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Know Your Smoke: Updated Smoke Modeling Tool Estimates Higher Particulate Emissions From Wildfire Than Previously Predicted

When smoke from a large wildfire blows into a community, daylight can blur into dusk and air quality can plummet, triggering a surge in emergency room visits for people suffering from asthma and other respiratory conditions. Additionally, smoke can create visibility problems on roadways, including the formation of "superfog," a combination of smoke and dense fog that has resulted in numerous fatal vehicle accidents over the past few decades.

Understanding potential smoke impacts from fire, either wildfire or prescribed, is of increasing importance for fire and land managers, public health officials, and air quality regulators. However, the complexity of smoke emissions makes accurate emissions projections using computer modeling challenging. Emissions from fires vary with combustion efficiency (the fraction of carbon released as carbon dioxide [CO_2]), which itself varies by

Communities must often contend with smoke from wildfires. The Rice Ridge Fire in Seeley Lake, Montana, 2017. Credit: Kurt Wilson, Missoulian (verbal permission).

SUMMARY

Reliable predictions of emissions from wildland fires are a key element of smoke management programs. Emission factors (the amount of pollutants produced per amount of fuel consumed) are used in models to estimate the composition of smoke. Over the past two decades, laboratory and field studies have made great progress in characterizing the chemical composition of smoke and quantifying emission factors. However, until recently, the widely used First Order Fire Effects Model (FOFEM) did not incorporate these advances in smoke science. A recent Rocky Mountain Research Station project reviewed and synthesized wildland fire emission data from over 40 studies to create an updated, comprehensive database of emission factors. The updated emission factor database provides emission factors for nearly 200 gaseous and particulate pollutants emitted by wildland fires. The emission factor database has been integrated into the most recent version of FOFEM,. The updated emission factors indicate that the particulate emissions from wildfire and prescribed fire are substantially higher than previous estimates before the update. However, it is not that fires are producing more emissions—just more than we previously realized.

ecosystem conditions, such as fuel type and fuel moisture, and fire type and intensity.

Enter Rocky Mountain Research Station fire science specialists Shawn Urbanski and Duncan Lutes.

Urbanski, a research physical scientist with the Rocky Mountain Research Station (RMRS) Fire, Fuel, and Smoke Program, conducted a comprehensive synthesis of wildland fire emission data from over 40 published studies (a combination of laboratory and field measurements) to create an updated database of emission factors. Emission factors quantify the relative abundances of pollutants present in fresh smoke. This updated database provides emission factors for nearly 200 gaseous and particulate pollutants emitted by wildland fires and is particularly useful for fire managers and air regulators.

Lutes, a fire ecologist with the RMRS Fire Modeling Institute at the Missoula Fire Lab, led the integration of the updated emission factors into the most recent version of the First Order Fire Effects Model (FOFEM), a computer model for predicting tree mortality, fuel consumption, smoke production, and soil heating caused by prescribed fire or wildfire. FOFEM is used by fire managers to estimate smoke for regional haze estimates and for localized impacts such as roadway visibility.

The revision is significant because the updated emission factors indicate that older versions of FOFEM substantially underestimated particulate matter emissions from certain fire types, in particular western wildfires. The updated particulate emission factors, which subsequent independent field studies confirmed (Liu et al. 2017), indicate that particulate matter emissions by wildfires may be twice that reported to the U.S. Environmental Protection Agency's 2017 National Emission Inventory (NEI). Likewise, particulate emissions from prescribed fires in heavy fuels are likely to be substantially higher than those reported in the NEI.

"FOFEM and a lot of the other models that land managers have been using to predict the amount of pollutants emitted by fires and to try to estimate smoke impacts on local communities were really 20 years behind in keeping up with the science," said Urbanski. "They didn't include emission factors that properly represented the amount of pollutants that are produced for different fire types, and they also didn't include many hundreds of pollutants that are known to be in wildfire smoke that we've discovered and quantified over the past 15 to 20 years of research."

The improved pollutant emission factors that have been implemented in FOFEM will enable land managers and air regulators to more accurately predict emissions and mitigate the adverse impacts of smoke on the public.

Is Air Quality a Barrier to Prescribed Fire?

Smoke management concerns are among the top impediments to prescribed burning. While nuisance smoke is the most common issue, prescribed fires can subject local communities and sensitive populations to unhealthy pollutant levels. Since wildland fires produce pollutants regulated under the federal Clean Air Act, prescribed burning can present substantial regulatory challenges by triggering violations of air quality standards, especially in areas that are in “nonattainment” with air quality standards.

Urbanski and Lutes are aware that air quality is often seen as a barrier to conducting more prescribed burning, and their finding of the presence of considerably more particulate matter in smoke emissions than previously estimated could be seen as another factor limiting the ability to get prescribed fire on the ground.

“A lot of people looked at the new emissions factors as a negative thing in that they wouldn’t be able to do perhaps as much prescribed burning as they did before because they’re producing more particulate matter,” said Urbanski. “But the reality is we were always producing that much all along but not accounting for it.”

Urbanski said he’s heard from land managers who say that FOFEM and some of the other models don’t always predict as much smoke from the smoldering phase as is later observed. They have seen significant smoke production, especially smoldering during the night.

“That’s when they get smoke intrusions into local communities and they get in trouble,” said Urbanski. “So, they know they’re producing too much. Situations like that are really important for land managers.”

Leland Tarnay, an ecologist with the USDA Forest Service Region 5 Remote Sensing Lab, also believes that having more accurate emissions factors will help with fire and land management over the long term.

“When it comes to smoke, the concern for everyone—air regulators and the public—is, how bad is bad? How long is it going to last? That’s all they really want to know.”

—Scott Williams
fire management specialist

“Air quality and forest health are joined at the hip rather than diametrically opposed,” said Tarnay. “There are narratives out there that cast air quality only as an obstacle to burning. Conversely the fires that we manage for resource objectives and the prescribed fires that we do, those proactive strategies produce way less smoke per day. Additionally, they produce lesser impacts at regional scales than these larger wildfires that dump smoke from larger areas in the air all at once.”

Scott Williams, a fire management specialist with the U.S. Forest Service Enterprise Program, uses FOFEM to quantify smoke and greenhouse gas emissions as part of the NEPA process for vegetation and fuels management projects in

MANAGEMENT IMPLICATIONS

- The emission factor database has been integrated into the most recent version First Order Fire Effects Model (FOFEM) to provide land managers and air regulators with more accurate estimates of pollutant emissions from fires.
- The emission factor updates to FOFEM will allow land managers to estimate emissions of hazardous air pollutants, which may be combined with ambient monitoring to assess fire fighter exposure.
- The updated emissions factors can help predict “superfog” events in which particulate seed particles in a smoke plume interact with dense fog to form a superfog wall with extremely reduced visibility (less than 10 feet), which can be deadly on roadways.
- With planned inclusion in the FlamMap fire behavior model, smoke production can be modeled as fire spreads across a landscape at relatively high spatial resolution. Improved predictions of emissions from prescribed fires and wildfires will help estimate potential impacts on local communities.

KEY FINDINGS

- Emission factors for particulate matter and gaseous pollutants vary considerably across fire types (prescribed vs. wild) and ecosystems (e.g., southern longleaf pine forests vs. Rocky Mountain mixed conifer forests).
- Emission factors used in older versions of FOFEM significantly underestimate emissions of particulate matter, especially PM10 and $PM_{2.5}$.
- The updated emission factors indicate particulate emissions from wildfires are likely twice that reported in the EPA 2014 National Emission Inventory. Likewise, particulate emissions from prescribed fires in heavy fuels are likely to be substantially higher than those reported in the National Emission Inventory.

national forests across the country. Williams said the FOFEM is a great communication tool for showing the differences in emissions between prescribed burns and wildfires.

"What we argue in our NEPA is if you don't like the smoke effects from a forest burned under prescribed fire conditions, take a look at what the emissions would be from a wildfire in very high 90th or extreme 97th percentile burn conditions in the same area," said Williams.

Smoke Erodes Air Quality

After they incorporated the updated emissions factors into FOFEM, Urbanski and Lutes estimated that wildfires and prescribed fires in western forests produced about twice as much particulate matter ($PM_{2.5}$) than the model originally predicted, depending on burning conditions.

"What this tells land managers is that fires in western forests are producing far more particulate matter than FOFEM had previously been indicating," said Urbanski.

Emission factors vary by vegetation type (e.g., grass vs. forest fuels) as well as burning conditions. Factors, such as fuel moisture, that impact fuel consumption make it difficult to give exact estimates of the changes the new emission factors produce. However, in most cases, the new updated emission factors result in an increase in the estimated production of the components. The table below shows prescribed fire emission estimates in an example interior ponderosa pine stand with moderate fuel moisture. $PM_{2.5}$ increases from 390 pounds/acre under the original emissions factors to 774 pounds/acre using the updated emissions factors.

Lab and field studies have identified hundreds of gases that are present in smoke along with particulate matter. Among the volatile organic compounds (VOCs) emitted from wildfires are many compounds listed as hazardous air pollutants by the EPA (https://www.epa.gov/haps), e.g., methanol, benzene, and formaldehyde. However, because the highly variable and complex processes of atmospheric dispersion are a key factor in determining ambient pollutant concentrations, there is a great deal of uncertainty around the dangers of exposure.

Fire emission estimates for an example ponderosa pine stand with moderate fuel moisture. Calculations generated using original FOFEM emission factors and the updated emission factors.

Component	Original emissions factors (pounds/acre)	Updated emissions factors (pounds/acre)	Difference (%)
$PM_{2.5}$	390	774	98
PM_{10}	460	913	98
CO_2	42,840	42,886	0
CO	4,814	5,272	10
CH_4	227	221	-3
NO_x	42	34	-19
SO_2	29	32	10

"When these gases are emitted into the atmosphere, they can undergo chemical reaction and produce ozone [O_3], which has negative health impacts on people," said Urbanski.

Tarnay believes that the inclusion of a broader range of emissions in the updated emissions factors will improve estimates of secondary reactions, such as the formation of O_3.

"When you know all the particles and gases coming off the fire, then you have all the pieces you need to do chemical calculations that will tell you what is going to happen farther downstream," said Tarnay. "Knowing the rest of the mix will help predict what happens to the smoke plume as it ages and use that for the ozone monitors farther downstream. This is definitely a step forward for getting the mechanistic models for secondary aerosol formation up to speed."

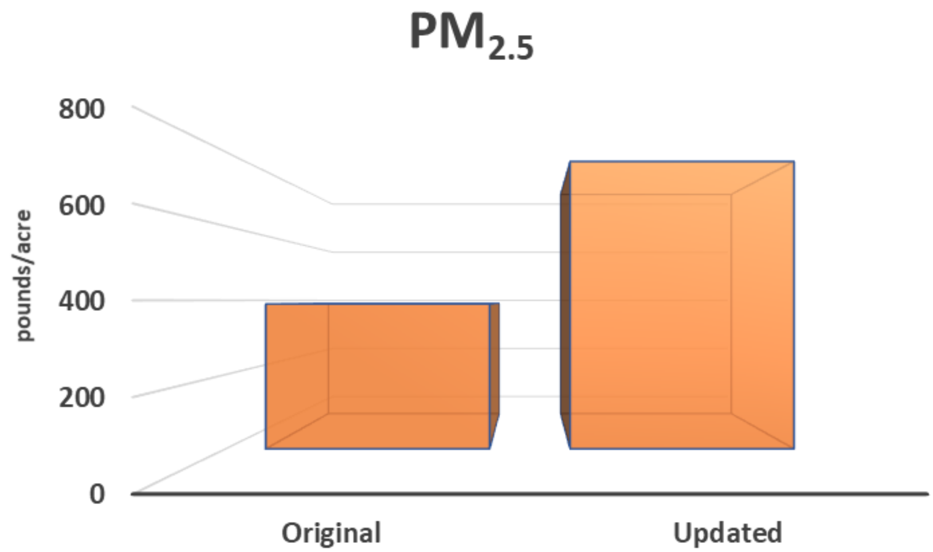

Figure 1: *The difference in estimated production of $PM_{2.5}$ between the original and updated emissions factors implemented in FOFEM.*

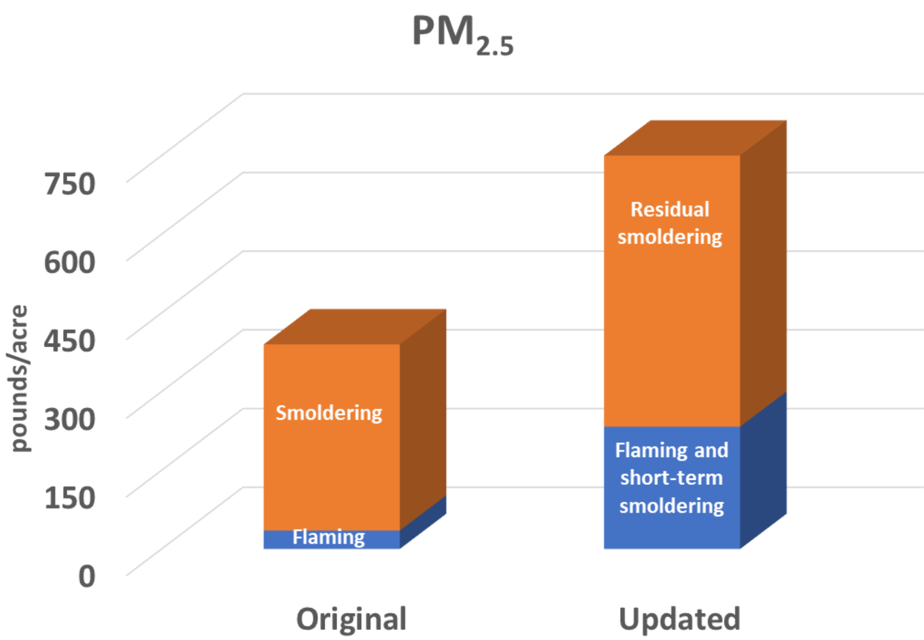

Figure 2*: In addition to the new emission factors in FOFEM, the application now takes advantage of the Burnup model for estimating emissions in modified combustion classes – short-term flaming and smoldering and residual smoldering.*

Flaming and Smoldering

All combustion is not equal when it comes to producing emissions. Many factors affect combustion, and hence emission factors. Principal factors are the structure and arrangement of fuels—the size, shape, and packing of fuel particles—and fuel conditions, which are affected by moisture content, growth stage, and soundness of woody material. Typically, fire emissions are characterized in terms of flaming or smoldering combustion. The general relationship among fuel bed properties, combustion processes, and emissions is depicted in figure 3. When a fire is dominated by flaming combustion, more of the carbon in the fuel is converted to carbon dioxide (CO_2), and as a fire shifts more toward smoldering combustion, the combustion processes are less complete, which results in production of more particulate matter and VOCs, such as methane (CH_4), methanol, and formaldehyde.

The original version of FOFEM recognized the differences between flaming and smoldering emissions and included emissions factors for each. Urbanski and Lutes decided it would be more accurate to consider emissions in two phases, with smoldering included in both. The first phase included emissions from both short-term flaming and smoldering, where some of the smoldering emissions, the post-frontal combustion, is entrained in the plume and goes up in the air. The second phase is the pure smoldering emissions, which occurs after the flaming front has passed through an area.

Lutes said adding the short-term flaming and smoldering component meant they couldn't just swap in the new emissions factors. The key was to take advantage of the embedded woody fuel consumption model (referred to as the Burnup model) to determine when to use which set of emissions factors. Based on the changes they've made, Lutes said they can easily modify the assumptions about what components burn in what phase, as that information becomes available. Also, emissions factors can easily be modified or added by users.

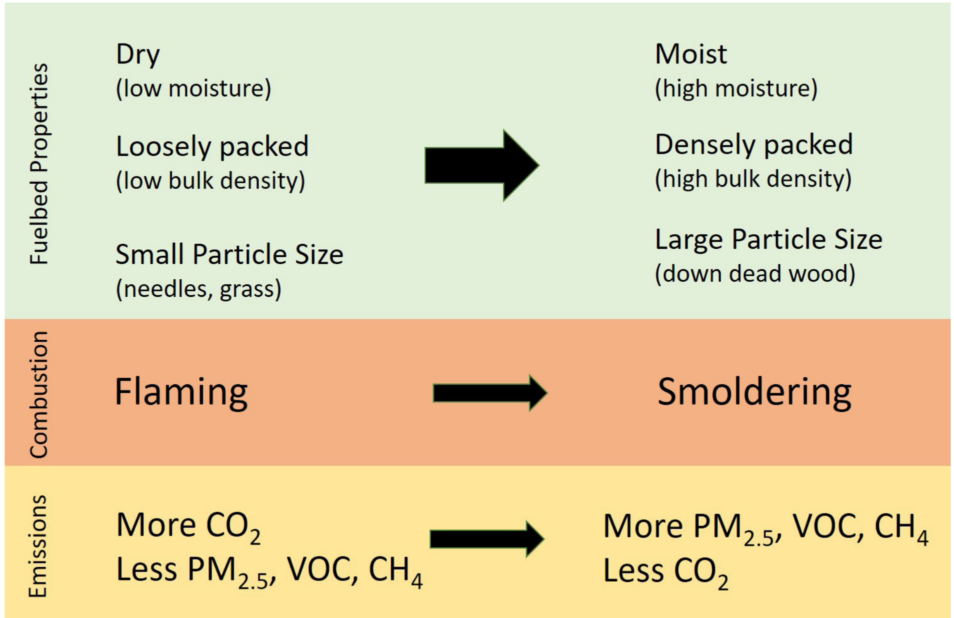

Figure 3. *Fuels that are dry, small diameter, and loosely packed favor flaming combustion. The more a fire smolders, the greater its production of harmful pollutants, such as $PM_{2.5}$, CO, CH_4, and VOCs.*

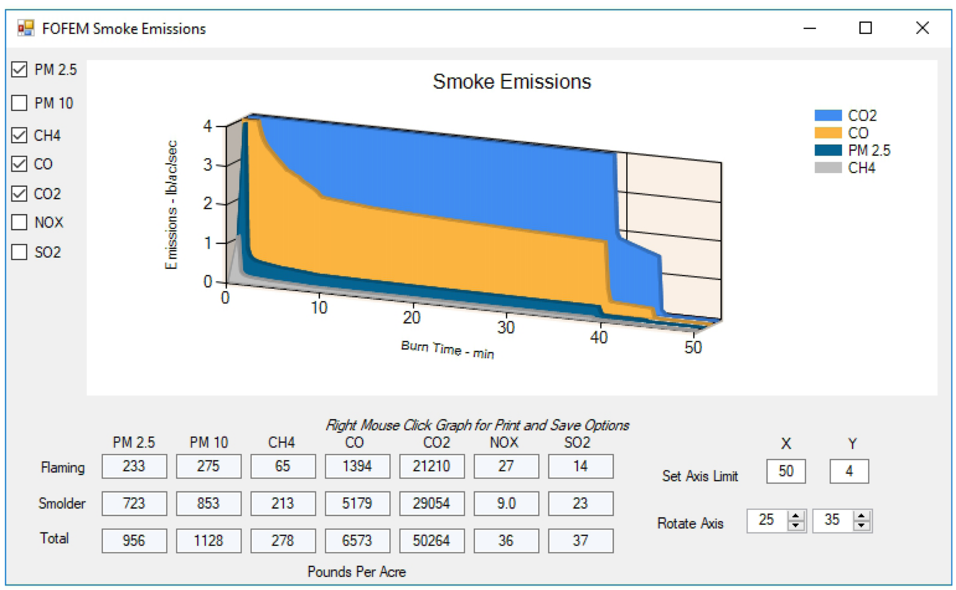

Figure 4. *FOFEM provides graphical representation of smoke production rate of seven components over time.*

"One output of Burnup is an estimate of fire intensity of the different diameter dead woody fuel components," said Lutes. "When fire intensity of a woody fuel component drops below 15 kilowatts per square meter, we use the smoldering emission factors. If intensity is above 15 kilowatts per square meter, then we use the short-term flaming and smoldering emissions factors. Except for duff, which we assume is always consumed in the smoldering phase, the other fuel components, like litter and grass, are modeled as being consumed in the short-term flaming and smoldering phase.”

Comparison of smoke impacts from prescribed fire and a wildfire taken from the same location in Wenatchee, Washington. Credit: John Marshall.

Since FOFEM does not have a spatial dispersion function for emissions, estimates of the impacts of emissions are limited to an area where fires are produced. Despite this limitation, Tarnay believes that the updated emissions factors can help with predicting “superfog” events in which the particulate seed particles in a smoke plume interact with dense fog to form a superfog wall with extremely reduced visibility (less than 10 feet). Over the past two decades, there have been a number of fatal accidents from superfog produced from smoldering wildfires and prescribed fires, including a 26-vehicle pileup that resulted in 11 deaths in Florida in 2011.

“Understanding the smoldering phase, what those emissions are, and the fact our previous factors were way too low, is going to help in predicting those local superfog situations,” Tarnay said.

Improving knowledge of smoke emissions could also benefit ongoing research into firefighter health and exposure to smoke over long periods of time (https://www.airnow.gov/).

“I think it goes back to having more accurate estimates,” said Lutes. “These new emission factors have a lot more information, like VOC emissions, which provides the potential for estimating secondary chemical reactions, and could have important health implications for firefighters and for communities with long-term exposure to smoke.”

Lutes said that one of the biggest limitations for FOFEM is the lack of a spatial component to the modeling of emissions, a situation he and his team are working to rectify with the development of a spatial version of FOFEM, which will allow fire managers to simulate a fire, either prescribed fire or wildfire, and project smoke production.

“We’re incorporating FOFEM, spatially, into FlamMap, a model for simulating fire growth and spread,” said Lutes. “We can run fire across a landscape and learn how quickly a fire burns through each cell and how much smoke is produced in that cell.”

Williams said incorporating the updated emissions factors into BlueSky (or other smoke dispersion models) and FlamMap would be a big step forward in that it would allow modeling of emissions from landscapes at higher detail.

“Including these emission factors into a model like FlamMap, which operates at 30 m^2 pixels, would capture more of the complexity on the landscape than is currently done in smoke dispersion models, such as BlueSky, which models 1 acre with the same fuel characteristics at a time, multiplied by the size of the area burned,” said Williams. “That would be huge.”

Smoke plumes from wildfires can travel long distances and impact communities far from the fire. Lolo Peak Fire,Montana (August 18, 2017) Credit: Shawn Urbanski.

Reversing Air Quality Trends

Over the past 20 years, air quality has improved significantly across the United States, especially in levels of two primary pollutants, ozone and $PM_{2.5}$. However, the one exception has been that in the portions of the western United States that are prone to wildfires, air quality with respect to $PM_{2.5}$ pollution has gotten worse (McClure and Jaffe 2018).

"Those trends show that regulations to improve air quality have been effective in improving air quality for most of the country," said Urbanski. "But we're at the point where the increased wildfire activity in the western United States is overcoming those efforts."

Urbanski said research aimed at understanding the factors underlying emissions from wildfires as well as the benefits in mitigating wildfire emissions using prescribed fire will be significant when it comes to understanding and addressing these trends in air quality, especially during wildfire season.

FURTHER READING

Liu, X.; Huey, L.G.; Yokelson, R.J.; [et al.]. 2017. Airborne measurements of western U.S. wildfire emissions: comparison with prescribed burning and air quality implications. Journal of Geophysical Research: Atmospheres. 122: 6108–6129. doi:10.1002/2016JD026315. https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2016JD026315

Lutes, D. 2019. FOFEM 6.5 first order fire effects model user guide. April 2019. https://www.fs.usda.gov/rmrs/publications/first-order-fire-effects-model-fofem-40-users-guide

McClure, C.D.; Jaffe, D.A. 2018. US particulate matter air quality improves except in wildfire-prone areas. Proceedings of the National Academy of Sciences of the United States of America. 115(31): 7901–7906. https://www.pnas.org/content/115/31/7901

Urbanski, S. 2014. Wildland fire emissions, carbon, and climate: emission factors. Forest Ecology and Management. 317: 51–60. https://www.fs.usda.gov/rmrs/publications/wildland-fire-emissions-carbon-and-climate-emission-factors

Urbanski, S. P. 2013. Combustion efficiency and emission factors for wildfire-season fires in mixed conifer forests of the northern Rocky Mountains, U.S. Atmospheric Chemistry and Physics. 13: 7241–7262. https://www.fs.usda.gov/rmrs/publications/combustion-efficiency-and-emission-factors-wildfire-season-fires-mixed-conifer-forests

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The following individuals were instrumental in the creation of this Bulletin:

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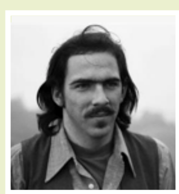

SCOTT WILLIAMS has worked 39 years for the USDI National Park Service and USDA Forest Service as a park ranger and fire management specialist and now serves detached from the Forest Service's Washington Office. He has been a coordinator and lead instructor for RX-410 Smoke Management Techniques classes taught in California since 1994. Connect with Scott at scott.c.williams@usda.gov

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