cell counts (inflammatory markers)
Black, 2017	Early Life Wildfire Smoke Exposure is Associated with Immune Dysregulation and Lung Function Decrements in Adolescence	California Air Resources Board air monitoring station (Ozone, $PM_{2.5}$)	Pulmonary function testing; PCR Array (signaling pathways, gene expression); In vitro peripheral blood cells with TLR Ligands (inflammatory markers)
Buchholz, 2022	New seasonal pattern of pollution emerges from changing North American wildfires	NASA/Terra satellite: MOPITT-Terra (CO) and MODIS-Terra (AOD); Emission inventories: Fire INventory from NCAR version 1.5 (FINN1.5), GFED version 4.1 with small fires (GFED4.1s), QFED version 2.5 (QFED2.5), CAMS-GLOB-ANT version 3.1 (CAMS-GLOB-ANT v3.1)	Not Assessed
Burke, 2022	Exposures and behavioral responses to wildfire smoke	EPA pollution monitors ($PM_{2.5}$); NOAA HMS (smoke plumes); SafeGraph (mobility); PurpleAir pollution monitors (indoor and outdoor $PM_{2.5}$)	GoogleTrends (health protective behavior); Twitter (sentiment/behavior)
Caamano-Isorna, 2011	Respiratory and mental health effects of wildfires: an ecological study in Galician municipalities (north-west Spain)	Ministry of Environment, number of wildfires that occurred in each municipality (three categories: none: 0-3, medium: 4-10, high: 10+)	Primary health care pharmaceutical billing database (prescriptions); Individual Health Card Database (indicators), Health Ministry's *Nomenclator Digitalis* (calculate number of daily doses); Daily Doses per Day (anxiolytics-hypnotics, drugs for obstructive airway diseases)
Cançado, 2006	The impact of sugar cane-burning emissions on the respiratory system of children and the elderly	Meteorologic station of the Escola Superior de Agricultura Luiz de Queiroz stacked filter units ($PM_{2.5}$, $PM_{>2.5}$); particle induced x-ray emission (elemental composition); Agricultural School of Sao Paulo University (min. temperature, relative humidity)	Brazil Health Agency hospital admission records (respiratory diseases)
Cândido da Silva, 2014	Low birth weight at term and the presence of fine particulate matter and carbon monoxide in the Brazilian Amazon: a population-based retrospective cohort study	Center for Weather Forecasting and Climate Studies of the National Institute for Space Research (INPE-CPTEC) using Coupled Aerosol and Trace Gases Transport Model for the Brazilian Development of the Regional Atmospheric Modeling System (CATT-BRAMS Model) ($PM_{2.5}$, CO)	Information System on Live Births of the Ministry of Health (SINASC)(birth weight)
Casey, 2021	Wildfire particulate matter in Shasta County, California and respiratory and circulatory disease-related emergency department visits and mortality, 2013-2018	NOAA HMS (to ID smoke plume exposed zip codes); US EPA monitoring data from Redding and Lassen stations; meteorological data from NOAA Local Climatological Data Daily Summary from Redding, CA station	Data from Shasta County Health and Human Services Agency (respiratory and circulatory-disease related ED visits and mortality)
Castro, 2009	Trend of mortality from respiratory disease in elderly and the forest fires in the state of Rondonia/Brazil - period between 1998 and 2005	National Institute of Space Research: Advanced Very High-Resolution Radiometer (AVHRR), Moderate Imaging Spectroradiometer (MODIS-Aqua, MODIS-Terra), and GOES (satellite remote sensing imagery of heat/burn outbreaks)	Mortality Information System of SUS (death certificates: respiratory disease, COPD); Brazilian Institute of Geography and Statistics (population estimates)
CDC, 2008	Monitoring health effects of wildfires using the BioSense system--San Diego County, California, October 2007	General exposure/proximity to event	CDC BioSense System (ED visits for respiratory disease)
Cleland, 2011	Multidisciplinary team response to a mass burn casualty event: outcomes and implications	General exposure/proximity to event	Ambulance Victoria records, Alfred's VABS data registry (burn injuries)
Cleland, 2021	Estimating the acute health impacts of fire-originated $PM_{2.5}$ exposure during the 2017 California wildfires: Sensitivity to choices of inputs	Four estimates of $PM_{2.5}$ using: permanent FRM/FEM and temporary non-FRM/FEM monitoring stations across California; EPA CMAQ model simulations; MODIS Terra Satellite (AOD)	EPA BenMAP-CE (hospital admissions for respiratory, cardiovascular, asthma)

Citation	Title	Exposure Metric	Health Metric
Cleland, 2022	Short-term exposure to wildfire smoke and $PM_{2.5}$ and cognitive performance in a brain-training game: A longitudinal study of US adults	EPA AQS, FRM/FEM monitors and PurpleAir monitors ($PM_{2.5}$); NOAA HMS (smoke plume)	Luminosity brain training platform, *Lost in Migration* (cognitive function)
Delfino, 2010	Associations of primary and secondary organic aerosols with airway and systemic inflammation in an elderly panel cohort.	Outdoor air sampling - Condensation Particle Counter (total particle number); OC_EC Analyzer ($PM_{2.5}$, organic and elemental carbon); Aethalometer ($PM_{2.5}$, black carbon); Sioutas Personal Cascade Impactors filters (size-segregated particle samples, $PM_{0.25}$-PM_{10}); EPA FRM (NO_x, CO, ozone)	Biomarkers (blood draws IL-6, exhaled NO)
Delfino, 2002	Association of asthma symptoms with peak particulate air pollution and effect modification by anti-inflammatory medication use	San Diego Air Pollution Control District TEOM (PM_{10}, Ozone, NO_2, temperature, relative humidity, wind speed); Burkard 7-day pollen and fungal spore collector (aeroallergen)	Asthma Diary (medication usage, respiratory infection, hay fever, asthma symptoms)
Dennekamp, 2015	Forest fire smoke exposures and out-of-hospital cardiac arrests in Melbourne, Australia: a case-crossover study	EPA Victoria ($PM_{2.5}$, PM_{10}, CO, ozone, NO_2, SO_2) central monitoring station suburban Melbourne; Bureau of Meteorology at Melbourne Airport (temperature, relative humidity)	Victorian Ambulance Cardiac Arrest Registry (out of hospital cardiac arrest)
DeYoung, 2018	The effect of mass evacuation on infant feeding: The case of the 2016 Fort McMurray Wildfire	Self-reported exposure (primary data collection)	Survey (evacuation destination, length of time evacuated, method of feeding infant before/during/after evacuation)
Dodd, 2018	Lived experience of a record wildfire season in the Northwest Territories, Canada	General exposure/proximity to event	Semi-structured interviews (health, environment, livelihood factors; relationship with wildfires; mental/emotional well-being)
Dohrenwend, 2013	The impact on emergency department visits for respiratory illness during the Southern California wildfires	US EPA AirNow (AQI: PM, ozone, CO, SO_2)	Kaiser Permanente electronic database (ED visits for respiratory syndromes)
Doubleday, 2020	Mortality associated with wildfire smoke exposure in Washington state 2006-2017: a case-crossover study	Air Indicator Receptor for Public Awareness and Community Tracking (AIRPACT-4) model domain ($PM_{2.5}$); Washington Air Quality Advisory (wildfire smoke-affected days classified by PM threshold)	Washington State Death Data (geo-coded mortality, ICD-10 codes)
Elliott, 2013	Time series analysis of fine particulate matter and asthma reliever dispensations in populations affected by forest fires	BC Ministry of Environment air quality monitoring network ($PM_{2.5}$, PM_{10}); MODIS (smoke plumes, fire radiative power FRP)	BC PharmaNet database (daily pharmaceutical dispensations: inhaled salbutamol sulfate)
Fann, 2018	The health impacts and economic value of wildland fire episodes in the US: 2008-2012	CMAQ ($PM_{2.5}$): CONUS WRF (meteorological fields); HMS and Sonoma Technology SMARTFIRE 2 (fire emissions); USFS Wildland Fire Assessment System (fuel moisture); Fire Emission Production Simulator (emission factors); Biogenic Emissions Inventory System (biogenic emissions)	EPA BenMAP-CE; CDC WONDER (premature deaths); HCUP (hospital admissions)
Gan, 2017	Comparison of wildfire smoke estimation methods and associations with cardiopulmonary-related hospital admissions	EPA AQS and Washington Dept of Ecology, WRF-Chem model, aerosol optical depth (AOD) from NASA Terra and Aqua satellites ($PM_{2.5}$); NOAA HMS (background $PM_{2.5}$)	Washington State Department of Health Comprehensive Hospital Abstract Reporting System (CHARS) (ED visits for respiratory and cardiovascular conditions)
Haikerwal, 2021	Wildfire smoke exposure and respiratory health outcomes in young adults born extremely preterm or extremely low birthweight	Online survey (self-reported location, proximity/timing in relation to Black Summer Wildfires)	Victorian Infant Collaborative follow up study - online questionnaire (proximity to wildfire, respiratory health and symptoms, overall health and symptoms, health services usage, medication uptake related to wildfire smoke exposure)
Heaney, 2022	Impacts of fine particulate matter from wildfire smoke on respiratory and cardiovascular health in California	GEOS-Chem ($PM_{2.5}$), NCEI (mean temperature)	CA Office of Statewide Health and Development (hospital visits for all respiratory and cardiovascular diseases)
Heft-Neal, 2022	Associations between wildfire smoke exposure in pregnancy and risk of preterm birth in California	NOAA's HMS (smoke plume)	Vital Records Department of Health in California (birth certificates, birth outcomes: gestational age)
Henderson, 2021	Staying ahead of the epidemiological curve: Evaluation of the British Columbia Asthma Prediction System (BCAPS) during the unprecedented 2018 wildfire season	Optimized Statistical Smoke Exposure Model (OSSEM)($PM_{2.5}$)	BC PharmaNet database (dispensations salbutamol sulfate inhalers)
Holstius, 2012	Birth weight following pregnancy during the 2003 Southern California wildfires	Defined potential exposure windows using California Department of Forestry and Fire Protection Moderate Resolution Imaging Spectroradiometer (MODIS) satellite imagery	California Automated Vital Statistics System provided by California's Center for Health Statistics at the California Department of Health Services
Howard, 2021	SOS! Summer of Smoke: A retrospective cohort study examining the cardiorespiratory impacts of a severe prolonged wildfire season in Canada's high subarctic	Yellowknife Air Quality Monitoring station ($PM_{2.5}$, PM_{10})	Stanton Territorial Hospital (ED visits and hospital admissions for cardiorespiratory diagnoses); Local outpatient pharmacy data (medication dispensations - salbutamol)
Hutchinson, 2018	The San Diego 2007 wildfires and Medi-Cal emergency department presentations, inpatient hospitalizations, and outpatient visits: An observational study of smoke exposure periods and a bidirectional case crossover analysis	Wildland Fire Emissions Information System (WFEIS) geospatial tool (wildland fire emissions); HYSPLIT ($PM_{2.5}$), Remote Automated Weather Station database (temperature, relative humidity)	CA Department of Health Care Services (DHCS) Management Information System/Decision Support System (MIS/DSS) data warehouse (ED visits, hospital admissions for cardiovascular and respiratory diagnoses)
Huttunen, 2012	Low-level exposure to ambient particulate matter is associated with systemic inflammation in ischemic heart disease patients	Fixed outdoor air pollution monitoring system (particle number concentration, $PM_{2.5}$); portable monitoring system ($PM_{2.5}$); municipal measurement station in city of Kotka Environment Center (PM_{10}, temperature, relative humidity)	Kymenlaasko Central Hospital and Health Care Center Kotka, Finland - ischemic heart disease patients (Health Questionnaire: health status, medications, lifestyle factors; blood samples: inflammatory markers)
Hyde, 2021	The Fort McMurray Mommy Baby Study: A protocol to reduce maternal stress due to the 2016 Fort McMurray Wood Buffalo, Alberta, Canada Wildfire	General exposure/proximity to event	Maternal Psychological health, Psychosocial Factors, and other maternal Measures (stress, anxiety, depression scales, coping styles, resilience, social support); Developmental milestones (infant development, language ability, social-emotional development); Face to face assessments (Anthropometric Measures and Body Composition, cognitive and motor function, attachment relationships, emotional availability)

Citation	Title	Exposure Metric	Health Metric
Isaac, 2021	A systematic Review of the Impact of Wildfires on Sleep Disturbances	General exposure/proximity to event	Clinician Administered PTSD Scale, The Sleep Medicine History, and Sleep-Disordered Breathing Diagnostic Criteria (sleep disturbances, PTSD)
Kiser, 2020	Particulate matter and emergency visits for asthma: a time-series study of their association in the presence and absence of wildfire smoke in Reno, Nevada, 2013-2018	Washoe County Health District Air Quality Management Division (WCHD-AQMD), Reno air quality monitors ($PM_{2.5}$, $PM_{10-2.5}$, PM_{10}, NO, Ozone, HYSPLIT, visibility); KRNO weather station (temperature, relative humidity)	Renown Health EHR (UC and ED visits: asthma)
Kiser, 2021	SARS-CoV-2 test positivity rate in Reno, Nevada: association with $PM_{2.5}$ during the 2020 wildfire smoke events in the western US	EPA FEM ($PM_{2.5}$); KRNO weather station (temperature, humidity)	Renown Health EHR (SARS-CoV-2 nucleic acid amplification (NAA) positive test)
Koman, 2019	Mapping modeled exposure of wildland fire smoke for human health studies in California	CMAQ (modeled $PM_{2.5}$), BlueSky framework (wildfire emission sources), SmartFire2 fire information system (satellite detections, incident reports, GEOMAC perimeters), Fuel Characteristic Classification System (FCCS) (fuel type and loading data), IMPROVE monitor network ($PM_{2.5}$)	CDC Environmental Public Health Tracking Network (ED visits for asthma and hospitalizations for heart attacks); CDC WONDER (live births)
Korsiak, 2022	Long-term exposure to wildfire and cancer incidence in Canada: a population-based observational cohort	National Burned Area Composite (burn areas)	1996 Canadian Census Health and Environment Cohort (CanCHEC) (lung cancer, brain tumors, non-Hodgkin lymphoma, multiple myeloma, leukemia)
Landguth, 2020	The delayed effect of wildfire season particulate matter on subsequent influenza season in a mountain west region of the USA	AQM Stations, MODIS ($PM_{2.5}$)	Montana HHS (positive influenza diagnoses)
Leibel, 2020	Increase in pediatric respiratory visits associated with Santa Ana Wind–driven wildfire smoke and $PM_{2.5}$ levels in San Diego County	MODIS (satellite images), FRAP (perimeter), National Centers for Environmental Predictions - National Center for Atmospheric Research (Santa Ana winds), EPA AQS ($PM_{2.5}$)	Rady Children's Hospital EHR (ED and UC visits for respiratory conditions)
Li, 2021	Exposure to landscape fire smoke reduced birthweight in low- and middle-income countries: findings from a siblings-matched case-control study	GEOS-chem ($PM_{2.5}$), GFED (fire emissions)	USAID Demographic and Health Surveys (DHS) database (birthweight, birth month)
Liu, 2017a	Wildfire-specific fine particulate matter and risk of hospital admissions in urban and rural counties	EPA AirData, GFED, GEOS-Chem ($PM_{2.5}$); NOAA NCEI (temperature)	Medicare Cohort Air Pollution Study (MCAPS) (hospital admissions for cardiovascular and respiratory diseases)
Liu, 2017b	Who among the elderly is most vulnerable to exposure to and health risks of find particulate matter from wildfire smoke?	GFED (daily emissions); EPA AQS via AirData ($PM_{2.5}$)	Medicare claims data (discharge codes: COPD, respiratory tract infections)
Liu, 2021	Health impact assessment of the 2020 Washington state smoke episode: Excess health burden attributable to increased $PM_{2.5}$ exposures and potential exposure reductions	Washington Department of Ecology - Washington's Air Monitoring Network ($PM_{2.5}$)	CDC WONDER, US Census (health impact assessment: all-cause mortality and cardiorespiratory diseases mortality)
Mahsin, 2021	Respiratory and cardiovascular condition-related physician visits associated with wildfire smoke exposure in Calgary, Canada, in 2015: a population-based study	AQM stations in Alberta and Calgary (CH_4, NO, O_3, $PM_{2.5}$, CO, NO_x, SO_2, hydrogen sulfide (H_2S), non-methane hydrocarbons and total hydrocarbons, temperature, relative humidity, wind speed and direction)	Practitioner Claims Database (asthma, COPD, ARI, pneumonia, acute bronchitis, emphysema, ischemic heart disease, congestive heart failure, myocardial infarction, cardiac arrest, stroke, angina, hypertension, and diabetes mellitus)
Masri, 2021	Disproportionate impacts of wildfires among elderly and low-income communities in California from 2000-2020	FRAP, NIFC (fire perimeters)	American Community Survey (social vulnerability factors)
Naqvi, 2022	Wildfire-induced pollution and its short-term impact on COVID-19 cases and mortality in California	US Geological survey (AAI, CO, NO_2, ozone); EPA, CAP AQI ($PM_{2.5}$, ozone, NO_2)	Worldometer, Johns Hopkins (COVID-19 cases and deaths)
Neumann, 2021	Estimating $PM_{2.5}$-related premature mortality and morbidity associated with future wildfire emissions in the western US	National Emissions Inventory ($PM_{2.5}$), GFED (wildfire emissions), GEOS-FP (meteorological data), GEOS-Chem (modeled $PM_{2.5}$)	EPA BenMAP - Community edition, CDC WONDER (morbidity and mortality)
O'Dell, 2021	Estimated mortality and morbidity attributable to smoke plumes in the United States: Not just a Western US problem	EPA AQS ($PM_{2.5}$), NOAA HMS (smoke plume), WE-CAN observations (HAP)	Healthcare Cost and Utilization Project (asthma hospitalizations and ED visits); Global Exposure Mortality Model (premature mortality, DALYs)
O'Hara, 2021	Impacts from wildfires on livestock health and production: Producer perspectives	Primary data collection: self-reported experience with wildfires during the 2020 wildfire season	Primary data collection: self-reported outcomes such as lost pasture, skin burns, death, reduced rates of conception, pneumonia, lower birthweights
O'Neill, 2021	A multi-analysis approach for estimating regional health impacts from the 2017 Northern California wildfires	IWFAQRP surface monitors ($PM_{2.5}$), CARB surface monitors ($PM_{2.5}$), EPA AQS ($PM_{2.5}$, ambient air pollution); GOES-16 Advanced Baseline Imaging (FRP), Terra and Aqua MODIS (AOD), SUOMI-NPP VIIRS instrument (fire emissions), WRF-CMAQ (regional air quality monitoring), BlueSky Smoke modeling framework (fire emissions)	CDC WONDER (all-cause mortality); NASA Socioeconomic Data and Applications Center (SEDAC) 2010 Census Grids (demographics)
Park, 2022	The association between wildfire exposure in pregnancy and foetal gastroschisis: A population-based cohort study	California Department of Forestry and Fire Protection (CAL FIRE) data	California Office of Statewide Health Planning and Development (linked birth file, gestational period)
Pazderka, 2021a	Collective trauma and mental health in adolescents: A retrospective cohort study of the effects of retraumatization	Primary data collection: self-reported - Questionnaires - adolescents who experienced Fort McMurray wildfire	Primary data collection self-reported (depression, anxiety, suicidality, PTSD)
Pazderka, 2021b	Model of Post-traumatic growth in newly traumatized vs. retraumatized adolescents	Survey (Wildfire Trauma Exposure)	Survey (friend/family support, anxiety, PTSD, self-efficacy, hopelessness)
Pearson, 2019	A review of coccidioidomycosis in California: Exploring the intersection of land use, population movement, and climate change	Literature review, examples include: PM_{10}, General Exposure/Proximity, Meteorological Data	Literature review, examples include: Lab tests, Serological Tests, Incidence (coccidioidomycosis/valley fever)

Citation	Title	Exposure Metric	Health Metric
Postma, 2022	Promoting risk reduction among young adults with asthma during wildfire smoke: A feasibility study	EPA AirNow Tech ($PM_{2.5}$, daily forecast)	Mobile app (wildfire smoke observations, health symptoms, behaviors); Asthma Control Test; spirometer (FEV)
Rappold, 2017	Community vulnerability to health impact from wildland fire smoke exposure	CMAQ ($PM_{2.5}$): CONUS WRF (meteorological fields); HMS and Sonoma Technology SMARTFIRE 2 (fire emissions); Biogenic Emissions Inventory System (biogenic emissions); USGS GeoMAC (wildfire perimeters)	Community Health-Vulnerability Index (socioeconomic factors, demographics, health outcome measures: Asthma and COPD, Hypertension, Diabetes, Obesity)
Rappold, 2019	Smoke Sense initiative leverages citizen science to address the growing wildfire-related public health problem	Smoke Sense App - AirNow (air quality), NOAA HMS (smoke plumes)	Smoke Sense App - self-report health symptoms (eyes and ears, respiratory, cardiovascular; duration of symptoms, whether medication was used, and whether it required a visit to physician)
Ré, 2021	Cytotoxic effects of wildfire ashes: In-vitro responses of skin cells	Ash samples/Aqueous Extracts of Ash (trace metals)	Immortalized human keratinocyte cells (HaCaT) used for cytotoxicity bioassays (cell viability, cell cycle)
Requia, 2021	Increased preterm birth following maternal wildfire smoke exposure in Brazil	National Institute of Spatial Research of Brazil (wildfire data); Environmental Information System for Health ($PM_{2.5}$, CO, NO_2, ozone); European Centre for Medium-Range Weather Forecast, NOAA, Climate Prediction Center (meteorological and precipitation data)	Ministry of Health in Brazil (birth data: gestational age)
Rodney, 2021	Physical and mental health effects of bushfire and smoke in the Australian Capital Territory 2019-20	General exposure/proximity to event	Online survey (REDCap) - demographics, heath (physical and mental, sleep), previous/current exposure to bushfires, and medical advice seeking
Sannigrahi, 2022	Examining the status of forest fire emissions in 2020 and its connection to COVID-19 incidents in West Coast regions of the United States	OpenAQ (in-situ air pollution measurements)	USAFacts dataset (COVID-19 cases and deaths)
Schwarz, 2022	Smoke and COVID-19 case fatality ratios during California wildfire	NOAA HMS (smoke plumes), US Bureau of Transportation (daily mobility statistics)	CDC COVID Data Tracker (COVID19 cases and deaths)
Shusterman, 1993	Immediate health effects of an urban wildfire	General exposure/proximity to event	Epi-Info, ED Visits and medical records (trauma, burns, chest pain, respiratory disorders, smoke inhalation disorders, medication dispensations); Alameda County Coroner's Office (fatalities); Carboxyhemoglobin (COHb) levels (carbon monoxide poisoning)
Solomon, 2021	Fire and water: Assessing drinking water contamination after a major wildfire	Paradise Irrigation District data; tap water sampling (VOC)	Not Assessed
Sorensen, 2021	Associations between wildfire-related $PM_{2.5}$ and intensive care unit admissions in the United States, 2006-2015	NOAA HMS (smoke plume); EPA AQS ($PM_{2.5}$, PM_{10}, ozone); NOAA National Climate Data Center (meteorological data)	Premier, Inc. - national-scale proprietary hospitalization database. Note that this encompasses 15-20% of all US ICU admissions during the study period
Sugg, 2022	Understanding the concurrent risk of mental health and dangerous wildfire events in the COVID-19 pandemic	Geospatial multiagency coordination (GeoMac)'s National Interagency Fire (fire perimeter)	Crisis Text Link (CTL) (mental health)
To, 2021	The impact of wildfires on mental health: A scoping review	Literature review, examples include: data from BC Ministry of Water, Land and Air Protection, fire event dates/locations	Literature review, examples include primary data collection (mental health: PTSD, depression, anxiety, substance use)
Wan, 2021	Chemical composition of soil-associated ash from the southern California Thomas Fire and its potential inhalation risks to farmworkers	Ash and soil samples (pH, TE, PAHs); Particle Emission Factor (pollutant exposure through inhalation) - dust generator simulation	Toxic Equivalent Factors (modeled respiratory inhalation)
Woo, 2020	Air pollution from wildfires and human health vulnerability in Alaskan communities under climate change	GEOS-Chem ($PM_{2.5}$); IMPROVE network (organic carbon); FAM-WEB (area burned)	US census data/NCHS (social vulnerability)
Yao, 2020	Sub-daily exposure to fine particulate matter and ambulance dispatches during wildfire seasons: A case-crossover study in British Columbia, Canada	1-h Optimized Statistical Smoke Exposure Model (OSSEM-1h) ($PM_{2.5}$)	BC Emergency Health Services (emergency ambulance data); BC Ministry of Health (hospital discharge data): cardiovascular, respiratory, diabetic
Zhou, 2021	Excess of COVID-19 cases and deaths due to fine particulate matter exposure during the 2020 wildfires in the United States	NOAA HMS (smoke intensity), AirNow ($PM_{2.5}$)	USAFacts dataset (COVID-19 cases and deaths)