Joint Fire Science Program

Fire Science Brief

RESEARCH SUPPORTING SOUND DECISIONS

Controlled burns of various fuels under laboratory conditions helped provide data to characterize smoke from wildfires, prescribed burns, and other sources.

Who Made That Smoke?

Summary

Management of smoke from prescribed fire activities is important. Consideration must be given to short-term effects of smoke on work crews and neighboring communities. This requires accurate real-time information for smoke forecasting. Tools have been created to help meet these needs of smoke managers for prescribed burns.

However, longer-term smoke effects are also important. Managers must meet state and federal regulations for air emissions, and must be aware of projects causing potential violations of National Ambient Air Quality Standards (NAAQS) and reduction in visibility. Both wildfires and prescribed burns can contribute significantly to fine particulate matter (PM) and ozone in the regional atmosphere. This report describes a research project that assists smoke managers in understanding the effects that emissions from prescribed burns can have on ambient particle concentrations and visibility.

Key Findings

- Increasingly, stringent air quality regulations require both land managers and air quality regulators to have a better understanding of the contributions of prescribed burns and wildfire to regional air quality and visibility levels.
- Constituents of smoke from wildland fires are identifiably different from emissions from industrial, residential, and mobile sources.
- Laboratory burns of fuels from the West and the Southeast demonstrate variability in smoke constituents and in their potential to contribute to reduced visibility.
- Levoglucosan and other carbohydrate constituents of wood smoke are potentially useful markers of wood smoke, allowing managers to understand the effects of smoke on general air quality and visibility.
- Accurate and affordable methods of analysis of marker carbohydrates promise to make post-fire evaluation of atmospheric smoke a common practice.
- Early analyses of smoke from actual field fires generally confirm the general conclusions from laboratory studies, but the wide variability in fuel and weather conditions in the real world means that more work is needed in applying these tools.

Wildland fire and air quality

Management of smoke from prescribed fires has both operational and regulatory aspects. Short-term needs include determining suitable times for burning and estimating the impact of smoke on neighboring communities as well as on crews working the fire. These operational considerations of smoke have received extensive attention and tools such as the BlueSky Modeling Framework have been developed to assist fire managers in planning prescribed burns.

Another aspect of these fires is their potential impact on local and regional air quality. The U.S. Environmental Protection Agency (EPA) has set National Ambient Air Quality Standards (NAAQS) for pollutants considered to be harmful to public health and the environment. These include primary standards, which protect public health, and secondary standards, set to protect human welfare such as visibility and ecosystem effects.

Fires can contribute significantly to levels of ozone and fine particulate materials (PM), causing nonattainment of both the primary and secondary NAAQS in communities and regions throughout the U.S. Regulations set limits on ambient concentrations allowed for hourly, daily and annual average values.

Smoke from prescribed burns provides an important data source in studying smoke characteristics.

Smoke from prescribed fires can also contribute to haze in national parks and in wilderness areas, collectively known as Class I areas (CIA). In these areas, haze is regulated using EPA's Regional Haze Rule (RHR), which requires each state to set "reasonable progress" goals to return visibility to natural conditions on the 20 percent of haziest days by 2064, while preventing degradation of visibility on the 20 percent of least-hazy days. Progress towards these goals is tracked using five-year-average values. Further, fire emissions also contain substantial levels of reactive nitrogen, and it is anticipated that at some time in the future there will be a secondary total reactive nitrogen deposition NAAQS standard. Tools are needed to help managers better understand the contribution of fire emissions to air quality in this broader context.

Challenges facing fire managers

Currently, both PM and ozone NAAQS are violated in a number of areas, and virtually all CIAs have haze levels above natural background levels. State and federal agencies are working to implement plans to reduce and manage emissions that contribute to this problem.

It is known that smoke is a contributor to fine particulate matter, haze, and ozone. This is particularly true in the western and southeastern U.S. NAAQS and RHR regulations require daily and annual air quality metrics. Thus, it is necessary to distinguish between the contributions of emissions from various fire types to $PM_{2.5}$, ozone, and visibility degradation.

One of the principal difficulties in understanding the role of smoke is that often more than 50 percent of the smoke particulate mass is secondary organic aerosols (SOA)—particulates formed in the atmosphere from emitted organic gases. These SOAs are similar in composition to SOAs formed from gases from plant respiration and are particularly important in the southeastern and northwestern U.S. where fire activity is also high. Further, these SOAs are important contributors to the formation of fine PM and ozone.

Finding the sources of smoke

The RHR and NAAQS require a clear distinction between the identification of the amount and type of haze and $PM_{2.5}$ from natural and anthropogenic sources and from natural and international sources that cannot be controlled. Haze and $PM_{2.5}$ from smoke originates from wildfires and from human-caused fires, including agricultural burning, prescribed fires, and residential wood burning. Understanding the relative contributions of natural and anthropogenic fires is essential for regulators to track progress in haze regulation implementation and to address $PM_{2.5}$ exceedances.

Currently wildfire accounts for the majority of smoke emissions in the western U.S. Anthropogenic fires tend to occur in different seasons and geographic regions than wildfire, but can contribute to haze on both best and worst haze days. In the West, wildfires tend to occur most often in the warmest months, while prescribed and agricultural fires occur most often in the cooler spring, fall and winter months.

Haze from non-fire-related sources is often lower during the winter months, and thus winter prescribed fires can diminish visibility on what would otherwise be some of the clearest days of the year. Smoke concentrations from residential wood burning also tend to occur in population centers during cold months and these can be transported to CIAs.

In the Southeast, smoke from prescribed fire emissions is generally greater than from wildfire and prescribed fires are typically used in this region from October through April. It is expected that in the future, prescribed fires will significantly increase, thereby reducing wildfires. In this way, there is an increased likelihood of even higher prescribed fire emissions. For these reasons, it is of growing importance to be able to properly differentiate between carbonaceous aerosol materials associated with smoke emissions from various fire types.

New tools needed

To evaluate and track the impact on air of prescribed burning, land managers and policy makers lack important tools, especially to differentiate between air contaminants originating from industrial- and mobile-source activity and those from natural and anthropogenic fires. To meet this need, a research team was formed and research initiated. One project, "Characterizing Particulate Matter Emissions by Wildland Fires Relevant to Visibility Impairment and PM Non-Attainment," was sponsored in part by the Joint Fire Science Program.

The Principal Investigator was Dr. William Malm from the National Park Service Air Resources Division, operating with the Cooperative Institute for Research in the Atmosphere (CIRA) at Colorado State University (CSU) in Fort Collins, Colorado. Co-Principal Investigators were Dr. Douglas Fox, CSU; Dr. Hans Moosmuller, Desert Research Station, Reno, Nevada; Dr. Sonia Kreidenweis, CSU; Dr. Jeffrey Collett, Jr., CSU; and Dr. Wei Min Hao, Forest Service, Missoula, Montana.

Malm explains, "This really is a first step along a path to understanding which of the many sources of smoke contribute to NAAQS violations and to impaired visibility as defined by the Regional Haze Rule."

The research project established several objectives. The first was to develop an "unambiguous, routine, and cost-effective methodology" to allow monitoring networks to characterize smoke marker species linked to primary emissions originating with prescribed fires and wildfire burn activities. Development would include generating smoke marker profiles using laboratory burns of various relevant fuel types.

Laboratory burns assisted in creating smoke profiles of various fuel types.

The second stage was to field-test the method developed, by making measurements in fresh smoke plumes from wild and prescribed fires in order to validate laboratory results. This would involve using the Interagency Monitoring of Protected Environments (IMPROVE) network sites and would assist in finalizing a proven composition source profile for distribution to federal land managers, air quality regulators, and policy makers.

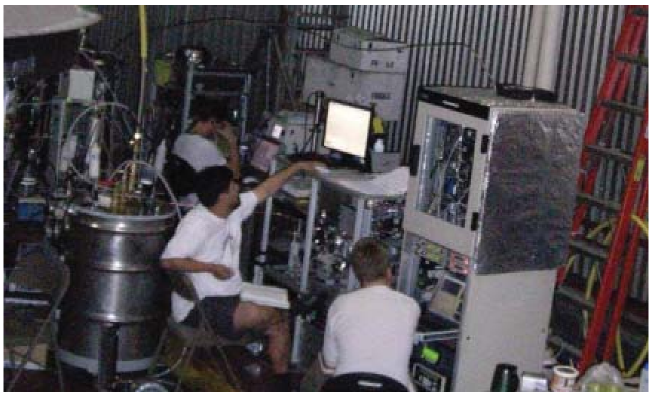
Researchers would also assess the dependence of optical scattering properties on relative humidity, as well as other physical and chemical properties such as particle size and composition. The potential for combustion particles to act as seeds for warm and cold cloud formation was assessed.

A secondary goal was to develop a methodology for a high-time-resolution measurement of elemental and organic carbon concentrations that would be potentially superior to previous thermal methods and to measure emissions of mercury from various fuel types.

Starting in the laboratory

Research began with development of an inexpensive and accurate smoke marker measurement tool. The initial work was primarily conducted at CSU by principal investigators and collaborators. This stage involved development of tools that could be used to characterize smoke in future investigatory burns.

In the second stage, investigators characterized the emissions from the open combustion of 33 plant species during a series of 255 controlled laboratory burns. The work was done at the Forest Service, Fire Sciences Laboratory in Missoula, Montana, and all of the project principal investigators participated in this stage. The organisms tested included the chaparral species of chamise, manzanita, and ceoanthus, in addition to a variety of species common to the southeastern U.S., including common reed, hickory, kudzu, needlegrass rush, rhododendron, cord grass, sawgrass, titi, and wax myrtle. Burns were also conducted with tree species, including ponderosa pine, lodgepole pine, Douglas fir, white spruce, black spruce, and oak.



Data from a wide variety of species established tentative emission factors for numerous gas and particulate smoke components.

The study established emission factors for gas-phase CO2, CO, CH4, C2-4 hydrocarbons, NH3, SO2, NO, NO2, HNO3, and particle-phase organic carbon (OC), elemental carbon (EC), SO4, NO3, Cl, Na, K, and NH. These generally varied both with fuel type and with the fire-integrated modified combustion efficiency (MCE), a measure of the relative importance of flaming- and smoldering-phase combustion to total emissions during the burn.

Researchers found that chaparral fuels tended to emit less particulate organic carbon per unit mass of dry fuel than did other fuel types. Southeastern species had the largest observed emission factors for total fine particulate matter. Measurements spanned a larger range of MCEs than earlier studies and, thus, will help to improve estimates of the variation of emissions with combustion conditions for individual fuels.

During the studies at the Forest Service, Fire Science Laboratory, high volume filter samples were collected for the various burns. Levoglucosan and other wood carbohydrates were measured in these samples using precision chromatography. The results showed that emissions of levoglucosan, mannosan, galactosan and other organic markers have the potential for modeling apportionment from various sources.

These have a strong correlation with primary organic carbon and are unique to biomass burning. The research team used the laboratory studies to develop an inexpensive method for measuring these smoke ingredients. The method is suitable for use in a routine monitoring network. Malm explains, “Levoglucosan is emitted at high concentrations in fine particles produced in biomass burning, making it easier to detect following plume dilution than other compounds emitted at much lower concentrations. It can be measured in a straightforward way by laboratory analyses of water extracts of aerosols collected on filters.” He notes that this marker is also relatively unique to biomass burning, thus helping to distinguish biomass smoke aerosols from other sources of PM2.5 and haze. Further, levoglucosan and the other carbohydrates are apparently quite stable in the atmosphere.

Other measurements

Optical characteristics of the wood smoke were also evaluated. A photoacoustic instrument was used to measure light scattering and light absorption by smoke from combustion of a variety of wood fuels. The measurements strongly suggest that not only does fire emit light-absorbing black carbon or soot, but also light-absorbing organic material.

Variation was found in the optical properties of wood smoke aerosols as compared with mobile or industrial sources, allowing optical differentiation of sources. Optical properties of biomass smokes could be classified by general fuel type, such as flowering shrubs versus pine needle litter. This information may help regulators gain a better understanding of the source of the smoke.

Another method that was evaluated was the use of a mobile lidar (Light Detection and Ranging) unit developed by the Forest Service, Fire Science Laboratory to measure back-scattered signals in two wavelengths, 1064 nm (infrared) and 355 nm (ultraviolet). The infrared signals are useful for determining plume dynamics and propagation, and the ultraviolet signals are used for determining smoke particulate optical properties.

According to investigator Sonia Kriedenweiss, the experiments helped show how much water can be associated with the smoke from various fuels, so that the calculation of expected visibility effects, especially in regions with high relative humidity, can be made more accurately. She also notes that the optical experiments indicated the variability of smoke effects on climate. “We found some fresh smokes that are ‘brighter’ (more cooling toward climate) than other darker smokes that can absorb solar energy. Darker smokes cause heating and stabilization of the atmosphere that inhibit cloud formation and affect dynamics.” She notes that the results can be used to get better estimates of the impacts of particles emitted from burning on climate. “Of course this is mostly from lab-based measurements so we need to do more field work to understand it fully.”

Taking it to the field

The methods developed and correlations found in two years of laboratory studies were then taken to the field to test with smoke plumes from wild and prescribed fires in order to determine their validity and applicability in the field. This work involved the first steps in evaluating smoke characteristics using the carbohydrate markers evaluated in the lab.

Research included measurement of both chemical and optical characteristics of smoke to allow evaluation of both air quality and haze characteristics.

The initial plan was to evaluate emissions from several prescribed burns. Because of weather conditions, these burns were not conducted. However, the researchers did perform field analyses of plumes from "burns of opportunity" during this fire season. According to Malm, "The field studies included in this project provide initial insight into properties of smoke particles emitted in real-world conditions." He feels that the results measured were neither more nor less valid than the prescribed burns originally planned. Malm points out, "Much more field work is needed, given the wide variety of fuel types and burn conditions that occur in the U.S."

Research work is not done

Malm indicates that work is continuing in this field. "First of all, we want to document the stability of tracer levoglucosan during long-range transport of smoke. Recent studies suggest it may be degraded by chemical reaction in aging smoke plumes." He indicates that the team needs to better understand the rate of destruction, whether traceable breakdown products are formed and whether it can serve as a "clock" for plume aging.

Second is a need for more information on continuing production of secondary aerosol particles during plume aging, "SOA production in the field can best be determined if chemical tracers of new particulate matter products by reaction of combustion gases can be identified. Work on both of these topics is now underway with new JFSP [Joint Fire Science Program] support."

Putting new tools to work

Malm emphasizes that this project is part of a larger monitoring and modeling effort to build a framework for retrospectively apportioning the contribution of smoke to particulate matter levels and haze. He notes, "This information is vital for regulators to understand the causes of exceedances of air quality standards and excess haze. Using it, they can develop meaningful control strategies to protect human health and welfare, as well as ecosystems."

Management Implications

- With tightening controls on secondary NAAQS violations and haze, it is increasingly necessary for federal land managers to understand the contribution of biomass burning to air quality.
- Tools are becoming available to sample source smoke and ambient air to estimate the contributions of biomass burning to potential NAAQS violations and haze.
- Test protocols are now available to use levels of levoglucosan and other carbohydrate components of smoke as markers of the contribution of biomass burning to air quality.
- Information will continue to be developed on correlations of specific biomass types to air quality characteristics.

Malm explains that as an example of how this information can be used by land managers, smoke managers, and regulators, if it is found that biomass burning from controllable prescribed fires is a small contributor to poor air quality, then smoke managers can assume that their current efforts are adequate to protect air quality. Similarly, if the exceedances are found to be due to uncontrollable wildfire, then again, smoke managers can assume that their current efforts are adequate. He stresses, "However, if smoke from controllable fires is found to be a significant contributor to the exceedances, then federal land managers and smoke managers may need to reassess their practices."

Laboratory tools

A specific test protocol for extracting the levoglucosan and other carbohydrates has been developed. The water extraction procedures for source and Hi-Volume samples is outlined in a report by Sullivan et al. (2008). Malm adds that the procedures should be modified depending on sample type.

The Sullivan report provides general guidance on the correlation of levoglucosan levels in smoke with a number of vegetation types. Malm says, "This is a primary smoke marker. Because particulate matter in a smoke plume will increase as the plume ages, due to the secondary formation of particulate matter from gases in the plume, other markers and analysis techniques are needed assess the level of SOA formation attributed to fire emissions as opposed to formation from natural vegetation respiration."

Malm emphasizes that the tools that are being developed are retrospective in nature; that is, they are tools used to estimate smoke contributions to air quality after the event has occurred. "Therefore, they will not help to predict into the future whether or not burning will contribute to a NAAQS violation." However, it is believed that with increased knowledge of the characteristics of smoke from biomass burning, better decisions can be made.

Further Information: Publications and Web Resources

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Scientist Profile

Dr. William C. Malm is a Research Scientist/Scholar at Colorado State University's Cooperative Institute for Research in the Atmosphere (CIRA) and a recently retired research physicist in the National Park Service Air Resources Division where he was program coordinator for the visibility/particulate research and monitoring program. He has previously worked as an EPA research scientist and as a professor of environmental science at Northern Arizona University in Flagstaff, AZ. His expertise is in the general area of visibility and related topics.

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