U.S. EPA Wildland Fire Research

How we can understand and mitigate the public health and environmental impacts of wildland fire

U.S. EPA/Office of Research and Development

TOC
Intro
What's in Smoke
Smoke Measurement
Water & Ecosystems
Human Health
Reducing Exposures
Future Directions

Table of Contents

1 Introduction to EPA's Wildland Fire Research

2 What is in smoke?

3 How to measure smoke emissions and air quality during smoke events?

4 What are the impacts of wildland fire on water quality and ecosystems?

5 What are the impacts of wildland fire smoke on human health?

6 What have we learned about reducing exposures to smoke?

7 Future Directions

1. Introduction to EPA's Wildland Fire Research

To support EPA's mission of protecting human health and the environment, EPA has studied the health and environmental impacts from wildland fires for over a decade.

Purpose

This briefing book contains EPA's completed research on the effects of wildland fire (i.e., wildfire and prescribed fire) smoke on air quality, the effects of wildland fire on water quality and ecosystems, the effect of smoke on public health, and actions that can be taken to reduce exposures to smoke. While we recognize that other federal agencies, educational institutions, etc., also conduct research on wildland fire impacts, this briefing book only covers EPA research.

Audience

This information is intended for state, local and Tribal air and water quality managers, health care professionals, and researchers. It also can be a resource for people impacted by smoke or fires.

Structure

Each section addresses a broad environmental issue related to wildland fires. Underlying sub-sections explore the issue through more refined research questions. Each sub-section begins with the peer-reviewed journal article, then presents the research through the commonly-used "Challenge, Approach, Result, Impact" structure. The sub-section closes with related resources, such as a website, if available.

Background Information on Wildland Fires

Fires occur naturally and play an important role in promoting healthy ecosystems in many landscapes across the United States. While the number of wildland fires over the past several decades has remained relatively constant, larger wildland fires in the western U.S. have become more frequent, as reported in the 5th National Climate Assessment. The increase in acres burned can be attributed to several factors, including more than 100 years of fire suppression that has resulted in a build-up of burnable material, and a changing climate with hotter and drier conditions. Collectively these factors contribute to the increasing size and severity of wildfires. In addition, as the wildland-urban interface (WUI) continues to grow, so does the risk that wildland fires will threaten communities.

In contrast to low-intensity wildland fires, high-severity wildfires – with their rapid spread and intense heat – have negative consequences for ecosystems and humans. In the aftermath, burned areas are prone to flooding and erosion. Ash and contaminants from smoke can settle in water reservoirs, streams, and lakes, and pollute drinking water and aquatic ecosystems.

Wildland fire smoke is a complex mixture of pollutants, and exposure can worsen respiratory and cardiovascular diseases, in some cases resulting in death. Communities near fires, as well as those far downwind of them, can be exposed to smoke.

TOC
Intro
What's in Smoke
Smoke Measurement
Water & Ecosystems
Human Health
Reducing Exposures
Future Directions

How does EPA decide what research is needed?

EPA is one of the world's leading environmental and human health research organizations. The Office of Research and Development (ORD) is EPA's scientific research arm and provides the foundation for EPA's credible decision-making to safeguard human health and ecosystems from environmental pollutants. Through its National Laboratories, Centers, and National Research Programs, as well as collaborations with federal, state, local and Tribal agencies and other organizations, ORD is well-positioned for this work.

Intramural research

EPA prepares strategic research plans- developed with considerable input from multiple stakeholders including state, local and Tribal environmental agencies, other federal agencies, and the broader scientific community – to guide future work. Recent plans (Air, Climate, and Energy Strategic Research Action Plan FY2023-FY2026 and Air and Energy Strategic Research Action Plan 2019 to 2022) included wildland fire research. EPA's recent wildland fire research follows the EPA Wildland Fire Research Framework 2019-2022 and reflects State and Tribal Wildland Fire Issues heard during listening sessions in 2021. Additional information is available at EPA's Wildland Fire Research website.

In partnership with stakeholders, EPA identified key research questions and used those to shape EPA's wildland fire research direction and goals:

- Study health effects of smoke and evaluate potential solutions to reduce impacts.
- Develop and improve methods to measure smoke emissions and models that predict smoke exposure.
- Assess impacts to drinking water from wildland fires.
- Identify and help protect susceptible human populations and ecosystems.
- Evaluate communication strategies to find effective ways to reduce risks.

Extramural programs

EPA also taps external expertise through the following programs:

- The Science to Achieve Results (STAR) Program leverages the scientific and engineering expertise of academic and non-profit institutions to conduct high priority environmental and public health research.
- The Small Business Innovation Research (SBIR) Program funds small businesses to develop and commercialize innovative environmental technologies in broad focus areas which include air quality, and clean and safe water.
- EPA Challenges & Prizes help bring the public's ingenuity and creativity to find solutions to an environmental challenge.

For over a decade, EPA researchers have used both intramural research and extramural programs to tackle complex issues about the impacts of wildland fires. By filling gaps in scientific information and developing resources and tools, researchers have helped EPA and partners respond to increasing health and environmental risks and impacts caused by wildland fire smoke and water quality degradation.

1.1 Definitions

Air Quality Index: The Air Quality Index, or AQI, is EPA's tool for communicating about outdoor air quality and health and can be seen on EPA's AirNow, a one-stop source for air quality data. The AQI is divided into six categories; each category has a different color and corresponds to a different level of health concern. The higher the AQI value, the greater the level of air pollution and the greater the health concern.

Ambient Air Quality Measurements: Air quality can be assessed using different technology and devices. **Air monitoring** uses electronic devices to provide real-time (or near real-time) readings of contaminants in the air. **Air sampling** uses a device that captures ambient air in a container and can be used to measure the amounts of contaminants over a given time duration; the sample is sent to a laboratory for analysis and the specific compounds are then identified and quantified.

Air Sensor: Air sensors refer to a type of air monitoring technology that is commonly less expensive, smaller, and often easier to operate compared to regulatory-grade air monitors. With a compact design that supports use in many locations, air sensors are widely used in the United States to understand air quality conditions. While air sensors can offer real-time data, the data quality can be highly variable and does not meet the stringent requirements needed for regulatory purposes. Related resource: EPA's Air Sensor Toolbox.

Biomass: Material from plants and animals. A common example is wood.

Disinfection by-products (DBPs): Chemicals that can form in drinking water treatment systems when chlorine reacts with organic matter during the disinfection process.

Emission factor: A value that relates the quantity of an emitted pollutant with an activity. For wildland fire smoke, emission factors will be specific to the different fuel layers and tree species that are burned.

Emissions inventory: A set of data that lists the amount of air pollutants emitted into the air, by source, over a period of time. Learn more.

FRM and FEM: Federal Reference Methods (FRMs) and Federal Equivalent Methods (FEMs) are ambient air criteria pollutant monitoring methods designated as appropriate for regulatory use by the EPA. These methods are designated in accordance with Title 40, Part 53 of the Code of Federal Regulations (40 CFR Part 53). Related resource: Ambient Monitoring Technology Information Center (AMTIC). Another related resource offers a discussion of the complementary nature of regulatory air monitoring instruments and non-regulatory sensor-based instruments: EPA's Tools and Resources Webinar: FRMs/FEMs and Sensors: Complementary Approaches for Determining Ambient Air Quality.

National Ambient Air Quality Standards (NAAQS): The Clean Air Act requires EPA to set national air quality standards for six commonly found "criteria" air pollutants which can be harmful to public health and the environment. (40 CFR part 50)

National Primary Drinking Water Regulations (NLDWR): EPA has established protective drinking water standards for more than 90 contaminants, which establish maximum contaminant levels (MCLs). These are the legal threshold limit on the amount of a substance that is allowed in public water systems under the Safe Drinking Water Act.

Prescribed Fire: "Any fire intentionally ignited by management actions in accordance with applicable laws, policies, and regulations to meet specific land or resource management objectives." (40 CFR § 50.1) Also called planned fires, controlled burns, or prescribed burns.

Pollutants: Any substances in water, soil, or air that degrade the natural quality of the environment, offend the senses of sight, taste, or smell, or cause a health hazard. The usefulness of the natural resource is usually impaired by the presence of pollutants and contaminants (EPA Terms and Acronyms).

Air pollutants of relevance to this briefing book:

- "Criteria" air pollutants: six commonly found air pollutants (ground-level ozone (O_3), particle pollution (PM), carbon monoxide (CO), sulfur dioxide (SO_2), and nitrogen dioxide (NO_2) regulated by the NAAQS. SO_2 is used as the indicator for the larger group of sulfur oxides (SO_x); NO_2 is used as the indicator for the larger group of nitrogen oxides (NO_x).
- Particle pollution, or particulate matter: a mixture of solid particles and liquid droplets found in the air. Fine particulate matter ($PM_{2.5}$) refers to inhalable particles with diameters generally 2.5 micrometers or smaller. (By contrast the average human hair is 70 micrometers in diameter, or 30 times larger than the largest fine particle.)
- Hazardous air pollutants (HAPs), or toxic air pollutants or air toxics: pollutants known or suspected to cause cancer and other serious health impacts, such as reproductive effects or birth defects, or adverse environmental effects.
- Volatile organic compounds (VOCs): certain compounds of carbon emitted from a wide array of products which participate in atmospheric photochemical reactions. (40 CFR § 50.100)

Water pollutants of relevance to this briefing book:

- Inorganic chemicals: salts and metals that may occur naturally or be the result of industrial, agricultural or other human activities; includes arsenic and nitrate. Regulated by the NLDWR.
- Disinfection byproducts: form when disinfectants used to treat drinking water react with naturally occurring materials in the water. Regulated by the NLDWR.

Slash pile: Slash piles are woody debris that remain after mechanical thinning or cutting of trees in the forest.

Solutions-driven research: An integrated and transdisciplinary research approach that brings together the diverse expertise of scientists, practitioners and stakeholders to identify solutions to socio-ecological challenges. The priority is finding practical solutions to real-world problems. Stakeholder involvement in identifying the problems is crucial.

Wildfire: Any fire started by an unplanned ignition caused by lightning; volcanoes; other acts of nature; unauthorized activity; or accidental, human-caused actions, or a prescribed fire that has developed into a wildfire. A wildfire that predominantly occurs on wildland is a natural event. (40 CFR § 50.1)

Wildfire Smoke: Wildfire smoke is a complex mixture of gaseous pollutants (e.g., carbon monoxide), hazardous air pollutants (HAPs) (e.g., polycyclic aromatic hydrocarbons [PAHs]), water vapor, and particle pollution.

Wildland Fire: Any non-structure fire that occurs in vegetation or natural fuels; includes both wildfire and prescribed fire. (National Wildfire Coordinating Group Glossary of Terms)

Wildland-Urban Interface (WUI): The WUI is the zone of transition between unoccupied land and human development. It is the line, area or zone where structures and other human development meet or intermingle with undeveloped wildland or vegetative fuels. (U.S. Fire Administration)

TOC
Intro
What's in Smoke
Smoke Measurement
Water & Ecosystems
Human Health
Reducing Exposures
Future Directions

2. What is in smoke?

EPA researchers developed, tested, and applied air measurement technologies to understand and measure smoke emissions.

In addition to the destruction and direct loss of life caused by wildland fires, the smoke they produce is a significant source of air pollution and is harmful to public health and ecosystems.

Because the pollutants in smoke vary with the fuel that is burned, EPA researchers have developed, tested, and applied air measurement technologies to understand smoke emissions and to measure the concentrations of pollutants from different types of fires.

With the growth of the wildland-urban-interface (WUI), there are instances of wildfire entering it and burning human-made structures and materials. The emissions from WUI fires can potentially contain greater amounts of hazardous air pollutants. The combination of more toxic emissions and the proximity to population centers makes WUI fires a unique threat to public health. However, areas further away can also be impacted because WUI fires can mobilize trace metals, and the smoke can carry the pollution far downwind.

2.1 Smoke from WUI Fires: Chemical Composition

2.2 Smoke from WUI Fires: Estimating Smoke Emissions

2.3 Smoke from Different Forest Types: Quantifying Smoke Emissions

2.4 EPA's Wildfire Smoke Emissions Inventory

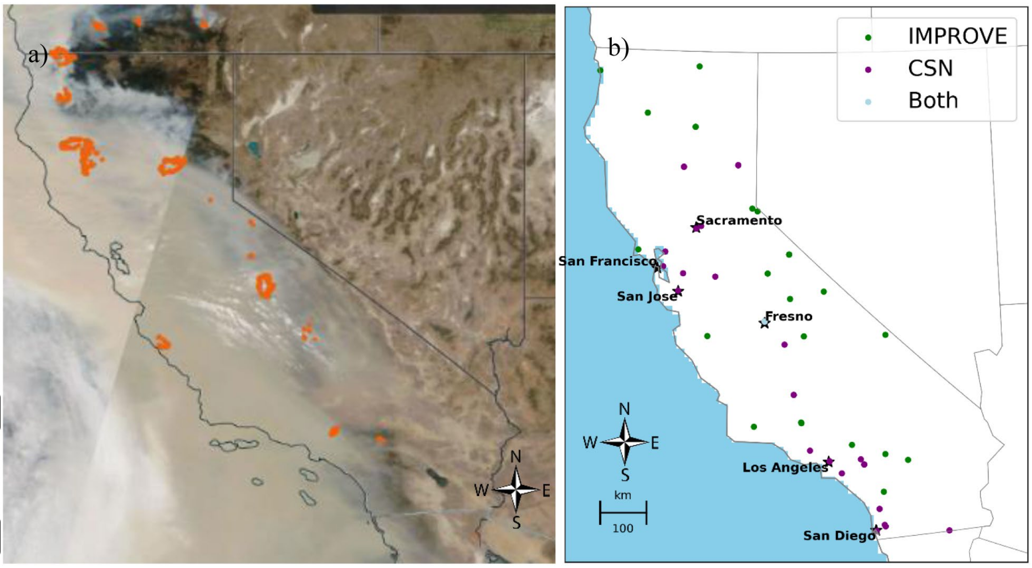
TOC
Intro
What's in Smoke
Smoke Measurement
Water & Ecosystems
Human Health
Reducing Exposures
Future Directions

2.1 Smoke from WUI Fires: Chemical Composition

➢ Beyond particulate matter mass: heightened levels of lead and other pollutants associated with destructive fire events in California (2023)

Challenge: What chemicals are emitted during wildland fires? We want to understand what is in smoke so we can better communicate appropriate actions that reduce the risks to public health.

Approach: To understand what chemicals are associated with the particulate matter in wildfire smoke, especially from WUI fires, EPA researchers analyzed 13 years (2006–2018) of $PM_{2.5}$ chemical composition data on smoky days. During this period, California experienced multiple destructive WUI fires. California also has one of the most extensive networks of $PM_{2.5}$ speciation air monitors in the U.S., which provide a detailed analysis of smoke, and researchers analyzed chemical data downwind of several specific fires.



Satellite image of smoke over California on September 10, 2020, with active fires shown as superimposed orange dots (left); and a map of Air Quality System $PM_{2.5}$ speciation network monitors (right). Source: Figure 1 in journal article.

Result: All types of fires produce certain chemicals, such as magnesium, aluminum, and calcium, and many of these (e.g., aluminum and sulfate) were statistically elevated on smoke-impacted days in over half of the years studied. However, WUI fires appear to have a unique chemical profile. Smoke from WUI fires contains other chemicals, mostly trace metals that are harmful to human health, including copper, lead, and zinc. Elevated concentrations of these metals were associated with the burning of structures; for instance, in 2018, lead was more than 40 times higher on smoke days, on average, at the Point Reyes monitoring station, likely attributable to the Camp Fire burning approximately 200 kilometers away.

Impact: The difference in the chemical composition of smoke, specifically an increase in toxic metals due to structural burning, has potential implications for public health and ecosystems, especially in downwind communities.

Related research investigating chemical composition of smoke and downwind impacts:

➢ Wildfires in the western United States are mobilizing PM2.5-associated nutrients and may be contributing to downwind cyanobacteria blooms (2023)

➢ Wildfires Increase Concentrations of Hazardous Air Pollutants in Downwind Communities (2023)

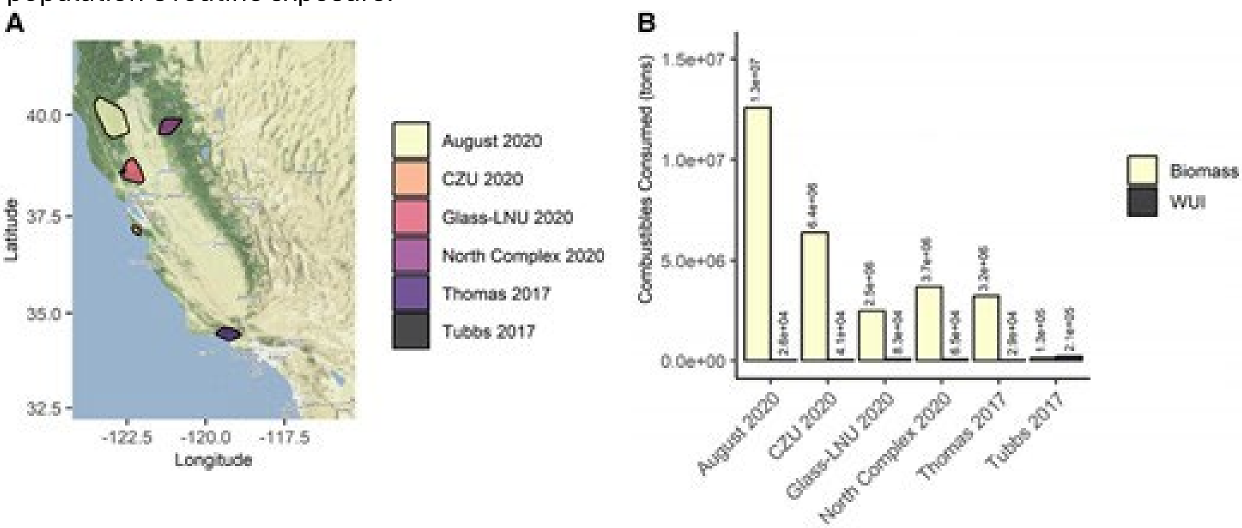
➢ Effects of Air Pollutants from Wildfires on Downwind Ecosystems: Observations, Knowledge Gaps, and Questions for Assessing Risk (2023)

2.2 Smoke from WUI Fires: Estimating Smoke Emissions

- Hazardous air pollutant emissions estimates from wildfires in the wildland urban interface (2023)
- Correction to: Hazardous air pollutant emissions estimates from wildfires in the wildland urban interface (2024)

Challenge: How different is smoke from a WUI fire burning human-made structures compared to smoke from a “normal” wildfire burning natural vegetation? A better understanding helps guide future measurement efforts, develop emissions inventories (detailed estimates of emissions into the air), and inform the public about health risks.

Approach: California wildfires in 2017 and 2020 included a variety of WUI fires, ranging from those with a very large burn area consuming primarily biomass fuels (such as the August 2020 Fire) to those with a relatively small burn area consuming large numbers of structures and vehicles (such as the Tubbs 2017 Fire). EPA researchers compared the emissions from each wildfire with emissions from other air pollution sources to provide a frame of reference for a population’s routine exposure.



Location of the fires (left) and the relative amounts of combustible materials (right). Source: Figure 3 in original journal article.

Result: Emissions from WUI fires were minimal for most criteria pollutants and much lower than wildfire emissions for oxygenated hydrocarbon species (e.g., formaldehyde, acetaldehyde) – not surprising as these emissions are associated with biomass burning. While WUI fires may not significantly contribute to elevated levels of criteria air pollutants or greenhouse gases, WUI fires can be a sizeable source of certain hazardous air pollutants. Researchers developed emission factors (EFs) that relate the quantity of a pollutant emitted with a burning activity to improve estimates of the emissions from WUI fires versus wildfires. The EFs for some toxic compounds like polycylic aromatic hydrocarbons (PAH) and toxic organic compounds were 5 – 2,500 times greater for WUI fires than those from natural fuels.

Impact: Emission inventories play an important role in identifying the major sources of air pollution. As WUI fires are a potential major source of hazardous air pollutants, this study is a critical first step to improving emissions inventories, which, until now, had not included structural fires.

2.3 Smoke from Different Forest Types: Quantifying Smoke Emissions

➤ Fuel layer specific pollutant emission factors for fire prone forest ecosystems of the western U.S. and Canada (2022)

Challenge: How can we evaluate smoke emissions between prescribed fire and wildfire scenarios in the western U.S.? To do so, EPA performed laboratory experiments for specialized information, called emission factors (EFs), that relate the quantity of air pollutant emissions in the smoke to the fire scenario. With accurate EFs we can estimate emissions for a particular activity, which helps us make decisions about the impacts of smoke on public health and build a national inventory of emissions.

Approach: Since the composition of smoke depends on the fuel type (tree species), EPA researchers considered the prevalent fuel types (black spruce, jack pine, Douglas fir, western larch and ponderosa pine) found in western U.S. forests, and the fire conditions (smoldering or flaming) often encountered with prescribed fires.

EPA collaborated with the US Forest Service to analyze gas and particle measurements in smoke from multiple fuel types of each species including downed needles, fine woody debris (dead branches and twigs), cones, litter (undecomposed or partially decomposed organic material) and canopy fuels (branches with live needles).

Laboratory analysis of smoke using a large-scale combustion chamber.

Result: Results include fuel-type specific EFs for criteria pollutants (CO, NO_x, SO_2, $PM_{2.5}$), ozone precursors, greenhouse gases (CO_2, CH_4) and hydrogen cyanide (HCN), an atmospheric tracer of biomass burning. The study found that the average EFs for NO_x and SO_2 were similar across all fuel types but EFs for $PM_{2.5}$ had the highest average value from the ponderosa pine needles and cones, and in general, increased when combustion efficiency was lower.

While the average EFs were similar across the ponderosa pine fuelbeds, one notable exception was the EF for methane (CH_4), which was 60% higher for the ponderosa pine needles and cones as compared with just the needles or the needles and fine woody debris.

Impact: The study addressed gaps in EFs for two forest types - Douglas fir canopy fuels, and black spruce/jack pine surface fuel – that are a significant part of western U.S. forests and was the first to quantify EFs for cones from ponderosa pine, an important component of the litter layer. With this knowledge, we can evaluate the consequences of the emissions due to different land management strategies, such as prescribed fires. This information helps land management agencies understand the public health impacts of the smoke emissions from prescribed fires vs. wildfires.

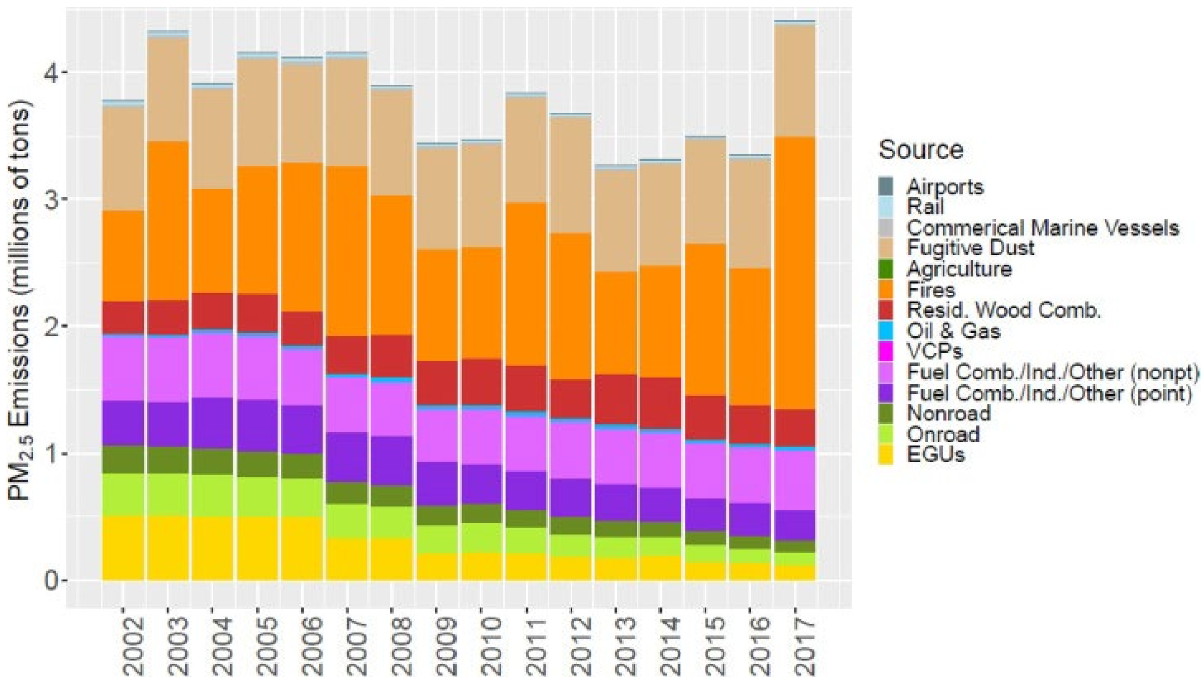
2.4 EPA's Wildfire Smoke Emissions Inventory

- [2002–2017 anthropogenic emissions data for air quality modeling over the United States](#) (2023)

Challenge: How can we accurately estimate emissions – including emissions from wildland fire smoke – so that we can model air quality as it changes over time? Accurate and consistent emission estimates are needed in regional air quality modeling, which we use to study air quality impacts on human health and ecosystems over time spans of decades, as we do in EPA's National Air Quality Trends reports.

Approach: As part of EPA's Air QUAlity TimE Series (EQUATES) Project, EPA researchers developed a consistent set of long-term emissions inputs spanning the years 2002 through 2017. To update the wildland fire emissions data, EPA researchers combined national fire activity data from multiple federal agencies through the BlueSky Framework, and generated emissions data using an approach that accounted for changes in methodology over the sixteen-year period.

Result: The EQUATES Project provided a multiyear set of updated emissions data for 14 source categories. The "Fires" category now includes reanalyzed (EQUATES Multi-Year Reanalysis of EPA's Fire Emissions Inventory) information that includes biomass burning from wildfires, prescribed fires, cropland fires, and grass or rangeland fires. The figure below shows the contributions to annual PM2.5 emissions from each source, including "Fires."



Annual total $PM_{2.5}$ emissions (10^6 short tons) by source (e.g., airports, fires) over the conterminous U.S. Source: Figure 5 in journal article.

Impact: Having a consistent set of emissions data, including for fires, is foundational for running simulations of air quality that allow decision makers to explore the effects of air quality management strategies and look at trends over time.

Related resources:

- 2004-2017 Geospatial Dataset of Wild and Prescribed Fire Activity Over the Conterminous United States (2024)

TOC
Intro
What's in Smoke
Smoke Measurement
Water & Ecosystems
Human Health
Reducing Exposures
Future Directions

3. How to measure smoke emissions and air quality during smoke events?

EPA researchers use smoke measurements to 1) improve smoke forecasting models, 2) examine the effects of longer-duration smoke exposures on human health, 3) develop preparedness and mitigation strategies for the future, and 4) understand the broader implications to air quality of increased wildfire and prescribed fire frequency and wildfire intensity.

During wildland fire smoke events, people rely on timely public health warnings to help them take appropriate actions. Those warnings rely on accurate and real-time air pollution measurements. While the nation's established ambient air monitoring network does not cover all locations affected by wildland fire smoke, sensors can help fill those data gaps. However, air monitoring technologies had not been tested or validated under high smoke concentration conditions, leading to uncertainties about their accuracy and robustness.

Because of the increase in wildfire area burned and severity across the U.S. in recent decades, there is interest in expanding the use of prescribed fires. Prescribed fires can be a forest management tool to remove excess fuel and reduce the risk of wildfire, but we need to understand the air quality impacts of fire management strategies that include prescribed fires compared with strategies that do not.

3.1 Uncrewed Aircraft System for Safe Sampling of Wildfire Smoke

3.2 Performance of Continuous Air Quality Monitors in Smoky Conditions

3.3 Performance of Small Filter-based Air Samplers to Measure Smoke

3.4 Challenge: Wildland Fire Sensors

3.5 Evaluation of Particulate Matter Sensors for Measuring Wildfire Smoke

3.6 Including Sensor Data on the AirNow Fire and Smoke Map

3.7 Wildfire Smoke Air Monitoring Response Technology (WSMART)

3.8 Prescribed Fires vs Wildfires: a Comparative Assessment

TOC
Intro
What's in Smoke
Smoke Measurement
Water & Ecosystems
Human Health
Reducing Exposures
Future Directions

3.1 Uncrewed Aircraft System for Safe Sampling of Wildfire Smoke

➤ Wildland fire emission sampling at Fishlake National Forest, Utah using an uncrewed aircraft system (2021)

Challenge: How can we measure $PM_{2.5}$ emissions from smoke during either a wildfire or prescribed fire while also keeping people and equipment out of harm's way?

The Kolibri being used to collect gas and particle samples from smoke generated by the June 2019 Crown fire, Utah. Photo credit: Jesse Juchtzer.

Approach: As part of EPA's wildland fire measurement research, researchers in the Mobile Ambient Smoke Investigation Capability (MASIC) study used an uncrewed aerial system ("UAS" or "drone") known as the Kolibri for aerial emission measurements. During the June 2019 Crown fire in the Fishlake National Forest of south-central Utah, the Kolibri was used to safely obtain and characterize gas and particle samples over three days during different stages of the prescribed fire: first slash piles (i.e., forest debris collected into piles on the ground) were burned, then the crowns (i.e., the tops of trees) of large stands (over a thousand hectacres) were ignited.

Result: Researchers flew sixteen flights and collected a sample for each flight using the Kolibri, plus one ground-based and one background ambient air sample. Researchers identified two key findings: 1) $PM_{2.5}$ emission factors varied 5-fold with emissions typically decreasing as the combustion efficiency increased, and 2) lower emission factors were measured from the burning of slash piles, compared to burning forest crowns.

Impact: This was the first time an uncrewed aircraft system (UAS) was used to sample smoke emissions for a prescribed fire with wildfire-like conditions, and the Kolibri allowed unprecedented access to capture fresh smoke, while minimizing risk to the operators and equipment. This flexibility allows us to better understand how $PM_{2.5}$ emissions vary with the fuel type (i.e., the materials burned) and fire conditions (i.e., smoldering or flaming).

Read more about the MASIC study at Studies Advance Air Monitoring During Wildfires and Improve Forecasting of Smoke.

3.2 Performance of Continuous Air Quality Monitors in Smoky Conditions

- Summary of $PM_{2.5}$ measurement artifacts associated with the Teledyne T640 PM Mass Monitor under controlled chamber experimental conditions using polydisperse ammonium sulfate aerosols and biomass smoke (2023)

A large-scale combustion chamber was used to evaluate continuous $PM_{2.5}$ air quality monitor measurements during smoke events. Fire test bed (left) and instruments (right).

Challenge: Continuous $PM_{2.5}$ air quality monitors are widely-used, automated, and provide real-time measurements, including during wildland fire events. However, smoke particles can interfere with how $PM_{2.5}$ is measured and make it challenging to obtain accurate data. How can we evaluate the use of continuous monitors in smoky conditions?

Approach: As part of EPA's wildland fire measurement research, researchers in the Mobile Ambient Smoke Investigation Capability (MASIC) study evaluated two continuous $PM_{2.5}$ air quality monitors (Teledyne API Model T640, Met One BAM 1022) against a filter-based $PM_{2.5}$ air quality monitor designated as a Federal Reference Method (FRM) - and the gold standard in accuracy - in high smoke conditions. The performance tests were conducted in two laboratory burn chambers with fuels of ponderosa pine, larch, and Douglas fir needles, cones, and fine woody debris.

Results: Researchers observed that the T640 had large positive and negative measurement artifacts and should be used with caution. The BAM1020 performs better in smoke and is comparable to the filter-based FRM in smoky conditions.

Impact: The findings from this research raise concerns that routine regulatory monitoring and wildland fire research study $PM_{2.5}$ measurements using optical measurement monitors may be reporting inaccurate data during smoke impacted events. State and local air monitoring agencies can immediately make use of this information to evaluate their monitoring programs.

Read more about the MASIC study at Studies Advance Air Monitoring During Wildfires and Improve Forecasting of Smoke.

3.3 Performance of Small Filter-based Air Samplers to Measure Smoke

- Evaluation of small form factor, filter-based $PM_{2.5}$ samplers for temporary non-regulatory monitoring during wildland fire smoke events (2021)

Challenge: One of the ways that ambient air quality is routinely measured is by filter-based $PM_{2.5}$ regulatory monitors. However, these instruments, which require a considerable investment in infrastructure, are not generally available in remote areas. However, rugged, lightweight, battery powered $PM_{2.5}$ filter-based air samplers (made possible by advancements in microelectronics and battery technology) could fill these spatial gaps. How do these smaller sized filter-based air samplers perform relative to regulatory-grade air quality monitors during wildfire smoke events?

Approach: As part of EPA's wildland fire measurement research, researchers in the Mobile Ambient Smoke Investigation Capability (MASIC) study partnered with the USDA Forest Service Rocky Mountain Research Station to evaluate the performance of three models of commercially-available filter-based $PM_{2.5}$ samplers against filter-based $PM_{2.5}$ FRM air quality monitors. Researchers systematically evaluated performance in a controlled burn combustion chamber operated by the USDA Forest Service and during typical ambient conditions.

Smoke plumes from a wildland fire.

Result: All samplers performed well in determining total $PM_{2.5}$ concentrations with accuracies ranging from 93.1 to 98.2%. One sampler provided $PM_{2.5}$ mass measurement accuracies that met regulatory monitor performance specifications.

Impact: The results provide confidence that small-sized, filter-based samplers can provide scientifically and regulatory relevant PM2.5 concentration data at lower cost and with easier deployment during wildland fire smoke events. All the samplers in this study can operate on battery power and are small and light enough that they could be carried in a backpack to otherwise inaccessible locations as needed by wildland firefighters. Several samplers also offer the addition of solar panel to extend the operational life while on battery.

The samplers can be used to fill in large spatial gaps in the air quality data and can help evaluate the field performance of other non-regulatory monitors and sensors under real-world smoke conditions. Additionally, researchers can evaluate collected $PM_{2.5}$ samples for health effects and emission factor characterization applications.

Read more about the MASIC study at Studies Advance Air Monitoring During Wildfires and Improve Forecasting of Smoke.

TOC
Intro
What's in Smoke
Smoke Measurement
Water & Ecosystems
Human Health
Reducing Exposures
Future Directions

3.4 Challenge: Wildland Fire Sensors

- The U.S. EPA wildland fire sensor challenge: Performance and evaluation of solver submitted multi-pollutant sensor systems (2021)

Challenge: Sensors need to be portable, durable, reliable, wireless, comparable to regulatory monitors, and capable of measuring fine particulate matter ($PM_{2.5}$), carbon monoxide (CO), ozone (O_3), and carbon dioxide (CO_2) during wildfire episodes. How can we encourage technological innovations? How can we test the performance of the new technologies?

Wildland Fire Sensor Challenge graphic (left) and Challenge partners and mission (right).

Approach: The Wildland Fire Sensors Challenge was the result of a multi-agency effort to spur innovations in air measurement technology. EPA and the US Forest Service (USFS) published technology requirements, solicited prototypes, and put all ten entries through a rigorous two-phase laboratory test in simulated wildland fire smoke conditions. Results were reviewed by an independent multi-agency award panel. Judges considered accuracy over a wide range of operational requirements (2/3 of score), with PM2.5 accuracy weighted highest followed by CO, O3, and CO2. Judges also considered form factor (size, weight), design durability, battery life, ease of use and ability to transmit data over long distances (1/3 of score).

Result:
First Place went to SenSevere/Sensit Technologies (Pittsburgh, PA), Second Place went to Thingy LLC (Bellevue, WA), and an Honorable Mention went to Kunak Technologies (Pamplona, Spain).

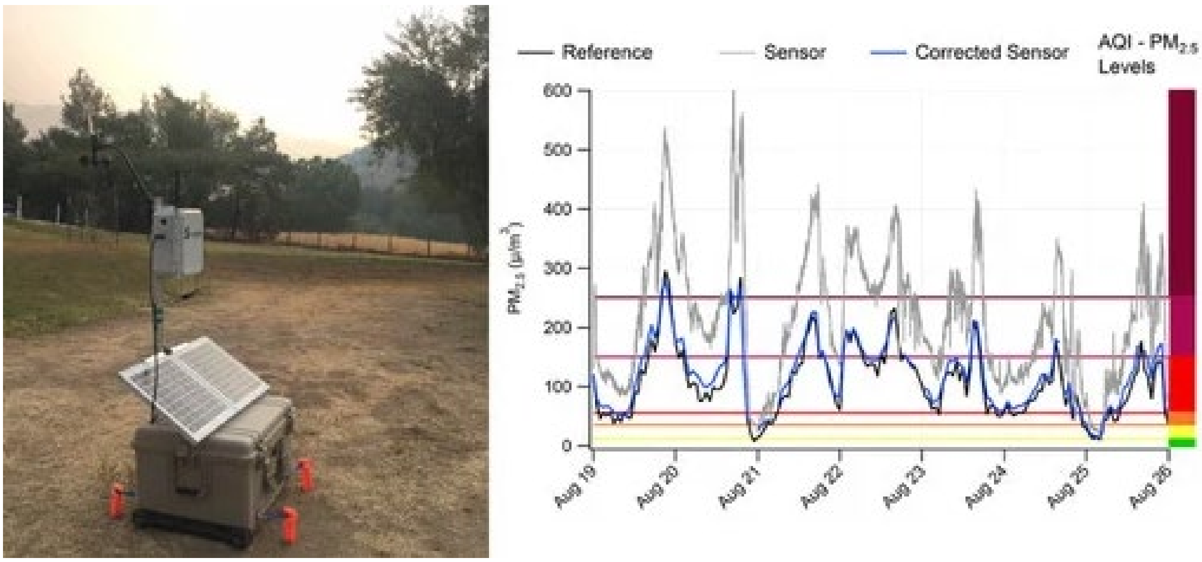
Impact: The Wildland Fire Sensors Challenge increased awareness of monitoring needs during wildfires and catalyzed the next generation of sensor technology systems for wildland fire applications. These sensors can greatly increase our knowledge of the temporal and spatial variation of smoke and provide information to better protect public health.

3.5 Evaluation of Particulate Matter Sensors for Measuring Wildfire Smoke

- Field Evaluation of Low-Cost Particulate Matter Sensors for Measuring Wildfire Smoke (2020)

Challenge: Ambient air quality is routinely measured by $PM_{2.5}$ regulatory monitors but they are expensive and require infrastructure and space for proper siting. Public interest in using $PM_{2.5}$ sensors to provide additional air quality measurements near homes and schools, as well as in more remote areas, is growing. However, we must ask, how do these sensors perform relative to regulatory monitors? How do these sensors perform in smoky conditions?"

Approach: EPA researchers examined the accuracy and reliability of three $PM_{2.5}$ sensor technologies: the Purple Air PA-II-SD (PA), the Aeroqual micro air quality station (AQY), and the SenSevere Real-Time Affordable Multi-Pollutant monitor (RAMP). These were deployed in wildfire smoke impacted areas alongside reference monitors. Datasets for each sensor were collected and using linear regressions, smoke calibration or correction factors were derived.



Sensor performance field testing site (left) and plot of reference, raw sensor, and corrected sensor $PM_{2.5}$ concentrations (right); Source: graphical abstract in journal article.

Result: All sensors generally matched measurements from reference monitors at lower $PM_{2.5}$ concentrations but reported higher concentrations during smoke-impacted times. Of all the sensors evaluated, the PA $PM_{2.5}$ sensor showed the highest correlation with the reference monitor and the AQY $PM_{2.5}$ had the poorest. Researchers developed correction equations specific to each sensor, which reduced the mean absolute errors to under 10 $\mu g/m^3$ in the hourly $PM_{2.5}$ concentrations for all sensors. With appropriate corrections, these sensors can provide accurate smoke $PM_{2.5}$ concentrations.

Impact: By using a smoke-specific correction factor, a sensor's $PM_{2.5}$ concentrations can be compared with current smoke monitoring networks. Sensors can be deployed in large numbers to fill in large spatial gaps in monitoring networks near wildfires, which greatly increases our knowledge of the temporal and spatial variation of smoke and helps support public health guidance.

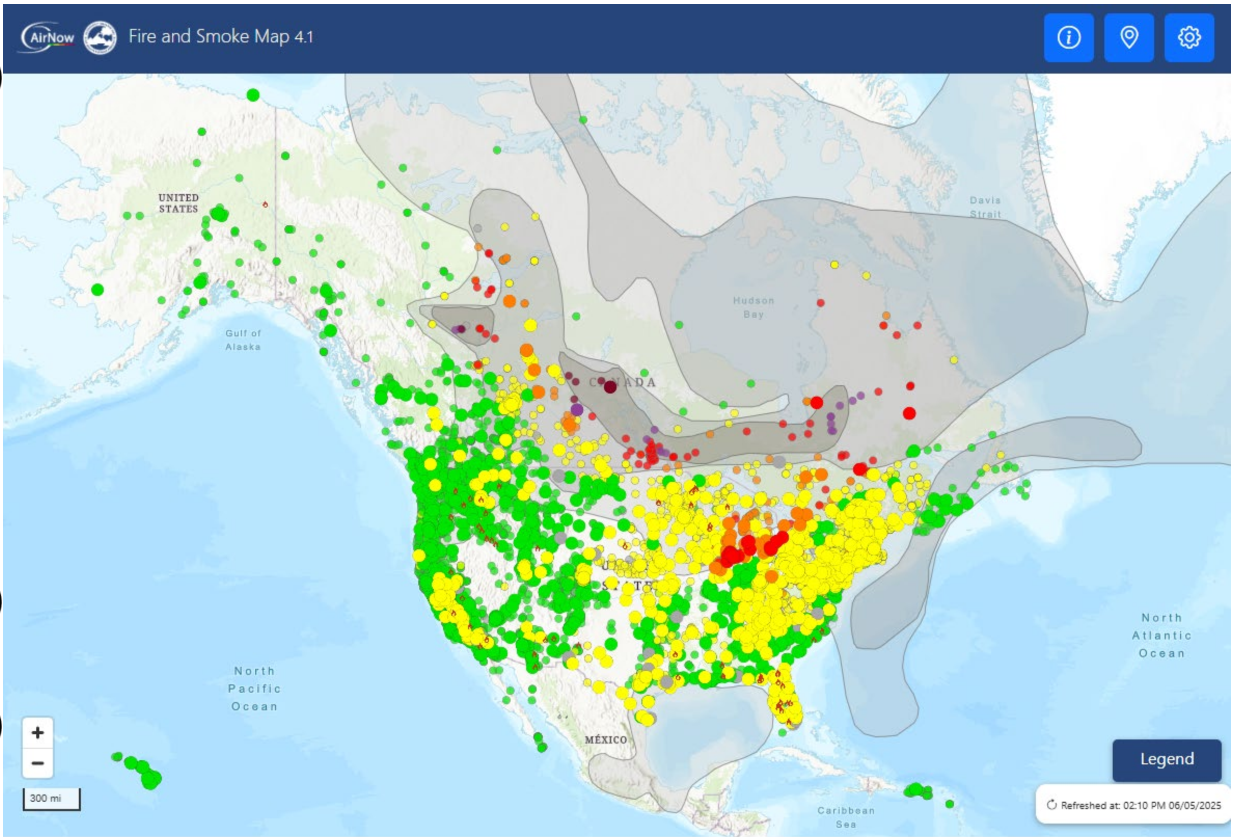
Related research:

- An analysis of degradation in low-cost particulate matter sensors (2023)

3.6 Including Sensor Data on the AirNow Fire and Smoke Map

- Correction and Accuracy of PurpleAir $PM_{2.5}$ Measurements for Extreme Wildfire Smoke (2022)
- Development and application of a United States-wide correction for $PM_{2.5}$ data collected with the PurpleAir sensor (2021)

Challenge: As $PM_{2.5}$ sensors become increasingly common across the U.S, can these help communicate air quality information during wildfire smoke events?



EPA's AirNow Fire and Smoke Map displays ambient air quality using EPA's air quality index (AQI), 6/5/2025.

Approach: EPA researchers co-located the widely used PurpleAir sensors with regulatory monitors and compared measured $PM_{2.5}$ concentrations. They also coordinated with Tribal, state, and local air monitoring agencies to collect data from other co-location efforts underway.

Results: Researchers developed a correction equation to improve the comparability of sensor data with regulatory-grade monitors when they are collectively analyzed or shown together on public information websites such EPA's AirNow Fire and Smoke Map.

Impact: The research was critical in being able to display data from $PM_{2.5}$ sensor networks (which can fill spatial and temporal gaps) on EPA's interactive map. This gives the public valuable and timely air-quality information during smoke episodes. Researchers provided an analysis framework as additional types of commercial and state run $PM_{2.5}$ sensor technologies are incorporated into the map and continue to serve as technical advisors to the AirNow Fire and Smoke Map team.

Related resources:

- EPA's Technical Approaches for the Sensor Data on the AirNow Fire and Smoke Map

3.7 Wildfire Smoke Air Monitoring Response Technology (WSMART) program

- Wildfire Smoke Air Monitoring Response Technology (WSMART)
- Performance of Vehicle Add-On Mobile Monitoring System $PM_{2.5}$ measurements during wildland fire episodes (2024)

Challenge: How can we provide frontline responders with easy-to-use and reliably performing monitoring solutions during wildfire smoke episodes in remote locations?

Approach: EPA began a sensor loan program to help air monitoring organizations gather timely data in areas affected by wildfire smoke. These (often remote) areas have limited or no existing air monitors. Loans are made to state, local, and Tribal agencies, and Air Resource Advisors serving through the Interagency Wildland Fire Air Quality Response Program. Available equipment includes a portable system called the Vehicle Add-On Mobile Monitoring System (VAMMS), a compact and battery-powered unit that can be mounted on any vehicle that was developed and field-tested by EPA researchers.

EPA's VAMMS mobile sensor available through WSMART.

EPA's VAMMS mobile sensor being used in the field.

Results: Over the past few years, the WSMART project has made over 60 loans to eligible participants. EPA researchers loan the monitoring technologies and provide training on the use of the equipment to state, local, and tribal governments. Loans have also been made to Air Resource Advisors (ARAs), technical specialists deployed with wildfire Incident Management Teams to provide smoke expertise. The following systems are currently available in the loan program: two stationary units – a PM2.5 sensor and multipollutant ($PM_{2.5}$, CO, and other gases) sensor – and the VAMMS. The VAMMS measures outdoor air using a window-attachable inlet and has a small GPS antenna to record location. Mobile $PM_{2.5}$ measurements taken with the VAMMS had high correlation with measurements from fixed site monitors during smoke events.

Impact: WSMART sensor loans provide supplemental sensors and mobile monitoring to help fill knowledge gaps in areas affected by wildfire smoke without fixed site monitors. The sensor measurements help assess the exposure of frontline workers and communities to smoke and add observations to inform air quality models.

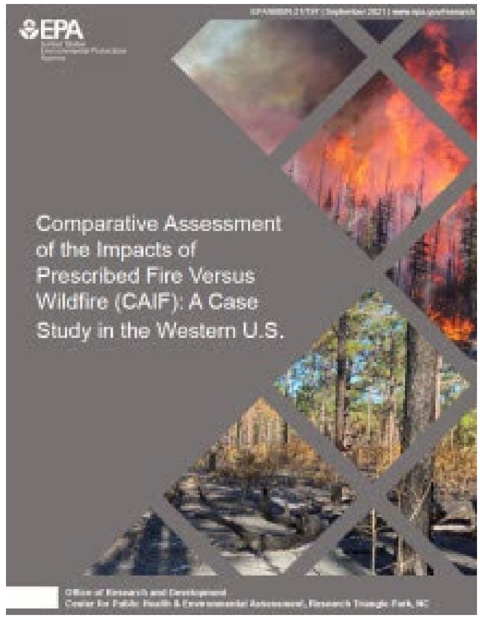
Related resources:

- EPA Science Matters: EPA Scientist Serves as Air Resource Advisor Trainee at the Lookout Fire
- EPA Science Matters: EPA Expands Air Monitoring Capabilities to Support Wildfire-Impacted States, Tribes, and Their Frontline Firefighters

3.8 Prescribed Fires vs Wildfires: a Comparative Assessment

➢ Comparative Assessment of the Impacts of Prescribed Fire Versus Wildfire (CAIF): A Case Study in the Western U.S. (2021)

Challenge: Prescribed fires can reduce biomass accumulation and thus reduce the risk of catastrophic wildfires. With the expanded use of prescribed fires, what are the trade-offs between the air quality and health impacts of smoke from prescribed fire compared to wildfire?



A prescribed fire (left) and the cover of the CAIF Report (right).

Approach: EPA researchers, with other federal partners, including the U.S. Forest Service (USFS), the Department of the Interior (DOI) and the National Institute of Standards and Technology (NIST), used emissions data, air quality modeling, and health impact analyses to examine the corresponding air quality and public health impacts due to actual fires and hypothetical fire scenarios based on different fire management strategies, as well as prescribed fire activity through two case study analyses (Timber Crater 6 Fire – Oregon; Rough Fire – California).

Result: Predicted concentrations of $PM_{2.5}$ from prescribed fires were smaller in magnitude and shorter in duration than hypothetical wildfire scenarios or actual wildfires. Smoke impacts of wildland fires are complex across space and time, and impacts on health are dependent upon the physical distance between a population area and the prescribed and wildfire events as well as the meteorology (e.g., wind speed and direction). The CAIF report concluded that well-designed prescribed fires may be able to reduce the size and intensity of future wildfires and ultimately reduce negative air quality and health impacts.

Impact: The CAIF report provides an initial assessment of the differences in air quality and public health impacts of smoke between prescribed fire and wildfire. This information provides guidance for multiple levels of government in planning for future land and fire management activities, and to the public and land managers in making more informed decisions, particularly as prescribed fires are increasingly being used to try to reduce the risk of future catastrophic wildfire and improve forest health. Additionally, the CAIF report identified future research needs to examine tradeoffs (i.e., air quality and public health impacts) from prescribed fire and wildfire.

4. What are the impacts of fire on water quality and ecosystems?

EPA researchers are examining long-term patterns in water quality and forest health after wildfires.

Wildland fires can impact water quality and forested ecosystems. Wildland fires burn vegetation that holds soil in place and retains water. Erosion and flooding can follow and cause changes to runoff, streamflow, and water quality (e.g., temperature and chemical concentrations). This can affect aquatic habitats (a special concern for sensitive species such as salmon) and, along with deposited pollutants from the smoke and damage to water infrastructure, can contaminate drinking water supplies. Wildland fire can also change the resilience of forests to other types of disturbances, such as insect infestations.

4.1 Drinking Water Quality: A Resource for Water Managers

4.2 Drinking Water Quality: Contaminant Levels

4.3 Drinking Water Quality: Comparing the Impacts of Wildfires vs Prescribed Burns

4.4 Stream Temperatures: Seasonal Changes

4.5 Stream Temperatures: Summertime

4.6 Stream Flow: A Statistical Analysis

4.7 Stream Flow: Field Studies

4.8 Forest Resilience to Fire: A Conceptual Framework of Biological Disturbance Agents, Fuels, and Fire

4.9 Forest Resilience to Fire: An Ecological Perspective

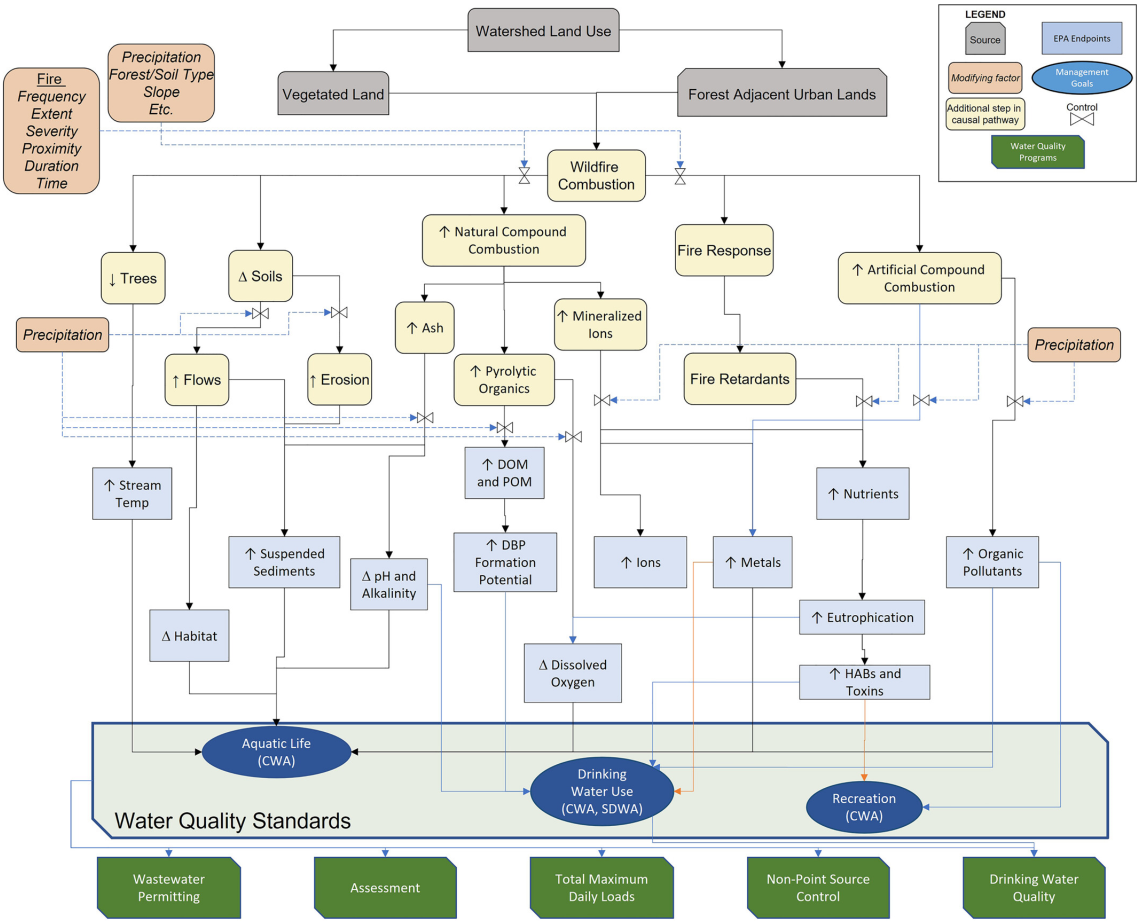
4.10 Tools and Models: HexFire

4.1 Drinking Water Quality: A Resource for Water Managers

- [Wildfire Induces Changes in Receiving Waters: A Review With Considerations for Water Quality Management](#) (2022)

Challenge: As area burned by wildland fires increase, including near populous areas, what are the potential impacts on water quality?

Approach: EPA researchers created a conceptual model to understand impacts of fire on water quality and guide a literature review synthesizing information on the impacts.



Conceptual model of the myriad ways that fire can affect endpoints (light blue boxes) of interest to water quality managers. Source: Figure 1 in journal article.

Results: Wildland fires impact physical, chemical, and biological water quality endpoints. Physically, streamflow, sediments and stream temperature all increased. Chemically, nutrients, ions, metals, and certain organic chemicals increased, sometimes 10–1000 times above unburned levels, and some post-fire chemicals (e.g., arsenic) in treated drinking water exceeded regulatory levels. Biologically, aquatic species commonly declined temporarily. The duration of effects was generally 5 years or less, but some effects could persist longer, especially after a severe fire and in drought conditions.

Impact: With greater fire activity, water resource managers can track these endpoints as they plan for, mitigate, and, if needed, recover from wildfire impacts to water quality. Communities who rely on a single municipal source or individual private wells could also use this information, as they could be especially impacted if those resources are damaged or contaminated.

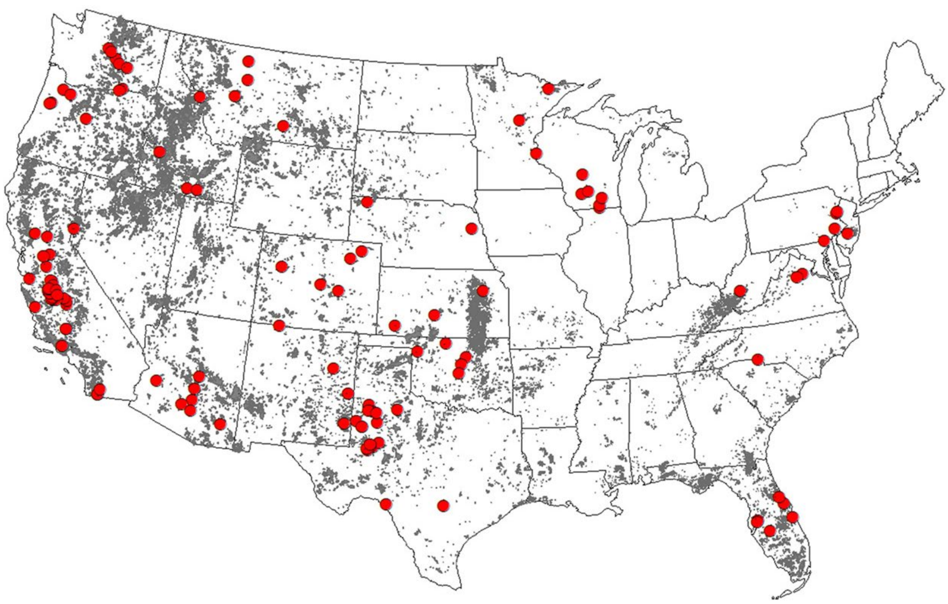
4.2 Drinking Water Quality: Contaminant Levels

➢ Wildfires can increase regulated nitrate, arsenic, and disinfection byproduct violations and concentrations in public drinking water supplies (2022)

Challenge: Pollutants mobilized during and after wildfires can threaten water quality. With an increase in wildfire activity, including in the wildland urban interface (WUI) near populous areas, more public water resource managers will need to proactively plan and prepare their water systems. What are the impacts of wildfires on contaminant levels in public drinking water systems?

Approach: EPA researchers examined the post-wildfire effects on water quality at public drinking water systems (PWSs) located downstream from wildfire events. This study evaluated maximum contaminant level (MCL) violations, as well as concentrations below the MCL, of selected contaminants regulated by the U.S. Safe Drinking Water Act (applies to every public water system in the U.S. and sets protective health-based drinking water standards). EPA researchers selected a subset of the over 90 regulated contaminants, including nitrate, arsenic, disinfection byproducts, and volatile organic compounds (VOCs). Violations were used to assess whether wildfires increase contaminant levels above the health-based standards and the concentrations were used to assess whether wildfires have a significant impact at levels below these standards.

Results: In certain circumstances after a wildfire, concentrations of nitrates, disinfection byproducts and arsenic exceeded drinking water standards.



Wildfires are associated with increased drinking water contaminant levels. Map of the conterminous U.S. showing wildfires (grey) and locations (red) with increased drinking water violations. Source: graphical abstract in journal article.

Impact: This study was the first to quantify the impacts of wildfires on drinking water violations and concentrations in PWSs. The information can help public water source operators, particularly in wildfire-prone regions, prepare public water systems and design post-wildfire water sampling and treatment plans.

TOC
Intro
What's in Smoke
Smoke Measurement
Water & Ecosystems
Human Health
Reducing Exposures
Future Directions

4.3 Water Quality: Comparing the Impacts of Wildfires vs. Prescribed Fires

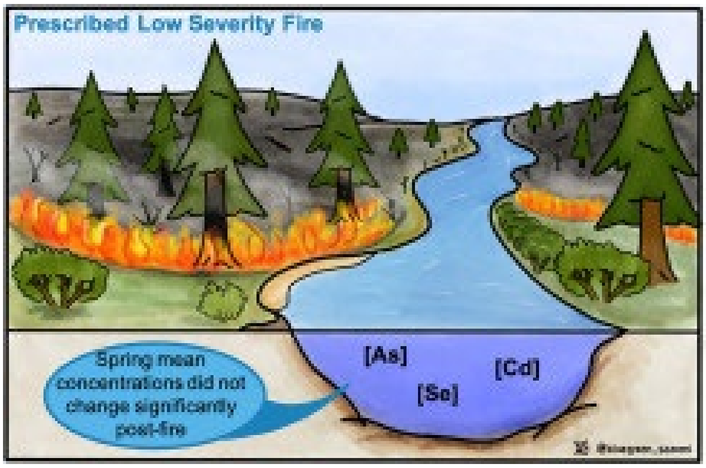
- [To burn or not to burn: An empirical assessment of the impacts of wildfires and prescribed fires on trace element concentrations in Western US streams](#) (2023)

Challenge: Prescribed fires are a land management technique that can reduce the impacts from high-severity wildfires. As wildfires increase in size and severity, prescribed fires may be used more frequently. What are the effects of prescribed fires, relative to the effects of wildfires, on water quality?

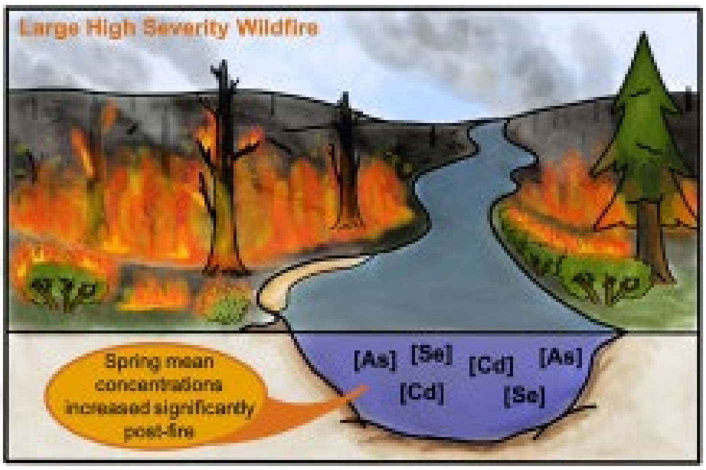
Approach: EPA researchers assessed the effects of 54 wildfires and 11 prescribed fires on the concentrations of trace elements (arsenic [As], selenium [Se], and cadmium [Cd]) in western U.S. streams that drain burned watersheds. Researchers selected stream sites with at least six spring (March-June) water quality samples of those three constituents over the 3–15 years before a fire, and six water quality samples over the first three years after a fire.

Results: In general, large, high-severity wildfires significantly increased spring mean concentrations of trace elements. In comparison, prescribed fires rarely did. The post-fire response was primarily influenced by burn area, burn severity, post-fire weather, surface rock characteristics, watershed physiography, and land cover.

Impact: Land managers need the ability to compare water quality effects of wildfires and prescribed fires to make informed forest management decisions. This study demonstrates that prescribed fires, when used to reduce future high severity wildfires, could also help reduce water quality impacts by decreasing the potential for concentrations of post-fire trace elements in downstream waters.



Comparison of wildfire and prescribed burn effects on stream trace element concentrations: Small, prescribed burns rarely raised stream trace element concentrations (top) while large, high-severity wildfires did (bottom). Source: graphical abstract in journal article.

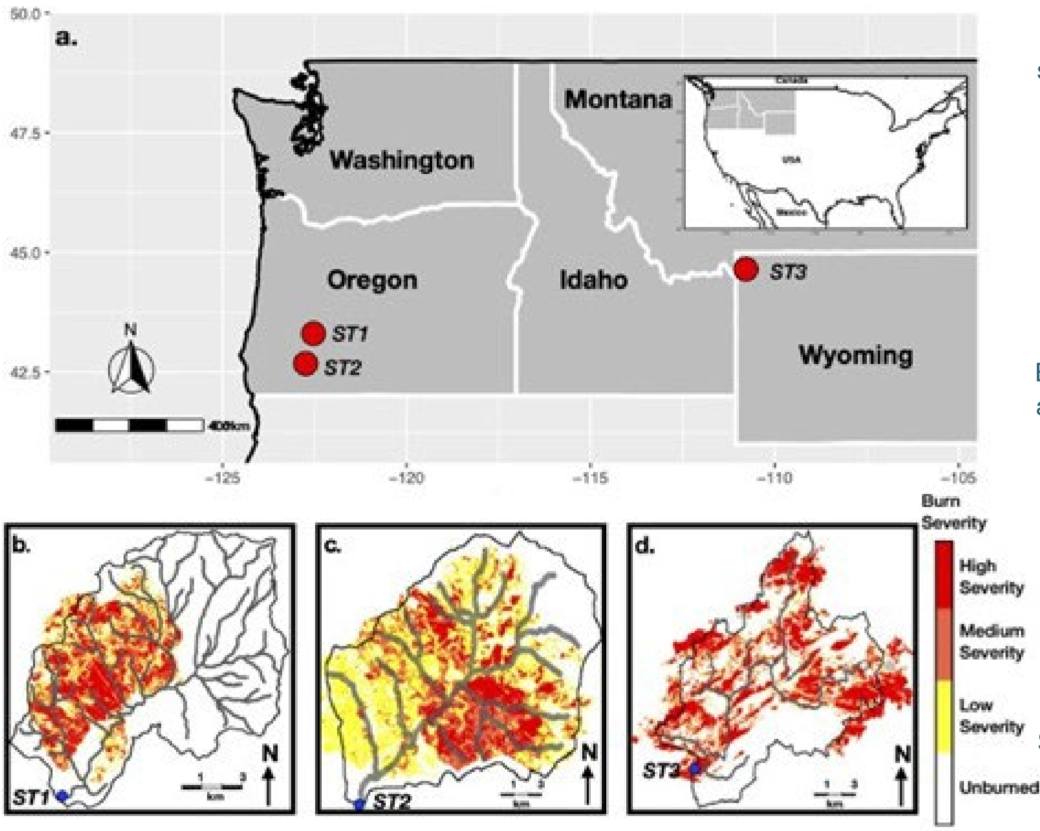


4.4 Stream Temperatures: Seasonal Changes

- [Variable wildfire impacts on the seasonal water temperatures of western US streams: A retrospective study](#) (2022)

Challenge: Large and severe wildfires in the western U.S. can impact water temperatures in stream habitats for cold-water fish, e.g., salmon, that are vital to the Pacific Northwest. These fish are sensitive to changes in water temperature, and their development stages (from egg hatching to migration) are linked to seasonal temperatures. What are the effects of wildfires on seasonal stream temperatures, especially for cold-water fish habitat?

Approach: EPA researchers selected three watersheds: ST1/Boulder Creek (OR) , ST2/Elk Creek (OR), and ST3/Gibbon River (WY). By using three statistical approaches to analyze the effects of a wildfire burn on downstream water temperatures, they could understand how burn area, severity, and distance from stream influence winter and summer stream temperatures.



(a) Location of studied stream sites in the northwestern U.S. and the extent and severity of wildfire burns at (b) Elk Creek, (c) Boulder Creek, and (d) Gibbon River stream site watersheds. (Blue filled circles represent the location of selected sites.) Source: Figure 1 in journal article.

Results: High-severity riparian (river vegetation) burns in the Boulder Creek (c) and Gibbon River (d) watersheds caused cooler winter water and warmer summer water in the downstream sites, which is consistent with previous studies that show riparian burning promoted the warming of summer water temperatures. In contrast, because of the distance from burned riparian areas, and the cooling effect of groundwater inflow and riparian vegetation downstream of the burn area, downstream sites in the Elk Creek (b) watershed did not have substantial winter or summer water temperature changes..

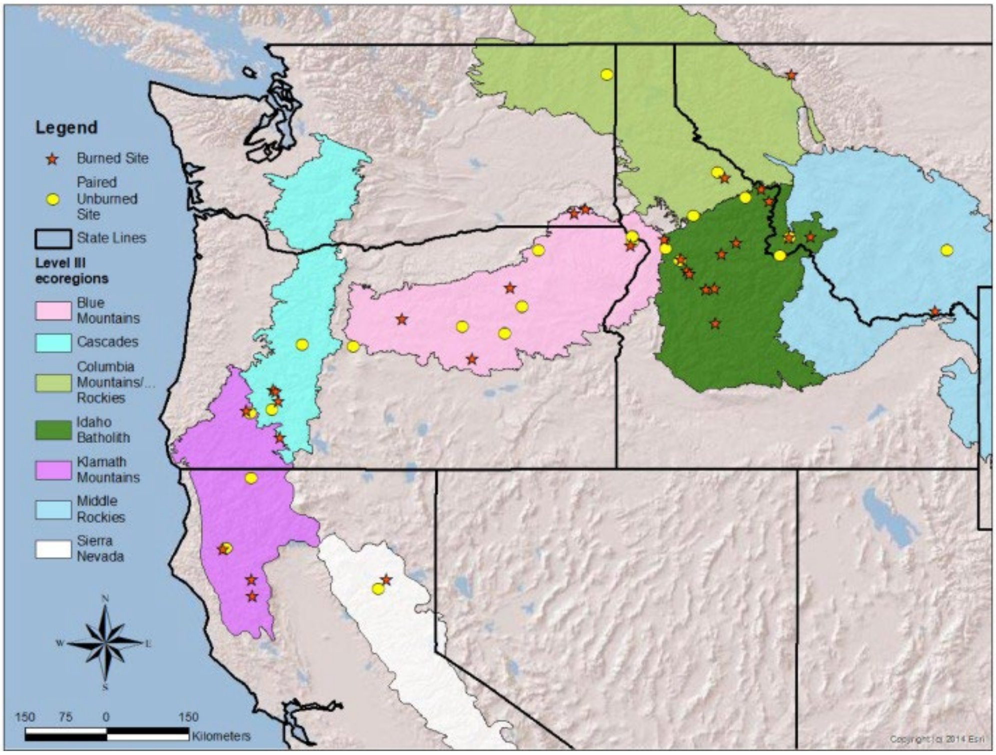
Impact: Knowing more about the effects on stream temperatures – whether from burn areas or a warming climate - helps water resources managers protect cold-water, thermally-sensitive fish habitats.

4.5 Stream Temperatures: Summertime

➢ Heterogeneity in post-fire thermal responses across Pacific Northwest streams: A multi-site study
Beyene (2024)

Challenge: Large and severe wildfires in the western U.S. can impact water temperatures in stream habitats for cold-water fish, e.g., salmon, that are vital to the Pacific Northwest. Can we help regional ecosystem managers by predicting the effect of wildfires on summer stream temperatures?

Approach: EPA researchers selected 31 burned and 19 unburned across six ecoregions: Blue Mountains, Cascades, Columbia Mountains/Rockies, Idaho Batholiths, Klamath Mountains, Middle Rockies, and Sierra Nevada (see figure). Burned watersheds had lost 10–100% of their riparian area (i.e., the strip of land within 100 meters of the stream channel) between 1990–2015. All were in areas that prohibited commercial logging and had daily summer (July to September) stream water temperature data.



Map of northwestern U.S. with location and ecoregion of studied, burned (labeled with red star) and paired unburned (yellow circle) stream sites. Source: Figure 1 in journal article.

Results: For the 31 burned sites, daily summer water temperatures had an average increase (0.3 – 0.9°C) for three years post-fire, with variation across the sites. An increase was more likely with greater riparian burn area and severity, but other factors (i.e., bedrock permeability, basin area, post-fire weather, winter snow-water equivalent, pre-fire forested and barren watershed area) were also important. In contrast, the six PNW ecoregions did not show a distinct variation in daily stream water temperatures.

Impact: This study increases understanding of post-fire stream temperature changes and will improve water temperature predictions. Using this information, regional ecosystem managers may be able to identify streams highly sensitive to wildfire effects and could provide a preliminary stream sensitivity ranking that could be used to prioritize sites for conservation or mitigation.

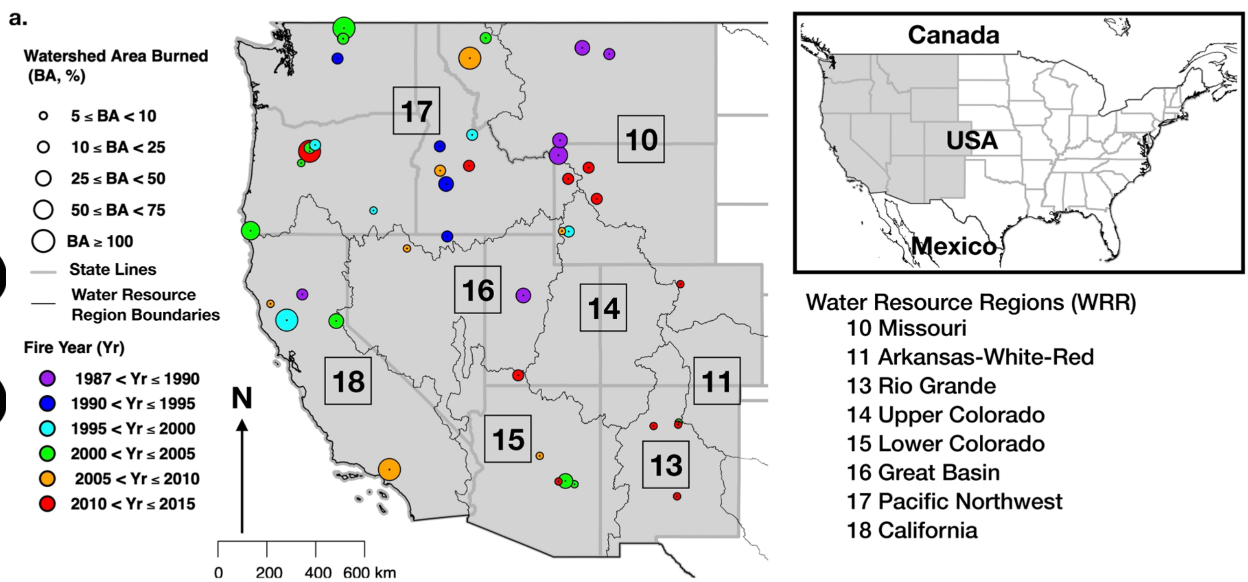
TOC
Intro
What's in Smoke
Smoke Measurement
Water & Ecosystems
Human Health
Reducing Exposures
Future Directions

4.6 Stream Flow: A Statistical Analysis

➢ Parsing Weather Variability and Wildfire Effects on the Post-Fire Changes in Daily Stream Flows : A Quantile-Based Statistical Approach and its Application (2022)

Challenge: Large and severe wildfires in the western U.S may disturb stream flows. Since water in the western U.S. is scarce, and much of the available public drinking water comes from streams in forested watersheds, water managers are concerned about any disturbances, from low water flow to flash floods that carry sediment and nutrients. What are the wildfire impacts on stream flows?

Approach: EPA researchers examined 44 stream sites with at least 5% of their watershed burned and analyzed pre-and post-fire streamflow data to understand how annual low and peak flows respond to fire effects. Flows at the lowest end of the distribution range (0.05th quantile) represent annual low, and highest (0.95th quantile) represent annual peak.



(a) Map of locations of selected streams. Source: Figure 2 in journal article.

Results: Sites with small (< 10%) watershed burns rarely had a wildfire-related increase in annual low and peak flows. In contrast, stream sites with large, high-severity watershed burns saw an increase in annual low (up to 5000%) and annual peak (161%) flows for five post-fire years.

Impact: Applying this analytical framework can show wildfire-related annual low and peak flows. Knowing how wildfires change the supply of fresh water can help water supply managers protect drinking water sources.

Related resources: EPA Science Matters: Wildfires: How Do They Affect Our Water Supplies?

4.7 Stream Flow: Field Studies

- [Science Matters: EPA Researchers Investigate Impacts of Wildfires on Water Resources]

EPA researchers collecting water quality samples.

Challenge: Wildfires can dramatically change vegetation cover and affect hydrological processes, with changes to runoff, streamflow, and water quality. What are the impacts of wildfires on water quality, particularly in the Cascade Mountain Region of the Pacific Northwest, which is impacted by wildfires and provides water for downstream uses?

Approach: In 2020, immediately after four Oregon "megafires" (Riverside, Beachie Creek, Lionshead, and Holiday Farm) in the Cascade and Coast Range mountains, EPA initiated a field program to sample the chemical composition of streams and rivers that drain fire-impacted watersheds and compare them with similar streams not affected by the fires. EPA scientists sampled 31 stream stations to follow post-fire trends. Scientists monitored water quality in these watersheds, and measured nutrients, sediments, metals, dissolved organic carbon, water temperature, and mercury, all of which can either impact human health or the aquatic environment. EPA scientists also examined water quality trends in relation to burn proportion and severity.

Results: The data collected as part of this study will be used to inform water models and programs that provide critical insight into mechanisms driving post-fire water quality changes. For example, the models can improve estimates of the vulnerability of valued resources such as clean water and fish populations to wildfire and other climate-related events. In the future, the program will expand the network of streams sampled to characterize the nature, magnitude, and duration of changes to water quality in watersheds of different sizes that experienced catastrophic wildfires.

Impact: Streams and rivers are important to downstream aquatic ecosystems, agriculture, hydropower, recreation, and municipal drinking water. When water providers and water resource managers better understand the downstream impacts of burned watersheds, they can try to minimize adverse water-quality effects, possibly by temporarily diverting compromised water or changing source water.

Related resources:

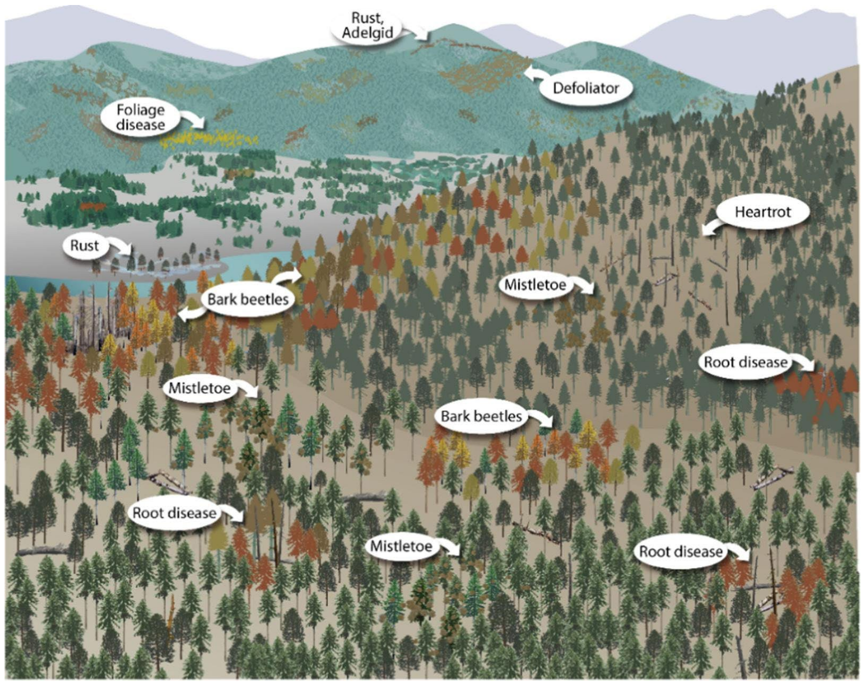
- Wildfires in the western United States are mobilizing PM2.5-associated nutrients and may be contributing to downwind cyanobacteria blooms (2023)

4.8 Forest Resilience to Fire: A Conceptual Framework of Biological Disturbance Agents, Fuels, and Fire

➢ The complexity of biological disturbance agents, fuels heterogeneity, and fire in coniferous forests of the western United States (2022)

Challenge: Biological disturbance agents (BDAs), i.e., insects, pathogens, and parasitic plants, are a natural part of western U.S. forest ecosystems. A common thought is that tree decline and mortality due to BDAs contributes to fire risk, since, as live trees die, the dead trees become fuel. How can we better understand whether BDAs increase fire risk?

Approach: To help understand BDAs and their effects on fuels and fire in the western U.S., EPA researchers developed a conceptual framework and reviewed scientific literature. The researchers asked: 1) What are the major BDA groups in western US forests that affect fuels? and 2) How do BDA-affected fuels influence fire risk and outcomes?



Common and natural BDAs in a western U.S. coniferous forest landscape. Source: Figure 1 in journal article.

Results: EPA researchers assessed three major groups of BDAs pervasive in western U.S. forests: 1) insects, 2) pathogens, i.e., root diseases, blights, and 3) parasitic plants. There was little evidence to support the common belief that BDAs predominantly increase the likelihood and severity of wildfire. In fact, native BDAs (such as bark beetles, rust fungi and dwarf mistletoe) can counteract negative fire outcomes by encouraging structural diversity (i.e., more variation in tree heights) and increasing landscape heterogeneity (i.e., a greater a mix of vegetation.)

Impact: Overall, this approach is a major step towards integrating all BDAs into fuels and fire science. This framework helps fire managers and land managers better understand the complex relationships between BDAs, fuels and fire, especially in the western U.S., where wildfire and BDA activity has increased in range, magnitude and severity under a changing climate.

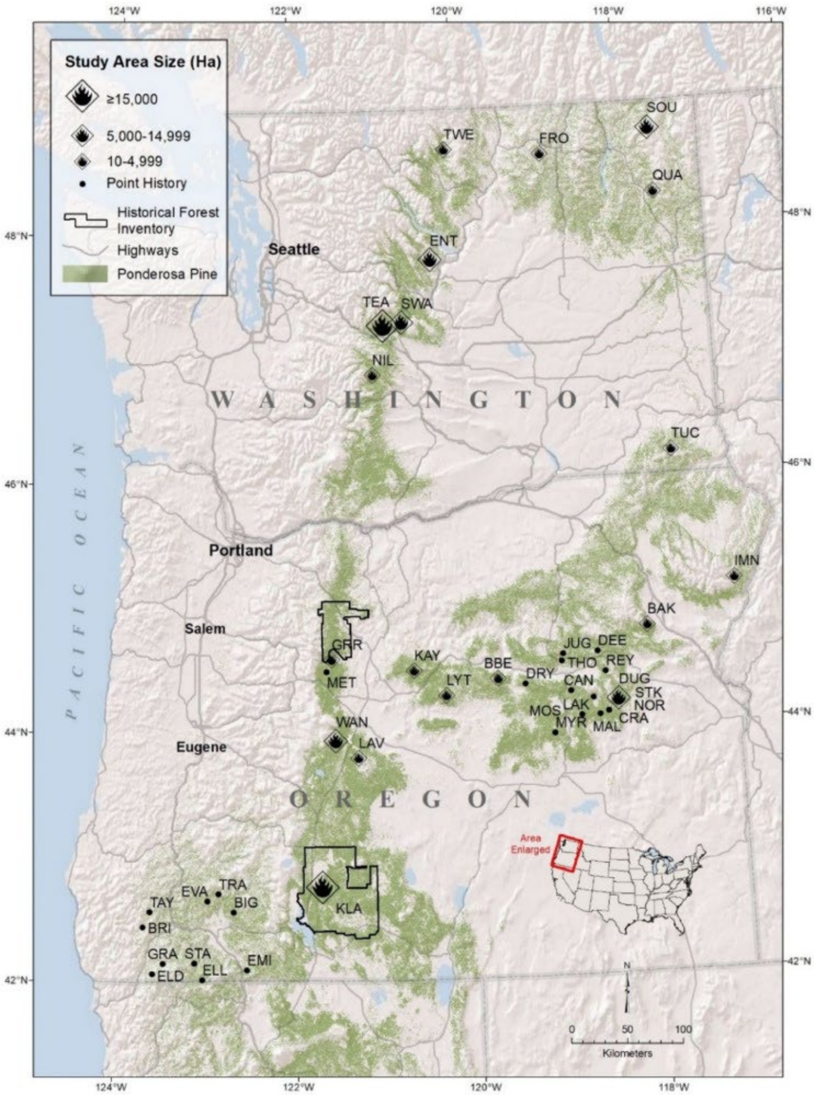
TOC
Intro
What's in Smoke
Smoke Measurement
Water & Ecosystems
Human Health
Reducing Exposures
Future Directions

4.9 Forest Resilience to Fire: An Ecological Perspective

➢ An ecological perspective on living with fire in ponderosa pine forests of Oregon and Washington: Resistance, gone but not forgotten

Challenge: Ponderosa pine forests are widespread in the western U.S., particularly Oregon and Washington, but more than a century of fire suppression has increased their susceptibility to the combined effects of drought and biological disturbance agents (BDAs). As the climate warms and disturbance frequency and intensity increases, can we better understand the ecology of these forests and plan to restore forest resistance?

Approach: EPA researchers synthesized extensive information on historical conditions and dynamics to provide an ecological context for how to live with fire. The goal is to understand how resistance was maintained historically, what it means in ponderosa pine ecosystems, and how it can aid regional and local planning efforts.



Range of ponderosa pine in Oregon and Washington. Source: Figure 1 in journal article.

Results: Researchers clarified that prescribed fires (i.e., the process of frequent intentional ignition of controlled low-severity fires) develop and maintain resistance and are critical to maintaining the ponderosa pine forest ecosystem. Large mixed- and high-severity fires are inevitable in the next several decades, as is elevated tree mortality from drought and BDAs. Given the expanding WUI, researchers describe the challenges to sustainably managing wildland fire and applying prescribed fire while preparing communities for the impacts.

Impact: This provides an assessment of what living with fire in ponderosa pine forests means in the 21st century. Resource managers can use this information to develop comprehensive plans to promote greater use of prescribed fire and management of reported fires for ecological benefits, and to increase responsibility and preparedness of local agencies, communities and individual homeowners.

TOC
Intro
What's in Smoke
Smoke Measurement
Water & Ecosystems
Human Health
Reducing Exposures
Future Directions

4.10 Tools: HexFire

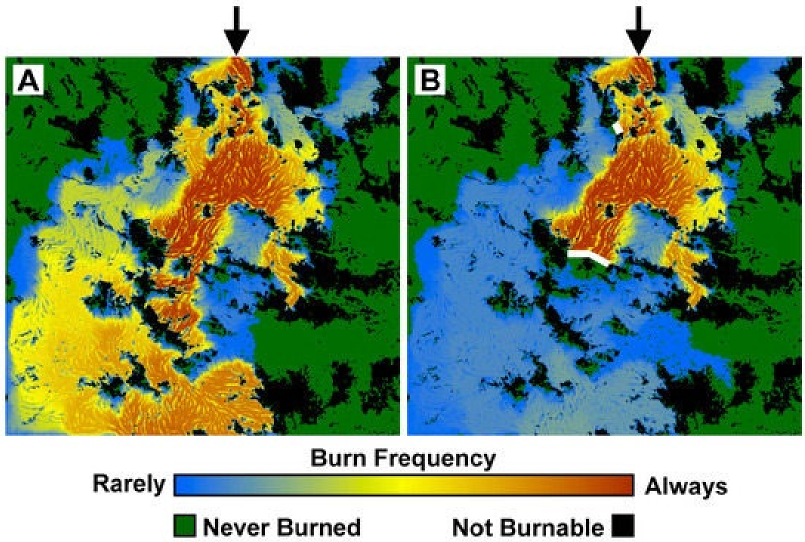
➢ HexFire: A Flexible and Accessible Wildfire Simulator

Challenge: Increasingly, as fire frequency and severity grows, more scientists will need to incorporate fire impacts into their research. How can we provide a wildfire simulation model that can be widely used by land managers and non-fire specialists?

Approach: EPA researchers developed a wildfire forecasting model, HexFire, using EPA's existing open-source HexSim model development platform. HexSim allows users to create sophisticated simulations of interactions without writing computer code. Although HexSim has traditionally been used to replicate wildlife and plant population dynamics, it has expanded to a wider range of topics. HexFire can easily incorporate multiple static or dynamic maps quantifying the amounts and patterns of fuels, moisture levels, wind, ignition sites, management interventions, and other drivers relevant to wildfire.

Results: HexFire helps anticipate where future wildfires are likely to occur, how significant their consequences might be, and what might be done to limit these impacts. For example, HexFire can simulate fire interactions with fuel breaks and active fire suppression.

The figure shows mean burn frequency (A) without fuel breaks and (B) with fuel breaks. Black arrows indicate the location at which fires were initiated. After running 100 simulations without fuel breaks, researchers inspected the spatial pattern of fire progression. Researchers then identified two locations where fuel breaks might limit the total area consumed by fire (depicted as the white lines in B) and ran 100 additional simulations, which showed that the two fuel breaks were generally effective in limiting the fire's spread.



Example to illustrate HexFire's ability to simulate fire suppression Source: Figure 6 in journal article.

Impact: Other wildfire simulations models are highly complex, time-consuming to learn, and geared towards fire specialists, but HexFire's ease-of-use makes it accessible to interdisciplinary non-fire experts. Ecologists, conservation biologists, planners, and land managers can use HexFire to simulate multiple combinations of fire environments, fuel treatments, fuel breaks, and back burns and to help quantify the outcomes of the combinations on plant and animal species.

TOC
Intro
What's in Smoke
Smoke Measurement
Water & Ecosystems
Human Health
Reducing Exposures
Future Directions

5. What are the impacts of wildfire smoke on human health?

Wildland fires can be destructive and cause loss of life, and the smoke they produce is a significant source of air pollution harmful to public health. Smoke is not only a concern in areas near a fire but can also drift long distances and affect regional air quality.

5.1 Toxicity of Smoke from Peat, Eucalyptus, and Oak Fires

5.2 Peat Smoke and Cardiovascular Health

5.3 Peat Smoke and Cardiorespiratory Health

5.4 Wildfire Smoke and Cardiovascular Health

5.5 Toxicity of Wildland Fire Smoke Mixtures

5.6 Toxicity of Smoke from Burning Anthropogenic Materials

5.7 Wildfire Smoke and Brain Function

As the number of acres burned from wildfire has increased, so has the amount of smoke emitted, increasing the extent of the U.S. population exposed to smoke. Smoke contributes to poor air quality in communities both near and far from a wildfire as smoke can travel hundreds to thousands of miles. Wildfire smoke is associated with a range of health effects, from less serious such as coughing and runny nose, to more serious such as respiratory and cardiovascular disease exacerbation, and even premature death. Additionally, some people may be at increased risk of experiencing health effects in response to smoke exposure or experience higher smoke exposures compared to others, which can be detrimental to their health.

5.1 Toxicity of Smoke from Peat, Eucalyptus, and Oak Fires

- The role of fuel type and combustion phase on the toxicity of biomass smoke following inhalation exposure in mice (2019)

Researcher using automated furnace system.

Challenge: How can we understand the public health implications of exposure to smoke from peat, eucalyptus, and oak fires?

Approach: EPA researchers developed a purpose-built automated furnace system to precisely control the burning of three different biomass fuels (eucalyptus, peat, and red oak) representing the biomes of different regions of the U.S. under two combustion conditions (flaming and smoldering). By using this system, researchers could carefully monitor and ensure stable biomass smoke concentrations in the inhalation chamber and thus test the toxicity on mice.

Results: Although flaming smoke contains much less particulate matter by mass than smoldering smoke, it is, by mass, more toxic. Fuel type is also a factor in toxicity, with smoke produced from burning peat and eucalyptus causing more lung inflammation than smoke from oak.

Impact: This study helps to understand how smoke may differ across regions of the U.S. based on the ecosystem impacted and whether there are differences in biological responses to the smoke. This could help us understand whether the exposure reduction measures being used are effective, regardless of smoke composition.

Also, the novel furnace system produces reproducible and reliable biomass smoke inhalation toxicity data, which can be broadly applied in future studies, possibly to in vitro cell-based samples, which would reduce the need for animal-based studies.

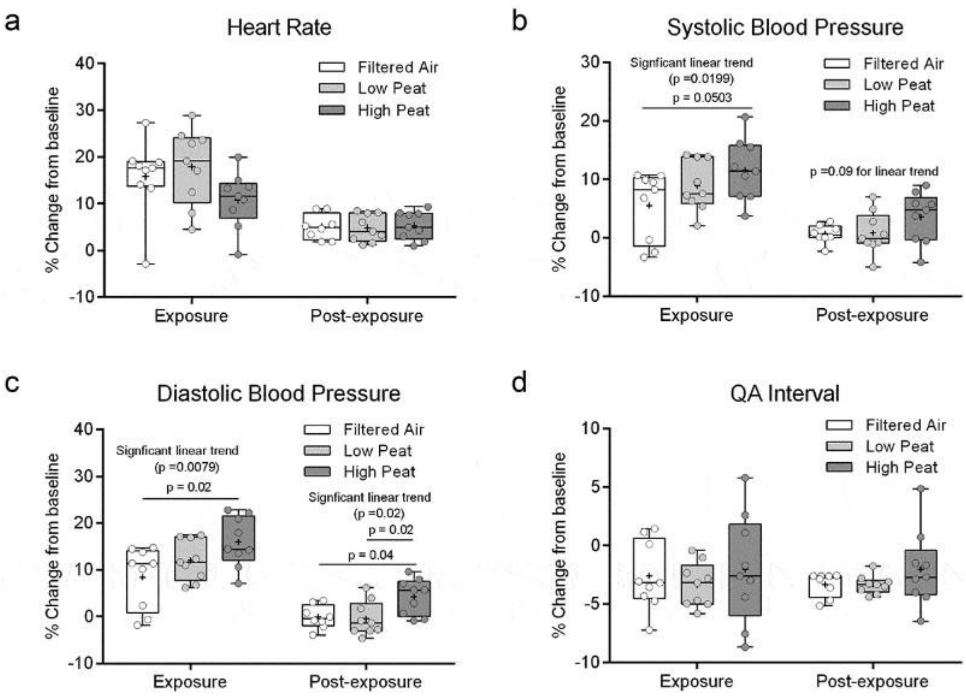
TOC
Intro
What's in Smoke
Smoke Measurement
Water & Ecosystems
Human Health
Reducing Exposures
Future Directions

5.2 Peat Smoke and Cardiovascular Health

➢ Peat smoke inhalation alters blood pressure, baroreflex sensitivity, and cardiac arrythmia risk in rats (2020)

Challenge: Smoke from peat fires can be a significant source of wildfire emissions for certain regions of the U.S. What are the effects of a single exposure to peat smoke on heart health, such as cardiac arrest risk?

Approach: EPA researchers generated peat smoke using an automated control tube furnace system and exposed rats once for a duration of 1 hour. The smoke contained either low (in the range of concentrations reported during previous (June 2008) peat fires in North Carolina) or high concentrations (on par with respirable PM exposure levels experienced by firefighters combating wildland fires) of particulate matter. The control was filtered air without smoke. Researchers measured heart rate and blood pressure using implanted telemeters and also measured other markers of inflammation.



Cardiovascular function during and after exposure to low peat, high peat, or filtered air, with values for heart rate, systolic and diastolic blood pressure, and QA interval (index of cardiac contractibility and a surrogate for heart function.) Source: Figure 4 in journal article.

Results: A single exposure to peat smoke produced markers of inflammation such as a rise in LDL cholesterol. Systolic and diastolic blood pressure showed an immediate rise upon smoke exposure, but the magnitude depended on peat smoke concentrations. Interestingly, exposure to low peat increased blood pressure, but there was no significant change to heart rate with high peat exposure.

Impact: Findings demonstrate that a single exposure to peat smoke has the potential to produce changes in cardiovascular function. Future studies could help identify the most offending chemical constituents of peat smoke and other biomass combustion emissions, as well as examine further how inflammatory markers change over time.

TOC
Intro
What's in Smoke
Smoke Measurement
Water & Ecosystems
Human Health
Reducing Exposures
Future Directions

5.3 Peat Smoke and Cardiorespiratory Health

➢ Peat bog wildfire smoke exposure in rural North Carolina is associated with cardiopulmonary emergency department visits assessed through syndromic surveillance (2021)

Challenge: In June 2008, smoke from burning peat deposits exposed rural communities in eastern North Carolina to haze and air pollution far in excess of National Ambient Air Quality Standards. What were the cardiorespiratory outcomes of those affected by the smoke?

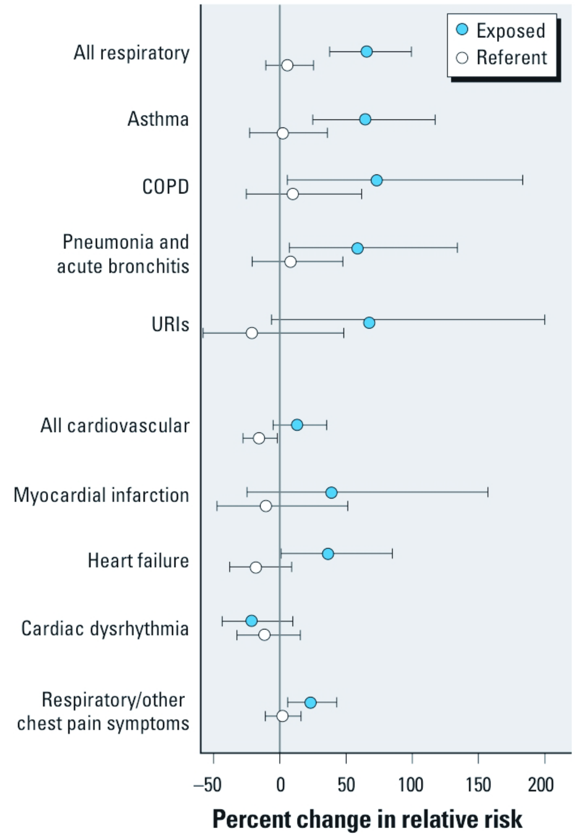
Approach: EPA researchers obtained data for emergency department (ED) visits for cardiac and respiratory conditions and combined with satellite data (provided measurements of aerosol optical depth to determine 3-day windows of high exposure). Counties were identified as either exposed (those most impacted by the dense smoke plume) or referent (surrounding areas).

Results: There is a consistent increase in relative risk in the exposed counties for nearly all outcome categories during and up to 5 days after exposure to wildfire smoke.

ED visits for all respiratory diagnoses were elevated in the exposed counties but not in the referent counties.

For individual respiratory outcomes, ED visits for sthma, Chronic Obstructive Pulmonary Disease (COPD), and Pneumonia and acute bronchitis increased significantly, while visits for Upper Respiratory Infections (URIs) also increased but were not statistically significant.

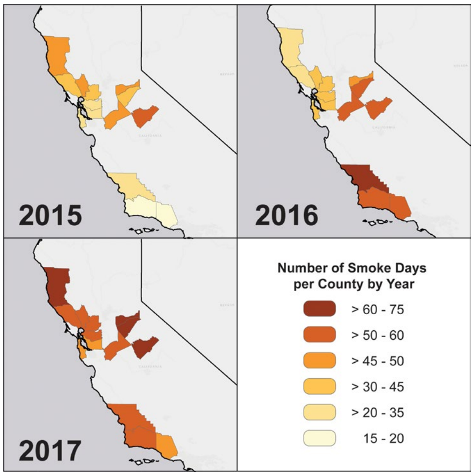
For cardiovascular outcomes, ED visits for Heart failure and overall cardiopulmonary symptoms increased significantly in the exposed counties.



Percent change in relative risk and 95% Confidence Intervals (CIs) by discharge diagnosis category for exposed and referent counties in North Carolina during the 3-day period of high exposure compared with the entire 6-week study period. The vertical gray line indicates the null hypothesis of no change in relative risk. Source: Figure 3 in journal article.

Impact: This is the first study to demonstrate both respiratory and cardiac effects after brief exposure to peat wildfire smoke. The increase in relative risk in the exposed counties is striking and has potentially significant public health implications, including how public health officials can raise awareness of health risks and improve their response efforts.

5.4 Wildfire Smoke and Cardiovascular Health

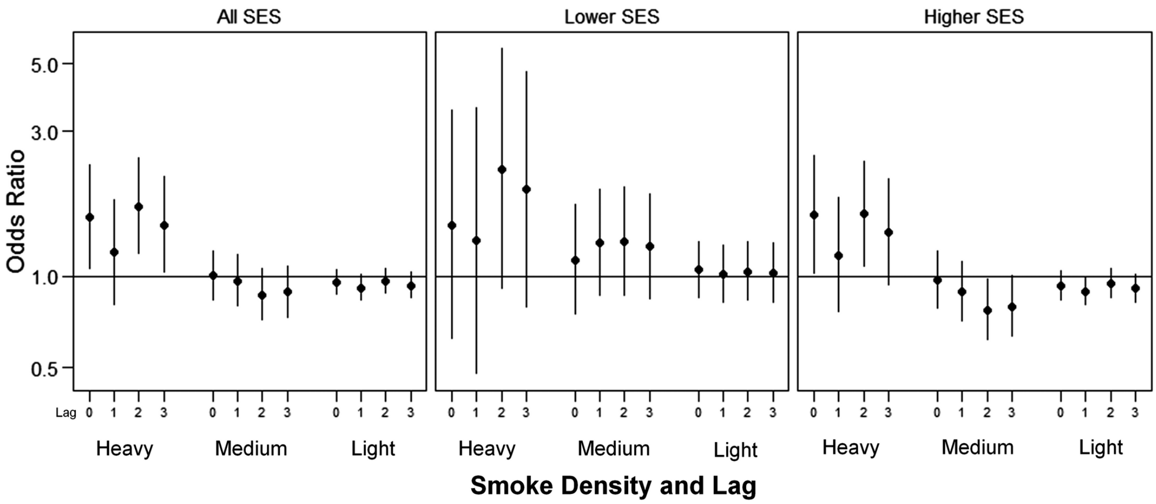


Map of the 14 California counties in the study showing the number of days impacted by wildfire smoke increased each year from 2015 to 2017. Source: Figure 4 in journal article.

- Out-of-Hospital Cardiac Arrests and Wildfire-Related Particulate Matter during 2015-2017 California Wildfires (2020)

Challenge: Does exposure to wildfire smoke increase the risk of out-of-hospital cardiac arrest (OCHA)?

Approach: Using observational epidemiologic data, EPA researchers examined the association between OCHA and wildfire smoke density (light, medium, heavy smoke) for 14 climactically and demographically diverse California counties during May-October (primary wildfire months), 2015 - 2017. Researchers used statistics such as odds ratios (which measure the strength of an association between exposure and outcome) and confidence intervals (CIs, which provide a range of plausible values).



Odds ratios and 95% CIs for out-of-hospital cardiac arrest in 14 California counties, May 2015 to October 2017, by wildfire smoke exposure on lag days 0 to 3 for the whole study population and stratified by socioeconomic status (SES). Source: Figure 2 in journal article.

Results: Smoke exposures from wildfires likely have the potential to trigger fatal and near-fatal cardiac arrest. The highest risk is on the heaviest smoke days, but risk persists for several days after (lag days). Lower socioeconomic status appeared to increase the risk. Both sexes and age groups 35 years and older were impacted on days with heavy smoke.

Impact: This was the first study in the U.S. to examine OHCA and wildfire smoke. As wildland fires become more frequent, more of the population will be exposed to smoke. Understanding the risk factors for adverse cardiovascular effects can help public health practitioners, especially those caring for the elderly and the most vulnerable populations, advise their patients about the risks of air pollution from wildland fire smoke.

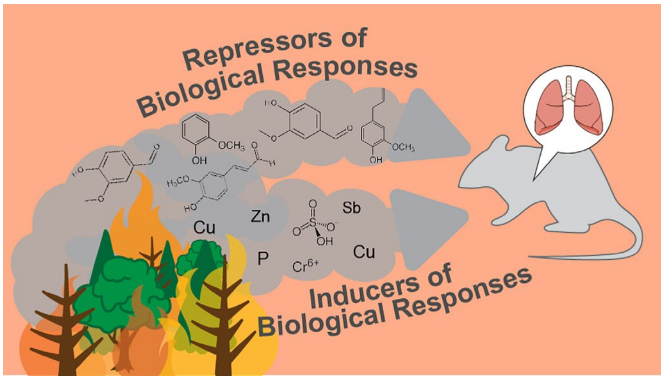
Related resources: US EPA's Learn about the Particle Pollution and Your Patients' Health Course

TOC
Intro
What's in Smoke
Smoke Measurement
Water & Ecosystems
Human Health
Reducing Exposures
Future Directions

5.5 Toxicity of Wildland Fire Smoke Mixtures

- [Mixtures modeling identifies chemical inducers versus repressors of toxicity associated with wildfire smoke](#) (2021)

Challenge: Wildfire smoke is a complex mixture of particulate matter (PM) and toxic gases that can cause a variety of health outcomes. Can we identify which chemicals (or mixtures of them) are primarily responsible for toxicity, and can these be used as common markers of exposure across different regions in the U.S.?



Mixtures-based approaches can identify groups of chemicals in wildfire smoke and the associated biological responses in the mouse lung show both potential drivers and inhibitors of toxicity. Source: graphical abstract in journal article.

Approach: Researchers used a purpose-built automated furnace system to burn five types of biomass fuel (eucalyptus, peat, pine, pine needles, red oak) representing the biomes of different regions of the U.S. under two combustion conditions (flaming and smoldering). A total of 86 chemicals were detected across the 10 resulting biomass smoke samples. Researchers exposed mice to individual and/or co-occuring chemicals, particularly those present in particulate matter and gas-phase semivolatile compounds.

Results: Researchers identified seven different groups of co-occurring chemicals and the biomass burn conditions that produced the greatest concentrations of chemicals in each group: peat flaming had the greatest overall concentration of inorganics and ionic constituents; eucalyptus smoldering had the greatest concentration of levoglucosan; pine needles smoldering had the greatest concentration of methoxyphenols and PAHs, and peat smoldering had the greatest concentration of n-alkanes. While some groups of chemicals, such as inorganics and ionic constituents, induced toxicity, other chemical groups, such as methoxyphenols, appeared to have protective effects.

Impact: While individual chemicals may have a small exposure effect, a mixtures modeling approach allowed researchers to look at the overall collective impact. Combining computational modeling of mixtures with biological responses allows decision-makers to understand how smoke may differ across the country and what wildland fire exposure conditions pose the highest risk to health. This can help guide strategies to reduce smoke exposures and protect public health.

5.6 Toxicity of Smoke from Burning Anthropogenic Materials

- Chemistry, lung toxicity and mutagenicity of burn pit smoke-related particulate matter (2021)

Burn pit at Millenia Productions – Burrton Superfund Site.

Challenge: Burn pits are a common way to dispose of military waste when standard waste management is not available, such as in a war zone. The open burning of humanmade materials can release pollutants hazardous to human health. We generally know what materials are being burned in the burn pits, but what is the potential toxicity of the pollutants that are released?

Approach: EPA researchers simulated military burn pits by burning anthropogenic materials under flaming and smoldering combustion conditions using a laboratory automated furnace. Selected materials were burned alone (cardboard, plywood, plastic), in a mixture (paper (49% by weight), plastic (27%), wood (24 %)), and as a mixture treated with diesel (10% by weight). (Jet fuel, diesel, or gasoline is added to ignite or accelerate the burn.) The smoke – the primary emissions and the smoke condensates (the particles created by burning) - were analyzed for a suite of chemical species, and the condensates were studied for pulmonary (lung) toxicity and mutagenicity (potential to cause genetic mutations).

Results: Significant increases in lung toxicity and mutagenicity were seen. The greatest effect was from burning plastic or plastic-containing waste, which emitted larger amounts of particulate matter compared to other types of waste. (Most of the smoke particles were less than 2.5 µm in diameter.) Comparing samples that have equal mass, the PM in smoke from the flaming combustion of plastic-containing wastes caused more inflammation and lung injury and was more mutagenic than other samples.

Impact: The findings help us understand how the waste type and combustion temperature influence the health effects of burn pit smoke exposure, while underscoring that burning plastic at high temperature is the most significant contributor to toxicity. This information can be used to protect the health of military personnel deployed in war zones. While this study focused on emissions from burn pits, the results can be relevant for smoke exposure to WUI fires, as the materials tested are also present during the burning of homes and structures.

Subsequent research (below) has further investigated the impacts of burn pit smoke on human pulmonary outcomes.

- Effects of simulated smoke condensate generated from combustion of selected military burn pit contents on human airway epithelial cells (2024)
- Simulated burn pit smoke condensates cause sustained impact on human airway epithelial cells (2025)

5.7 Wildfire Smoke and Brain Function

- Short-Term Exposure to Wildfire Smoke and $PM_{2.5}$ and Cognitive Performance in a Brain-Training Game: A Longitudinal Study of U.S. Adults (2022)

Challenge: Research on wildland fire smoke and health has focused primarily on physical health outcomes. What are the potential impacts of wildland fire smoke on brain health?

Approach: To understand how cognitive performance is influenced by short-term exposures to wildfire smoke, researchers conducted a study using the game app Lumosity, which is meant to test a player's ability to keep their focus. Researchers analyzed more than 10,000 Lumosity players between 2017 and 2018 and used game scores from players residing in areas with wildfire events to understand the effects of smoke on their performances.

Results: The study group included 10,228 contiguous U.S. users and 1,809 western U.S. users. Users had very similar characteristics; most were female and ≥50 years of age, and more than 90% lived in metropolitan areas across the U.S.. Western U.S. users were exposed to higher levels of PM2.5 on the day or hour of playing the game. Daily and subdaily $PM_{2.5}$ exposure were associated with decreased attention in adults within just hours of exposure.

Impact: This study adds to the growing evidence base indicating that wildfire smoke exposure can impact brain health, such as cognitive performance. As such, it supports the need to ensure risk communication and public health action includes information to protect physical health and brain health.

Related resources:

- EPA Science Matters: Fighting the Haze: Effects of Wildfire Smoke and Particulate Matter on Brain Function

6. What have we learned about reducing exposures to smoke?

Wildland fire smoke is a major public health issue. EPA's 2020 National Emissions Inventory estimated 52% of the total $PM_{2.5}$ emitted in the U.S. was from wildland fires. As wildfire smoke continues to impact the health of people across the United States, state agencies and community leaders want to know how best to educate and prepare residents on ways to reduce their smoke exposure and protect their health.

6.1 WF-ASPIRE

a) Field Studies: Indoor and Outdoor Concentrations
b) Lab Studies: Low-Cost Indoor Air Cleaners
c) Field Studies: Low-Cost Indoor Air Cleaners
d) Challenge: Cleaner Indoor Air During Wildfires
e) Wildfire Smoke Guidance for Building Managers

6.2 Smoke Sense

6.3 Smoke Ready Communities

6.4 Research Grants: Interventions and Communications Strategies to Reduce Health Risk

6.1 Wildfire Advancing Science Partnerships for Indoor Reductions of Smoke Exposures (ASPIRE) Study: A Solutions-Driven Research Pilot Project

- Lessons learned and recommendations in conducting solutions-driven environmental and public health research (2024)

Communities can be exposed to smoke from wildland fires for days, weeks, or even months each year. This smoke exposure can lead to increased health risks. To reduce exposure, a common recommendation is to stay indoors and close all windows and doors, but wildland fire smoke can infiltrate indoors. What actions can be most effective for building owners and the public to reduce health risks during smoke events?

Wildland fire smoke can infiltrate indoors.

ASPIRE study locations.

EPA researchers applied the principles of solutions-driven research, an approach that emphasizes working directly with stakeholders to develop solutions.

Stakeholders, including the Missoula Public Health, were interested in understanding indoor air quality and reducing indoor smoke exposures during wildfire smoke events. The Missoula, Montana area has mountain valleys and is frequently impacted by smoke from local and distant wildfires.

EPA researchers also partnered with the Hoopa Valley Tribal EPA in Hoopa, California, where tribal partners were interested in smoke impacts from residential wood burning and wintertime thermal inversions.

The communities were active partners in developing the study's the research questions:

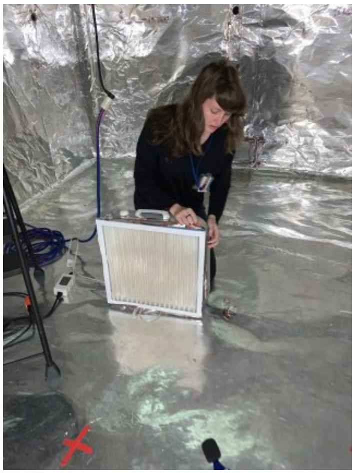
- How effective are air filtration systems during smoke events?
  - What are the concentrations of PM2.5 indoors and outdoors?
  - How does filtration effectiveness vary by outdoor concentration and type of air handling system?
- How effective are portable air cleaners in reducing PM2.5 concentrations?
  - What factors (e.g., operation and maintenance) are important in air cleaner effectiveness?
- What innovative approaches can help reduce wildfire smoke exposures?

Related resources:

- Wildfire Study to Advance Science Partnerships for Indoor Reductions of Smoke Exposures
- Preparing for Wildland Fire Smoke
- ASPIRE webinar (2025)

6.1a Lab Studies: DIY Air Cleaner Evaluations

- Impact of do-it-yourself air cleaner design on the reduction of simulated wildfire smoke in a controlled chamber environment (2022)
- Research on DIY Air Cleaners to Reduce Wildfire Smoke Indoors (website)

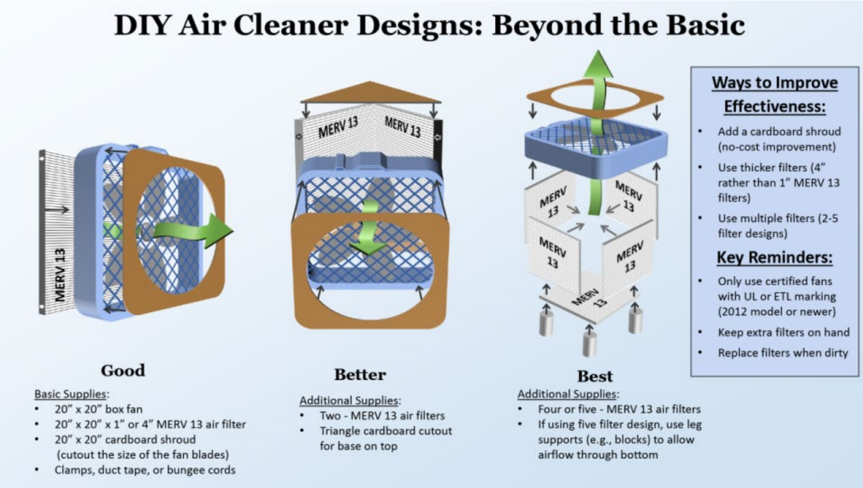


EPA researcher testing a DIY air cleaner.

Challenge: Are do-it-yourself (DIY) air cleaners safe and effective in a laboratory setting?

Approach: EPA researchers tested of the effectiveness and safety of low-cost, accessible, DIY air cleaners in improving indoor air quality during wildfire smoke events. Simulated wildfire smoke (from smoldering pine needles) was used in a room-sized chamber located in EPA's Research Triangle Park, NC laboratories. Researchers determined the Clean Air Delivery Rate (CADR) of the air cleaners. (The CADR is a standard measure of how well a commercial air cleaner can remove particles of a specific size from a standardized room.)

Results: DIY air cleaners can effectively reduce smoke concentrations in a laboratory setting. Increasing the fan flow (by changing the fan type, fan setting, or reducing the pressure drop across the filter surface) increased the CADR, but filters heavily loaded with smoke greatly reduced the CADR. The most cost-effective designs were those with multiple filters (the "beyond the basic" design). However, the use of a single 4" MERV13 filter was also highly effective and may be more suitable for small areas that cannot accommodate multi- filter designs.



EPA's infographic on DIY air cleaner designs.

Impact: This study provided a list of safety tips to follow when using DIY air cleaners, EPA's DIY design infographic to help the public build and use DIY air cleaners, and the recommendation that frequent filter changes may be needed during smoke events.

Related resources:

- An Evaluation of DIY Air Filtration
- EPA Science Matters: Do-It-Yourself Air Cleaners: Making Cleaner Air More Accessible

6.1b Use of Portable Air Cleaners in Hoopa Valley

- Usage and impact of a do-it-yourself air cleaner on residential $PM_{2.5}$ in a smoke-impacted community (2024)

Challenge: Are do-it-yourself (DIY) and commercial portable air cleaners (PACs) effective in a real-world setting?

Smoke pooling in Hoopa Valley, CA. Images taken by study personnel in the mornings of Oct. 11, 2019 (left) and Feb. 22, 2022 (right), the latter coinciding with the wood stove study. Source: Figure 1 in journal article.

Approach: Researchers measured indoor and outdoor $PM_{2.5}$, indoor CO_2, and main door activity in homes on the Hoopa Valley Indian Reservation during 8 wildfire and 11 woodstove pilot studies. Measurements were taken initially, then sequentially after providing homes with a DIY PAC (box fan with a MERV 13 filter attached), a commercial PAC, and a real-time air quality display with participants' choice of either or both air cleaners. Researchers then quantified reductions in total indoor infiltrated $PM_{2.5}$ and interviewed participants to learn about the barriers and facilitators of PAC usage.

Results: In the wildfire field study, DIY PACs reduced total indoor $PM_{2.5}$ and infiltrated $PM_{2.5}$ by 7–11%, while commercial PACs reduced infiltrated $PM_{2.5}$ by 18%, only slightly better. Outdoor $PM_{2.5}$ levels were low throughout the wildfire study and participants' use of doors and windows was not controlled.

In the wood stove field study, commercial PACs reduced total indoor $PM_{2.5}$ and infiltrated $PM_{2.5}$ almost twice as much as DIY PACs. During interviews, participants identified cost, noise and access to replacement filters as barriers to using PACs. While PACs can reduce $PM_{2.5.}$, their efficacy in smoke-impacted communities may depend on prior PAC ownership, ambient smoke conditions, and factors that affect user behavior (e.g., noise, size and appearance, and cooling effects).

Impact: Low-cost DIY PACs can reduce infiltrated and indoor-generated smoke (as quantified by $PM_{2.5}$) in residences at least as effectively as a commercial PAC with a similar CADR. ((The CADR is a standard measure of how well a commercial air cleaner can remove particles of a specific size from a standardized room.) One drawback of a DIY PAC is the box fan's noise level and undesirable cooling effect during cooler weather, which hinders consistent and long-term use; nevertheless, study participants indicated that they would use the DIY PAC during periods of significant wildfire smoke. For public health and local air quality agencies, an important takeaway is that PAC efficacy and usage depend on support for filter replacement (frequent filter changes may be needed during smoke events) and that quiet, unobtrusive designs are more likely to be used.

Related resources:

- EPA Science Matters: Multi-faceted EPA Research Addressing Threats to Public Health from Wildfire Smoke

6.1c Indoor $PM_{2.5}$ concentrations in Missoula

- [Influence of Building Characteristics on Wildfire Smoke Impacts on Indoor Air Quality]

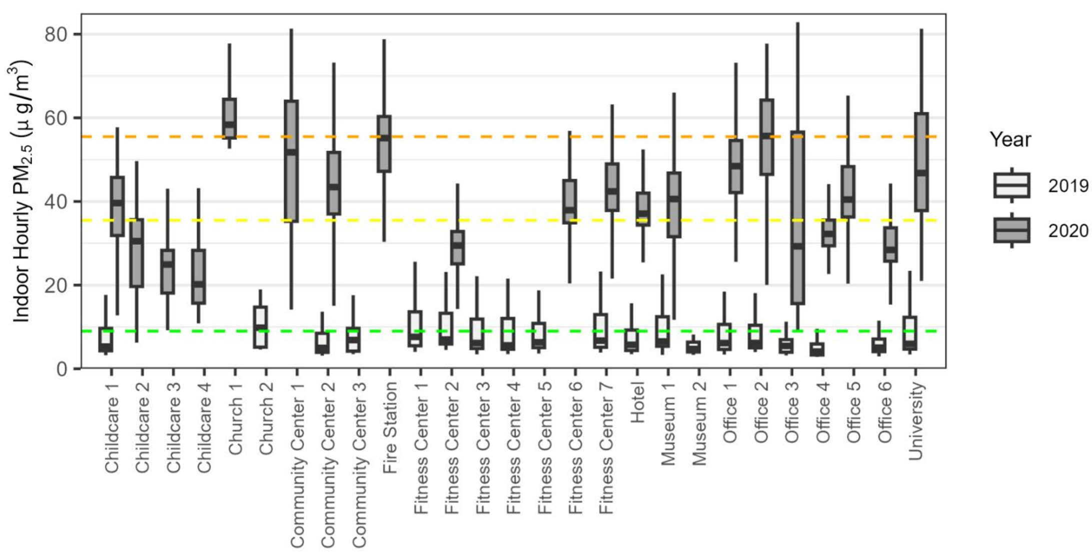
Challenge: How do building characteristics and heating, cooling, ventilation and air conditioning (HVAC) systems influence indoor $PM_{2.5}$ concentrations during smoke events?

Approach: EPA researchers, in partnership with Missoula Public Health, measured indoor and outdoor $PM_{2.5}$ in public/commercial buildings in and around Missoula, MT. Indoor sensors were installed in common areas, optimally near breathing height (but occasionally elevated to prevent tampering) and away from indoor sources or sinks of $PM_{2.5}$ (e.g., HVAC vents, air cleaners), and were paired with an outdoor sensor often adjacent to the building.

Locations of selected indoor sensors. Source: US EPA

Results: Indoor air quality was only minimally impacted in 2019, but 2020 – with a week of heavy smoke from western wildfires - had much higher outdoor smoke concentrations. The study found large PM2.5 reduction variability among study buildings and identified HVAC operation and maintenance characteristics that likely influenced indoor PM2.5 concentrations.

Indoor hourly $PM_{2.5}$ concentrations across all study locations during smoke events. (Not displayed are hours dominated by indoor sources.) Source: Holder, et al. submitted



Impact: Building managers received evaluations of their air ventilation systems. These evaluations identified how building characteristics or occupant practices affected indoor air pollutant concentrations. To prevent unhealthy smoke concentrations indoors, particularly in areas where wildfire smoke is more common, HVAC maintenance (e.g., replacing dirty filters, repairing dampers) is crucial. Also important is modifying the HVAC system (e.g., increasing the filter MERV rating), improving building weatherization, and managing door and window use.

Related resources:

- [EPA Science Matters: In the Field with EPA: Monitoring the Impact of Wildfires and Woodsmoke on Indoor Air Quality]

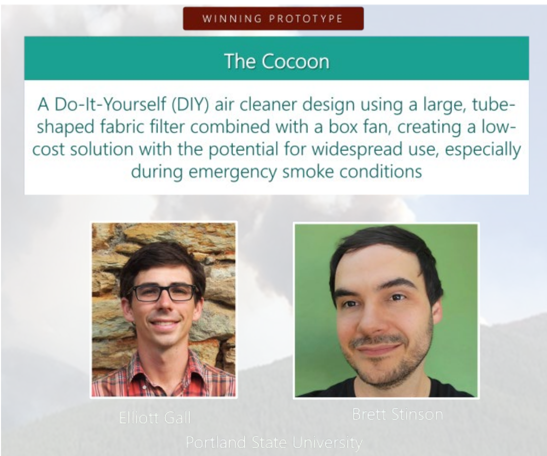
6.1d Challenge: Cleaner Indoor Air During Wildfires

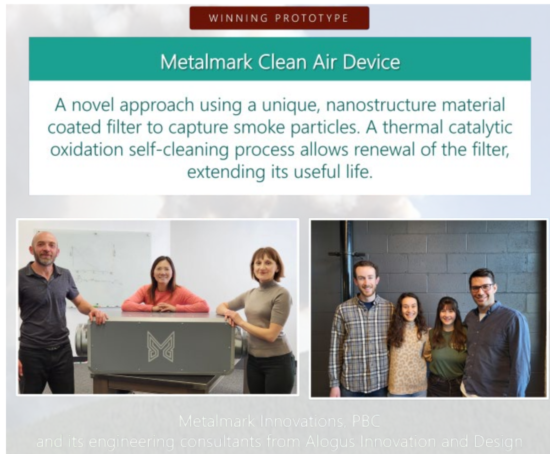
Challenge: How to encourage the development of new, effective, low-cost technologies that can clean indoor air during wildland fire smoke events?

Approach: EPA researchers launched a public prize challenge to spur innovation in developing lower cost approaches to provide clean air during smoke events.

Phase 1 was a theoretical or design challenge requiring an in-depth written proposal. Phase 2 encouraged the Phase 1 winners and honorable mentions to develop and submit a prototype of their proposed air cleaning technology. EPA evaluated prototypes on their ability to reduce smoke concentrations in a controlled environment, as well as safe operation, ease of use, low initial and operating costs, and ability to cool as well as clean.

Results: The results from Phase I were a set of potentially effective technologies. Results from Phase 2 were the two winning designs:





The Cocoon uses a large, tube-shaped, washable fabric filter combined with a box fan to create a low-cost air cleaning device.

The Metalmark Clean Air Device uses a nanomaterial coating on a filter to break down captured PM when the filter is heated to high temperatures.

Impact: This challenge resulted in two winning technologies that can reduce costs of providing cleaner air during wildfires. Metalmark Innovations, creator of the Metalmark Clean Air Device, subsequently received a Phase I award as part of EPA's annual Small Business Innovation Research program to develop a new nanostructured coating on the HVAC filter media to improve the removal of wildfire smoke.

Related resources:

- Winners of the Cleaner Indoor Air During Wildfires Challenge
- Cleaner Indoor Air During Wildfires Challenge (Webinar)
- EPA Awards Nearly $2.2M to Small Businesses to Advance Innovative Environmental Technologies

6.1e Wildfire Smoke Guidance for Building Managers

- Best Practices Guide for Improving Indoor Air Quality in Commercial/Public Buildings During Wildland Fire Smoke Events (2025)

Challenge: Can we provide plain language strategies that can help communities reduce indoor smoke exposures in commercial, public, and multi-unit residential buildings during wildland fire smoke events?

Approach: EPA researchers built upon the knowledge they gained during the field studies in Missoula, MT and Hoopa, CA (including building inspections) and worked with HVAC professionals and ASHRAE (formerly the American Society of Heating, Refrigerating and Air Conditioning Engineers) to develop best practices for reducing smoke exposures in buildings.

Results: EPA's Best Practices Guide is a concise and complete source of information on reducing the impacts of wildfire smoke indoors in commercial or public buildings. It is for 1) individuals and groups who make decisions regarding public, commercial, and multi-unit residential buildings including building owners and managers, school administrators, and facility managers, and 2) federal, state, local, and Tribal environmental and public health organizations that provide information to communities to reduce exposure to wildland fire smoke in public or commercial spaces. Contents include:

- HVAC Enhancements: Improving filtration and adjusting settings during smoke episodes.
- Building Adjustments: Improving weatherization and reducing indoor pollution sources.
- Air Sensors: Monitoring and comparing indoor vs. outdoor pollutant levels.
- Occupant Behavior: Managing HVAC operations and filtration, keeping windows closed.
- Example Smoke-Ready Checklist: Helping building managers prepare for, navigate, and recover from smoke events.

ASHRAE's version (Guideline 44: *Protecting Building Occupants from Smoke During Wildfire and Prescribed Burn Events)* is available from the ASHRAE Bookstore

Impact: Public health guidance that recommends individuals remain indoors during a smoke event are hampered if commercial and public buildings allow smoke intrusion through their HVAC systems or other building factors. This guidance provides best practices for building operators on how to reduce smoke infiltration and exposure and provide cleaner indoor air for occupants during wildland fire smoke events.

HVAC equipment on rooftop of a commercial building. Best practices are designed for commercial and public buildings that use HVAC systems with air handling units that bring in outside air or recirculate indoor air.

More information:

- Wildfires and Indoor Air Quality in Schools and Commercial Buildings
- An Introduction to ASRHAE Guideline 44: Protecting Building Occupants from Smoke During Wildfire and Prescribed Burn Events (Webinar)

6.2 Smoke Sense

Challenge: During smoke events, what communication is most effective in helping people understand the health risks of smoke exposures and what they can do to protect themselves? Can we improve communication strategies using input from citizen scientists?

Approach: EPA's Smoke Sense was a crowdsourced, citizen science research initiative. The goal was to better understand the health effects of wildland fire smoke and identify effective risk communications strategies. A central component was the Smoke Sense smartphone app, which encouraged public participation. Through the app, users could access current and forecasted air quality information, a map with current fire locations and smoke plumes, and educational information. Users could report personal health symptoms and smoke observations.

Results: Smoke Sense was a platform to demonstrate and test how social science concepts can be used to improve current health risk communication strategies. Between 2016 and 2024, the Smoke Sense app was downloaded by more than 60,000 users, who learned about smoke and air quality conditions in their area and provided observations about their experiences with smoke, health symptoms and exposure-reducing behaviors. User participation with the Smoke Sense app generated many research findings. One study identified five traits (Protector, Cautious, Proactive, Susceptible, Unengaged) of app users that characterized their relationship with health, air quality, and exposure-reducing behaviors. Another study found that participants expected to use the app and crowd-sourced data to enhance and support their existing smoke outreach and communications. Overall, there was a clear demand for personally relevant data during wildfire episodes motivated by recognition of environmental hazard and the personal concern for health.

Impact: While no longer active, the Smoke Sense app played a pivotal role in advancing our understanding of risk communication and health protective behaviors for wildfire smoke exposure. Smoke Sense pioneered innovative engagement strategies leveraging smartphone app technologies, interactive data visualization tools, and gamification elements to enhance user participation and comprehension. By making complex scientific information accessible and engaging, we can engage diverse audiences, reach more people, and empower them to make informed decisions on proactive measures that could protect their health during wildfire smoke exposure.

Related resources:

- Smoke on the horizon: leveling up citizen and social science to motivate health protective responses during wildfires (2024)
- Estimating spatially varying health effects of wildland fire smoke using mobile health data (2024)
- Promoting risk reduction among young adults with asthma during wildfire smoke: A feasibility study (2021)
- Knowing Your Audience: A Typology of Smoke Sense Participants to Inform Wildfire Smoke Health Risk Communication (2020)
- Scaling Up: Citizen Science Engagement and Impacts Beyond the Individual (2020)
- Smoke Sense Initiative Leverages Citizen Science to Address the Growing Wildfire-Related Public Health Problem (2019)

6.3 Smoke Ready Communities Research to Prepare for Wildfires

Challenge: How can we improve the ability of communities to plan for and respond to smoke from wildland fires? Does a collaborative approach to planning for future wildfire smoke events influence community public health readiness?

Approach: EPA researchers partnered with the U.S. Forest Service on a multidisciplinary project built around a series of interactive workshops with local community public health partners in Butte-Silver Bow, Montana and Garfield County, Colorado. Local teams collectively developed their community smoke response plans. Researchers examined the *process* of collaboration, specifically the role of community-level influencing factors and early outcomes.

Results: Local teams developed tailored wildfire smoke public health response plans that have been used to protect public health during at least two wildfire seasons. The Garfield County Public Health Department brought together a multidisciplinary team with representatives from the local public health, government, land and resource management, Spanish interpretation and translation, fire rescue, and communications sectors. The Butte-Silver Bow Health Department also participated in the initiative and formed a multidisciplinary team that assessed their community's needs related to wildfire smoke and wrote a community smoke readiness plan.

Impact: The Smoke Ready Communities research demonstrated the effectiveness of using a collaborative governance approach to strength community resilience to wildfire smoke and to inform the development of a Smoke Ready Communities program. This approach can be used by public health professionals, emergency response organizations, air quality managers and others to assist communities in preparing for wildfire smoke events.

Related resources:

- Smoke-Ready Toolbox for Wildfires
- EPA Science Matters: Partners Collaborate in Smoke-Ready Communities Research to Enhance Local Readiness for Wildfires
- Smoke Ready Communities Research Study (Webinar)

6.4 Research Grants: Interventions and Communications Strategies to Reduce Health Risk

- Interventions and Communication Strategies to Reduce Health Risks of Wildland Fire Smoke Exposure

Challenge: How can we engage experts in institutions outside EPA to help understand what actions might be effective for reducing exposures to wildland fire smoke and how best to communicate these actions to various groups?

Approach: In 2021, as part of its Science to Achieve Results (STAR) program, EPA funded 12 external research grants to 1) assess the effectiveness of interventions to reduce individual and community exposures and associated health risks from wildland fire smoke and 2) develop and assess the effectiveness of health risk communication strategies in supporting actions to reduce wildland fire smoke exposure.

Results: Publications with the research results are available for the 12 projects:

- Informing School Decision-making During Wildfire Events: Evaluation of Indoor $PM_{2.5}$ Exposures and Associated Health Impacts in Children
- School Resilience to Wildland Smoke and Outdoor Sources of Fine & Ultrafine Particles
- **H**ousehold **A**tmospheric **D**ynamics under **E**levated **S**moke (HADES): Holistic Evaluation Of Interventions For Reducing Indoor Levels Of Wildland Fire Emissions
- Participatory Design Of Effective Risk Communication About Wildfire Smoke For Hard-to-reach Populations
- **F**iltration For **R**espiratory **E**xposure To Wildfire **S**moke From **S**wamp **C**ooler **A**ir (FRESSCA)
- Development, Implementation, and Evaluation of Stakeholder-driven Wildfire Smoke Monitoring and Messaging in Rural Nevada
- Assessing the Transport of Wildfire-generated Particulate Matter into Homes and Developing Practical Interventions to Reduce Human Exposure (WildPM)
- Evaluating the Effectiveness of Interventions on Reducing Wildfire Smoke Exposure and Health Risks in Low-income Hard-to-reach Communities in California
- Enhancing Communication to Reduce Health Risks of Wildland Fire Smoke Exposure due to Prescribed Burns
- Integrated Communication and Intervention Strategies to Reduce Exposure to Prescribed Wildland Fire Emissions in Schools, Schoolchildren and Communities
- A Community-aligned Action Plan for Effective Communication of Wildland Fire Smoke Exposure Risks
- Smoke-ready Communities, Creating and Sustaining Air Quality Information Using Targeted Communication Interventions

Impact: The research findings have helped us understand practical actions that can reduce exposures to wildland fire smoke and better ways to communicate these actions to different groups.

7. Future Directions

EPA is at the forefront of understanding wildfire smoke, with an early recognition of the significant and increasing impact on air quality and public health.

This briefing book is an overview of EPA wildland fire research with publications spanning from 2019 to 2024. Over that time, EPA improved models and measurement methodologies to assess emissions, determined what ecosystems and populations are vulnerable to wildland fires and smoke, and developed and evaluated approaches to mitigate risks to human health and ecosystems.

EPA continues to work on still unanswered questions and unaddressed challenges. We are well-positioned to provide research – through our expertise in emissions, air quality, health and ecosystems - for those affected by wildland fires.

Check back with us through our [Wildland Fire Research](#) web page as we support the following topics:

- **7.1** Emissions from Wildland Fire
- **7.2** Air Quality Measurements During Smoke Events
- **7.3** Ecosystem Impacts of Wildland Fire Smoke
- **7.4** Health Impacts of Wildland Fire Smoke
- **7.5** Interventions to Reduce Smoke Exposures

TOC
Intro
What's in Smoke
Smoke Measurement
Water & Ecosystems
Human Health
Reducing Exposures
Future Directions

7.1 Emissions from Wildland Fire

EPA researchers *developed, tested, and applied emerging air measurement technologies* to measure and understand smoke emissions and air quality. The foundation has been laid through *mobile monitoring units* that can assess real-time smoke conditions in affected areas, *remote sensing technologies* to aid in the tracking of smoke and using *controlled burns in a laboratory setting* to estimate emissions generated from actual wildland fires.

Future:

- The U.S. is experiencing greater frequency of fires in the wildland-urban interface (WUI) and recent fires have resulted in substantial destruction of buildings and vehicles. Potential EPA research will help to *improve emission factors related to WUI fires* that include the burning of human-made structures and materials.
- While prescribed burns may individually produce less smoke than a wildfire, they may be more frequent and widespread. Potential EPA research will help understand the *air quality and health impacts of smoke emissions from repeated and simultaneously occurring prescribed fires* and *develop air quality models to understand the public health impacts* of wildland fire smoke from prescribed fires and wildfires over time and across geographic areas.

7.2 Air Quality Measurements During Smoke Events

EPA researchers have *increased coverage of particulate matter concentration* measurements during wildland fire smoke events, *supplemented air monitoring in areas affected by wildfire smoke* through the WSMART program, and used air monitoring instruments to *analyze smoke composition and predict where smoke would travel*. This work has helped reduce public health risks.

Future:

- Potential EPA research will help develop and evaluate *air quality sensors for pollutants beyond particulate matter*.
- With demonstrated state, local, and Tribal interest in supplemental air monitoring, a possible focus is on *sensor loan availability and training* to support the WSMART program.

7.3 Ecosystem Impacts of Wildland Fire Smoke

Wildland fire smoke is a complex stressor that can have both short-term and long-term effects on the structure and function of ecosystems. By examining the *effects of wildland fires on salmon populations* in the Pacific Northwest and finding that while salmon populations are declining due to raised temperatures of wildland fires, EPA researchers have investigated cold water refuges (areas of a river that are colder in temperature than the main body of the river) and how these can ensure salmon survival. EPA researchers also analyzed the water quality in 31 streams in Oregon to provide insight into *post-fire water quality changes* and provided information that can be used by drinking water providers and water resource managers.

Future:

- Potential EPA research will continue mapping and modeling *watershed resilience to wildfire*.
- By evaluating strategies that reduce adverse hydrologic and water quality effects from wildfires, we can understand *how ecosystems respond to a changing climate*.

7.4 Health Impacts of Wildland Fire Smoke

The *health effects of wildland fires and smoke have extensive, cascading consequences*, affecting not only the immediate physical health of individuals exposed, but also their long-term well-being. EPA researchers made many key advances in understanding how smoke affects human health and those most vulnerable. EPA researchers developed a *better understanding of how smoke exposure effects brain function*. They also investigated the difference in emissions and health effects from different types of fuel (such as peat vs eucalyptus) burned under different types of wildland fire combustion (such as flaming vs. smoldering).

Future:

- Potential EPA research will continue *to improve understanding of how wildland fire smoke exposure affects human health*.
- The results of the ASPIRE-Health study, started in 2021, are being analyzed to determine baseline air quality conditions in homes with DIY air cleaners and any *health benefits of DIY air cleaner use*.
- EPA researchers continue to analyze how smoke affects health, including through gestational and postnatal exposure to wildfire smoke. EPA researchers are investigating *how wildland fire smoke exposures affect birth outcomes*, including low birth weight and preterm birth.

TOC
Intro
What's in Smoke
Smoke Measurement
Water & Ecosystems
Human Health
Reducing Exposures
Future Directions

7.5 Interventions to Reduce Smoke Exposures

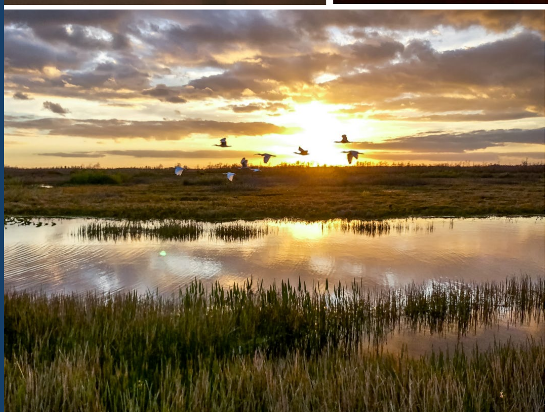
With larger and more intense wildfires, there is a greater potential for smoke production and chronic exposures in the U.S. Effects of smoke from wildfires can range from eye and respiratory tract irritation to more serious disorders, and smoke exposures are known to cause increased visits to hospitals and clinics. Children, pregnant women, and the elderly are especially vulnerable to smoke exposure.

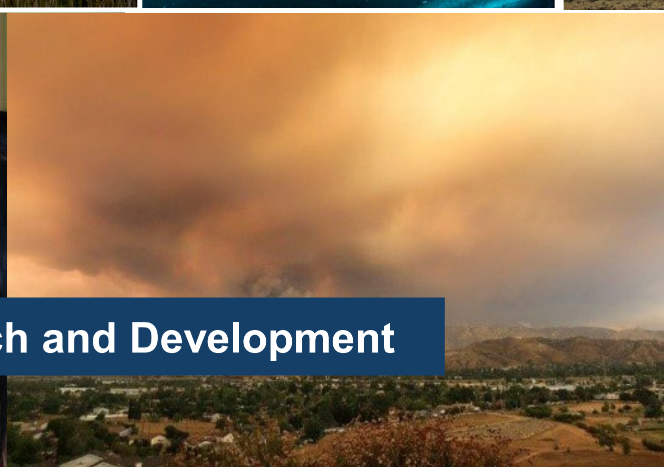
Reducing smoke exposures is critical to mitigating widespread health and environmental consequences. EPA researchers have worked on strategies to communicate, educate, and prepare people who may be at risk to smoke exposure. Smoke Sense, a citizen science mobile phone app, was developed to share real-time fire, smoke, and air quality data, and more than 60,000 users downloaded it to share their experiences with smoke and its impacts on their health. The ASPIRE study *evaluated Do-It-Yourself (DIY) air cleaners* to answer questions from EPA partners and the public about their effectiveness and safety. Researchers showed that DIY air cleaners, made with a box fan and MERV 13 air filter(s), were a cost-effective method for reducing indoor smoke concentrations.

Future:

- Potential EPA research will continue identifying how to *best communicate, educate, and prepare people* who may be at risk to smoke exposure.
- Potential EPA research will continue work in developing and evaluating methods to *reduce individual and community air pollution exposures* in the coming years.

Close the Binder





Office of Research and Development