Joint Fire Science Program
Fire Science Brief
RESEARCH SUPPORTING SOUND DECISIONS

Yosemite Valley on a clear day and a day obscured by smoke from fires.
Credit: Interagency Monitoring of Protected Visual Environments, or IMPROVE.

Seeing Through the Haze: A Tool for Apportioning Emission Sources for Use in Smoke Management Programs

Summary

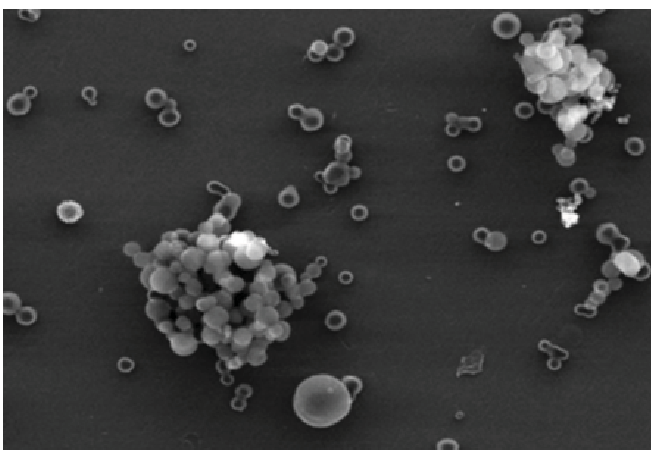
Evidence shows that smoke from fires (wildfire, controlled burning, and agricultural burning) is contributing significantly to fine particulate matter ($PM_{2.5}$) and haze in many urban and rural areas, affecting health, visibility, and ecosystems. In addition to the primary particulate matter directly emitted by fires, gaseous organic compounds are emitted that transform into “secondary” particulate matter downwind from fires, which contributes notably to $PM_{2.5}$ and haze. States and tribes are required to implement programs to reduce emissions to meet the requirements of the Environmental Protection Agency’s (EPA’s) National Ambient Air Quality Standards and Regional Haze Rule, and central to any meaningful implementation plan is an understanding of which sources contribute to these pollutants. Air quality regulators must be able to correctly identify the sources so that managers can implement emission reduction strategies that will assist in the attainment of air quality standards. This project has developed new methodologies and tools for use by experts to better quantify what portion of fine particulates comes from fire, and of that amount, to determine how much comes from wildfire, prescribed fire, and agricultural burning. This information can then be directly used by air quality regulators to develop and implement plans to reduce $PM_{2.5}$ and haze below regulated thresholds. However, information gaps remain: secondary particulate matter is not currently properly accounted for in estimates of contributions from fires and other sources, and information classifying fire type has not been integrated into emissions inventories. Several entities are currently working towards routine generation of this much needed information.

Key Findings

- Smoke from fire affects air quality significantly; thus, managers need tools to retrospectively assess its contributions to fine particulate matter.
- Twenty-five to fifty percent (or more) of the annual average fine particulate matter comes from biogenic sources, including fires and secondary organic material from the natural respiration of vegetation.
- Emerging evidence indicates that secondary particulate matter can significantly increase the amount of fire's contributions to fine particulate matter levels.
- We currently lack the mechanistic understanding to predict the amount of secondary particulate matter from fires, and thus current models can inaccurately attribute the secondary material from vegetation to fires and vice versa. Such misidentification can cause states to implement smoke mitigation strategies that do not assist the federally required attainment of air quality standards.
- By combining source-oriented air quality models with receptor models, hybrid source apportionment modeling was successful at improving estimates of fire's contributions to fine particulate matter.

Smoked out

Seeing and breathing. We tend to take both for granted until arriving at, say, Yosemite National Park, ready for the dazzling views and wait, where are the mountains? They were *right here* last time. Or you have to forego the daily run or dog walk due to air choked with particulates. And then consider the individuals dealing with asthma. Air quality regulators—the folks working on such problems—have two over-arching goals: 1) reduce fine particulate matter to safe health levels, and 2) reduce haze in national parks and wilderness areas to natural conditions.



Electron microscopy of fine particulate matter from fires.

So, what exactly is fine particulate matter? Also known as $PM_{2.5}$ (referring to particles less than 2.5 microns), it is composed of compounds from different sources, such as the combustion of fossil fuels in power plants and cars, and also biogenic sources, such as fire and secondary organic material formed from gases emitted by the natural respiration of vegetation. Until recently, air pollutant regulators were looking mainly at reducing $PM_{2.5}$ contributions from power plants, factories, and vehicles. But emissions from many of these sources have significantly decreased over the past two decades, thanks mainly to stricter legislation. So, they began looking to other sources. Evidence revealed that smoke from fire is contributing considerably to fine particulate matter and haze, but just how much was still unclear because the tools necessary to determine amounts were lacking. It turns out that biogenic sources are contributing significantly to fine particulate matter: over 50 percent of $PM_{2.5}$ in many rural and urban areas (see Figure 1). In addition to affecting visibility and creating adverse health effects, smoke from fires also influences earth's radiation balance and ozone levels. The haze both absorbs and reflects solar radiation, thereby affecting climate. Moreover, emissions from fires contribute to elevated ozone concentrations that can damage plants and also affect nitrogen deposition, which can alter plants in the ecosystem.

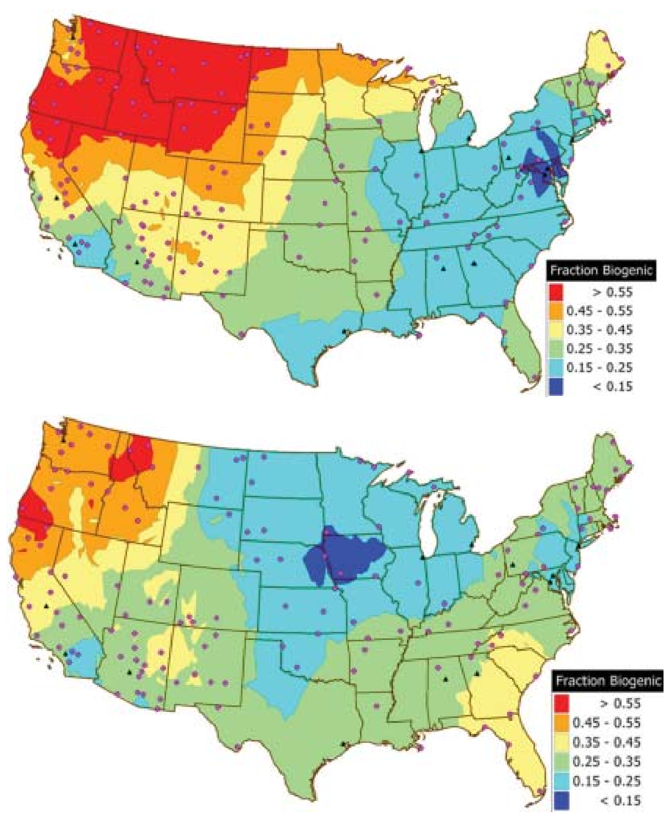


Figure 1: Contribution of biogenic sources, including fires, to fine particulate matter during the summer (top) and winter (bottom).

Following the rules

Ambient $PM_{2.5}$ is regulated under the Environmental Protection Agency's (EPA) National Ambient Air Quality Standards (NAAQS), which set limits on the concentrations allowed to protect public health and the environment. Haze in national parks and wilderness areas, collectively known as Class 1 Areas (C1As), is regulated via the EPA's Regional Haze Rule (RHR). Haze from smoke arises from both natural wildfires and human-caused fires, including controlled and agricultural burning, both inside and outside the United States. The RHR requires that a clear distinction be made between natural and anthropogenic sources, in addition to identification of the amount and type of haze. Both the RHR and NAAQS have routine monitoring programs to support these regulations. The Interagency Monitoring of Protected Visual Environments (IMPROVE), a federal land management agency/EPA monitoring program that collects data on fine particulate matter concentrations in and near C1As, was established to track progress toward the RHR goal. And the Chemical Speciation Network (CSN), a U.S. EPA monitoring system that's similar to IMPROVE, was established to help understand the causes of $PM_{2.5}$ exceedances and trends in $PM_{2.5}$ over time. States and tribes are required to 1) develop and implement plans and programs to reduce emissions sufficient to attain and protect the NAAQS and 2) make reasonable, steady progress to reduce anthropogenic emissions to achieve the RHR's long-term natural visibility and ecosystem protection goals.

Sleuthing out the sources

So, central to any meaningful implementation plan is an understanding of which sources contribute to these pollutants, and regulators are beginning to look to sources of smoke to achieve needed decreases. The smoke source type is important since natural sources of haze are not controllable under the RHR, but human-caused are. Although annual natural wildfire accounts for the majority of smoke emissions in the western United States, prescribed fires can significantly contribute to haze (in some cases close to 100 percent) and $PM_{2.5}$ events. Most controlled burning in the U.S. takes place from late winter to late spring (although burning varies by region) whereas wildfires typically occur in the summer. In Figure 2, you can see that fires during the spring months contribute about 10 percent to fine particulate matter in the Northwest and up to 30 percent in the Southeast.

Not only do we need to differentiate between natural and human-caused sources, but yet a finer distinction must be made at the modeling level to account for how much of the $PM_{2.5}$ is composed of primary particulate matter and how much is secondary particulate matter. Some brief background here: fires emit both primary particulate matter and also gaseous organic compounds (called volatile organic carbon or VOCs). Some of these gaseous compounds will undergo chemical reactions, transforming them into "secondary" particulate matter. In addition, non-burning vegetation also emits VOCs, contributing to secondary particulate matter. In short, the total $PM_{2.5}$ is the sum of the primary and secondary particulate matter.

The project team was surprised to find just how much secondary particulate matter is contributing to $PM_{2.5}$. We know that fires contribute significantly to the air pollutant problem, and when the contribution of secondary particulate matter from vegetation is added into the mix, the total $PM_{2.5}$ that comes from biogenic sources rises considerably. In Figure 1, you can see that during the summer in the Northwest, approximately 60 percent of the $PM_{2.5}$ was due to biogenic sources (fires and secondary particulate matter). In Figure 2, of that 60 percent $PM_{2.5}$ from biogenic sources, fires account for about 40 percent of the summertime fine particulate matter in the region. So, doing the math, the remaining 20 percent would constitute contributions from secondary fine particulate matter from vegetation. Moreover, near the fire, concentrations of primary $PM_{2.5}$ are high; but downwind from the fire, the primary tends to become diluted and, at the same time, the chemical reactions of the gaseous compounds are taking place and increasing the concentrations of the secondary $PM_{2.5}$. Principal investigator Bret Schichtel explains the significance, "Being able to model and account for the secondary $PM_{2.5}$ is what's important. The current models do not adequately do this, so they're going to overestimate concentrations near the fire and underestimate them further away. So if we properly account for the secondary fine particulate matter, we can better simulate fire's contributions to $PM_{2.5}$."

So, the bottom line is that, without the measurement and analysis tools to properly identify the sources of $PM_{2.5}$, smoke from fire management practices could be misidentified as the cause of haze and violations of air quality standards. Such misidentification can cause states to implement smoke mitigation strategies that do not assist the federally required attainment of air quality standards and progress toward improving haze conditions in parks and wilderness areas.

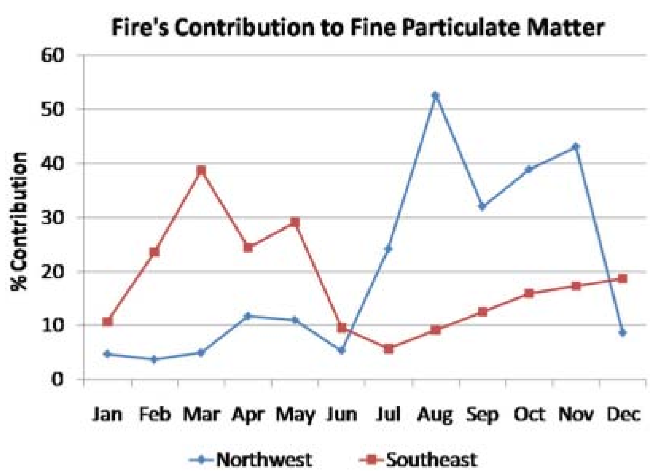


Figure 2: Estimated seasonal contribution of fires to fine particulate matter in the rural Northwest (states: Washington, Oregon, Idaho, and Montana) and the rural Southeast (states: Arkansas, Alabama, Georgia, and Florida).

Tools for following the rules

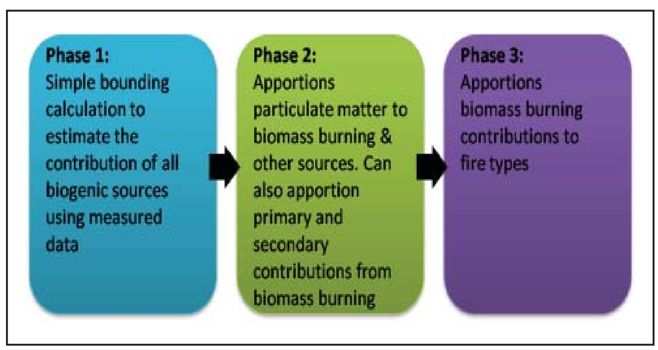
To obtain the goals of the RHR and meet the requirements of the NAAQS, air quality regulators need routine and cost-effective analysis tools, and these can be categorized into Operational and Retrospective tools. An example of operational tools in use would be a controlled burning situation where managers need to know if it's okay to burn. Models that simulate where the smoke will go help managers make "go/no-go" decisions. And in the case of a current fire, such models can also allow for advanced warning to communities if it appears the smoke is heading their way. Retrospective tools, on the other hand, provide information on the causes of past air quality events, which is needed to assess the efficacy of smoke management policies. Or, if a particulate exceedance occurs in an area, regulators need to be able to determine what caused the exceedance and why the management plans in place are not adequate. The purpose of this study was to develop a framework for apportioning smoke contributions to particulate matter. Note that it was not meant to develop operational tools suitable for use by general air quality regulators; rather, the investigators have been using these retrospective tools for internal studies and have then been sharing the information with states, which use this information in State Implementation Plans.

Merging models

Smoke source apportionment has traditionally been conducted using source-oriented air quality models (also called chemical transport models) and receptor models. Both have strengths and weaknesses. Air quality models start from the source and attempt to directly simulate pollutant emissions, their transport, and fate. Receptor models, on the other hand, work from the end-point. They rely on the fact that sources emit a unique proportion of aerosol constituents known as their "source profile," and then use measured chemical and physical characteristics of the particulate matter to apportion it to various source types, such as fires or mobile (automobile) and point (industrial plants/factories) sources. Schichtel illustrates: "The air quality models are forward-looking; they start with the fire, it emits material, we trace that through the atmosphere, and look at it when it hits the receptor. The receptor models look back in time; we begin by measuring the material that's hitting the receptor and then try to determine where it came from." Both types of models have their limitations, however. The air quality models can't distinguish well between primary and secondary fine particulate matter. They can "take a stab at it," but the results are subject to large unconstrained errors and biases. And although receptor models are constrained by measured data, which can reduce their errors, they have difficulty in separating fire's contributions to $PM_{2.5}$ from contributions of secondary organic material, and some receptor models account only for the primary particulate matter, not the secondary. In addition, these models have difficulty in differentiating between smoke type sources.

Hybrid source apportionment modeling directly combines measured data from the receptor models with air quality modeling results, ideally preserving the source type resolving power of the air quality models and satisfying the source profiles of the receptor models, all with results that are bounded by measured data. Air quality and receptor models have complementary benefits, and combining their results helps to offset the limitations of using either model alone, thereby reducing errors in the final source attribution results.

The hybrid receptor modeling methodology developed as part of this project has three phases. The first phase involves a simple bounding calculation to estimate the contribution of all biogenic sources. Schichtel explains, "Basically, we look for patterns or 'finger prints' in the measured data. Different sources have different profiles." The model measures the ratio of elemental carbon (EC) to organic carbon (OC) because fossil sources (such as industrial plants) have a different EC/OC profile than do biogenic sources. The biogenic sources then become the upper bound for determining contributions from fires. The second phase apportions the particulate matter to fires and other sources (such as mobile and point). And if it has the necessary inputs, it can also apportion average primary and secondary contributions from fires. Phase 3 builds on the information from phase 2 to apportion fire's contributions to fire types. This is done using air quality modeling results and relies on fire classifications in the emissions inventories; however, this information is generally missing and represents an issue requiring future activity. Lastly, future plans include developing the ability to apportion fire's contributions to source regions, such as individual states. Because of a current lack of necessary inputs, however, the model can only successfully perform the first two phases. According to Schichtel, "As things now stand, we're basically 'stuck' in phase 2 because we don't yet have the emissions data—the necessary model inputs—to complete phase 3."



Hybrid source apportionment modeling methodology. The process begins with measured data (applying the receptor modeling framework). Each phase requires additional information, and phases 2 and 3 build upon data from previous phases. Data needed for phase 3 are not yet readily available and represent an issue requiring future activity.

The project involved extensive outreach to the federal, state, and private scientific and regulatory communities. The research team was actively involved with the IMPROVE Program, the Western Regional Air Partnership (WRAP), the Forest Service, and the Fish and Wildlife Service. Through a series of meetings and workshops, the team shared information on the project and solicited feedback, learning about the existing needs and also explaining what the models can provide. Work groups were formed, including participants from the Forest Service, National Park Service, and the Western Governors Association, to address the information gaps and enhance the data in the emissions inventories. In addition, WRAP and other regional planning organizations are working to implement the RHR, so they are holding extensive discussions about the type of data needed to satisfy the requirements of the RHR. In the future, WRAP will be revisiting the regional haze issue and contributing sources. At that point, these hybrid models will become highly important to both states and the EPA.

We have presented here only a very simplified version of the hybrid source apportionment model. If you are interested in learning the technical details of the methodology, refer to the final project report located on the Joint Fire Science Program's website, project 05-3-1-04.

Finishing the job

Work remains. First, as mentioned above, secondary particulate matter contributions are not adequately accounted for in estimates of fire's contributions. Specifically, the current source-oriented models do not contain all of the needed information to simulate the secondary material, and the compounds necessary to estimate the contributions of secondary particulate matter from smoke have not yet been identified for use in receptor models. Second, information classifying fire type for many fires does exist in ground-based fire reports, but is not integrated into routine emissions inventories. Once this information has been incorporated, the hybrid receptor models can, in concept, be used to apportion the smoke to different fire types. Third, the hybrid receptor models require refinement to incorporate this information, which will reduce the user judgment required by providing a best set of default options.

Several entities are currently working towards routine generation of the much needed information. The Bluesky Gateway framework at the National Oceanic and Atmospheric Administration (NOAA), the EPA, and the Forest Service are all working on improving simulations of secondary particulate matter contributions into the source-oriented models. In addition, a workshop was held on "developing fire emission products suitable for operational and retrospective analyses." The workshop's purpose was to initiate the Collaborative Fire Emissions Analysis and Inventory (CFEAI) project's pilot study to integrate ground-based and remote sensing data, which involved the Forest Service AirFire, Forest Service Remote Sensing Applications Center, WRAP, NPS, and the EPA. In this study, protocols and methods will be developed and data sources identified to develop routine fire inventories that incorporate additional metadata, including the type of fire. Schichtel points out, "So, we've moved the conversation forward from 'Is it important?' to 'How do we get it done?'"

Furthermore, the Joint Fire Science Program has funded a project (09-1-03-1) involving Colorado State University, Carnegie Mellon University, Washington University, and the NPS to identify and measure the compounds necessary to apportion the contributions of secondary particulate matter from fires and to refine the hybrid receptor models to incorporate the additional information so that the models can be used in a more routine fashion by new users. Lastly, future plans include developing the ability to apportion fire's contributions to source regions, such as individual states. And the eventual goal will be to incorporate the hybrid receptor models and results into existing decision support systems (DSS), such as the BlueSky Gateway framework and the VIEWS DSS.

In short, we need to know where the smoke is coming from in order to see if we need to do something about it, and the hybrid source apportionment model can do just that once the needed data inputs become available. Various groups are working diligently to make that happen, and we should then all be able to breathe a little easier.

Management Implications

This project has developed methodologies and tools for use by experts to quantify what portion of measured fine particulates ($PM_{2.5}$) comes from fire, and of that amount, to determine how much comes from wildfire, prescribed fire, and agricultural burning. This information can then be directly used by air quality regulators in developing regional haze and $PM_{2.5}$ State Implementation Plans to reduce haze and $PM_{2.5}$ below regulated thresholds. Results can also be used to assess the effectiveness of emissions reduction techniques for application in smoke management programs, and to help identify whether controlled burns are the cause of a poor air quality day or if the problem is stemming from other sources. Providing more accurate estimates of smoke emissions may lead to additional controlled burning opportunities.

Haze from a prescribed fire in Grand Canyon National Park. Credit: Bill Malm.

Further Information: Publications and Web Resources

Schichtel, B.A., W.C. Malm, G. Bench, S. Fallon, C.E. McDade, J.C. Chow and J.G. Watson. 2008. Fossil and Contemporary Fine Carbon Fractions at 12 Rural and Urban Sites in the United States. *J. Geophys. Res*., 113, D02311.

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Schichtel, B.A.; Hybrid Source Apportionment Model: an operational tool to distinguish wildfire emissions from prescribed fire emissions in measurements of $PM_{2.5}$ for use in visibility and PM regulatory programs; Final Report, JFSP Project Number 05-3-1-04.

Characterizing Particulate Matter Emissions by Wildland Fires Relevant to Visibility Impairment and PM Non-Attainment. Joint Fire Science Program project number 05-3-1-06. www.firescience.gov.

Project Website: http://vista.cira.colostate.edu/improve/Studies/SmokeApp/SmokeApp.htm

Scientist Profile

Bret Schichtel is a Physical Scientist for the Air Resource Division of the National Park Service. His research focuses on understanding the causes of poor air quality in national parks and other areas, including the causes of excess particulate matter, haze, and nitrogen deposition. A central focus of his research activities has been on determining the sources and their contribution to the air quality issues.

Bret Schichtel can be reached at:
Cooperative Institute for Research in the Atmosphere
Colorado State University
1375 Campus Delivery
Fort Collins, CO 80523-1375
Phone: 970-491-8581 • Email: Schichtel@cira.colostate.edu

Collaborators

Dr. William C. Malm, National Park Service
Dr. Douglas Fox, Colorado State University
Dr. Jeffery L. Collett, Colorado State University
Ms. Leigh A. Munchak, Colorado State University
Ms. Amanda S. Holden, Colorado State University

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The information in this Brief is written from JFSP Project Number 05-3-1-04, which is available at www.firescience.gov.

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John Cissel
Program Manager
208-387-5349
National Interagency Fire Center
3833 S. Development Ave.
Boise, ID 83705-5354

Tim Swedberg
Communication Director
Timothy_Swedberg@nifc.blm.gov
208-387-5865

Writer
Christine Frame
cframe@landfire.org

Design and Layout
RED, Inc. Communications
red@redinc.com
208-528-0051