Wildland Fire PM Emission Factor Workshop Summary

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61 Forsyth St SW, Atlanta, GA 30303

Hosted by: Tall Timbers Research Station and Land Conservancy, Florida A&M University, and Environmental Protection Agency Region 4

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Purpose: The purpose of the workshop was for research scientists, air quality specialists, policy administrators, and others to present and discuss recent advances in research relating to estimation of emission factors for particulate matter (PM) and its constituents (organic carbon, black carbon, etc.) emitted from wildland fires, including wildfires and prescribed burning. The workshop consisted of presentations by attendees and discussions aimed at sharing technical information, evaluating measurement approaches, and suggesting applications to air quality monitoring and policy development.

Prepared by: Kevin Robertson, Fire Ecologist, Tall Timbers Research Station, 13093 Henry Beadel Drive, Tallahassee, FL 32312, krobertson@ttrs.org, 850-893-7678 x 254

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Introduction

Development of sound, science-based policy guiding the use of prescribed burning for the greatest public benefit has never been more important than now. Restrictions on prescribed burning where it is not warranted may place the public at greater risk of wildfires, which usually emit many times the particulate matter (PM) of prescribed burns, while threatening the health and biodiversity of fire-dependent ecosystems. At the same time, under-estimation of PM emissions from prescribed burning may allow public health risks to go undetected, which is an increasing concern as human populations continue to grow.

Various research programs and agencies recently have been conducting independent lines of research to better estimate emission factors for the most important wildland fire pollutants. However, communication and collaboration among them have been limited. This workshop seeks to promote transfer of knowledge and future collaboration that will assist the efforts of participating researchers and improve their capacity to serve the general public.

The following workshop summary is intended to synthesize the salient ideas presented and discussed by workshop participants, with undated citations referring to the presenters and discussion participants where appropriate (see Appendix A, Workshop Participants). The summary is organized according to the seven questions that served as the guide for the discussion portion of the workshop, although it includes topics from both presentations and the discussion, with an effort to incorporate the broad range of topics addressed. The General Background section with references to published literature provides a basic understanding of emission factors as background to the subsequent summary.

General Background

Emission factors represent the amount of a substance emitted into the air relative to the amount of total material combusted. Emission factors (EFs) for particulate matter (PM) emitted from wildland fires are typically reported in grams of emitted PM per kilogram fuel combusted. EFs are an essential component in the sequence of steps taken for estimating wildland fire emissions, specifically estimation of 1) burned area, 2) fuel loading, 3) fuel consumption, 4) emissions using EFs, and 5) subsequent transport and dispersion (Goodrick et al., Ottmar et al.). Most PM emission research currently focuses on PM smaller than 2.5 microns ($PM_{2.5}$) because of its health effects and regulation by the U.S. Environmental Protection Agency (EPA).

The ratio of carbon emitted as carbon dioxide (CO_2) to carbon emitted in other forms is referred to as "combustion efficiency" (CE). Since carbon monoxide (CO) usually makes up a very large percentage of non-CO_2 carbon emitted, the fraction of emitted CO_2+CO made up of CO_2, called "modified combustion efficiency" (MCE), is often used as a surrogate for CE (Urbanski et al. 2009, Janhäll et al. 2010).

PM EFs increase as CE decreases in a fairly predictable and general relationship (Yokelson et al. 2007a, Janhäll et al. 2010), although exceptions were presented during the workshop and are discussed further below. PM EF and CE are strongly related to phase of combustion, which corresponds to oxygen availability during the combustion process. The flaming combustion phase, characterized by gases being rapidly volatized from the fuel and undergoing exothermic chemical reactions (flame), represents combustion with high oxygen availability. Flaming combustion transitions to the smoldering combustion phase after the rate of volatization of gases decreases to where flaming cannot be sustained, marking a decrease in oxygen available for combustion, a decrease in CE, an increase in the relative production of CO, and an increase in incompletely oxidized combustion products (including PM), which translates to a higher EF. After volatiles are drawn out from deeper in the fuel and more or less exhausted (forming charcoal), the glowing combustion phase begins, which involves reaction of surface oxygen directly with the residual carbon (Ward et al. 1989, Ward et al. 1993, Janhäll et al. 2010). Glowing combustion has relatively high CE and low PM EFs, as the remaining fuel being combusted is mostly carbon, and thus it has received relatively little attention as a source of PM.

A limited amount of research has related PM EFs to fuel characteristics. PM EFs generally increase with increasing fuel moisture. When fuel moisture increases, volatized gases are diluted by steam, the rate of oxidation reactions and flame temperature is reduced, and volatized substances are less completely combusted (Ward et al. 1983). Higher fuel particle size and bulk density (packing ratio) also tends to increase PM EF, because of lower oxygen availability and indirectly because larger and more densely packed fuels tend to better retain moisture (Ward et al. 1993). Fuel chemical composition may also have a significant effect on PM EF (Goodrick et al., Ward et al. 1983, Urbanski et al. 2009).

PM EFs are generally estimated by comparing amount of carbon emitted to PM emitted, then calculating fuel consumption based on the amount of carbon emitted, based on the assumption that consumed fuel is composed of approximately 50% carbon. Most of the carbon emitted is in the form of CO_2, although a significant amount may also be released as CO, hydrocarbons, and PM itself (Lee et al. 2005, Urbanski et al. 2009). The typical method for estimating PM EFs from wildland fires has been the "mass balance method" (also called the "excess concentration method"), which involves estimating gases and PM emitted from fire as the difference between their concentrations found in the fire plume and their concentrations in the ambient (pre-fire) air (Ward et al. 1980). Typically, CO_2, CO, and PM are measured for calculation of the PM EF, although hydrocarbons may also be considered for a more complete account of C released through combustion. Measurements are taken within the smoke plume, but vertical location of measurement relative to the ground have ranged from about two meters (e.g., Ward and Hardy 1989, Urbanski et al. 2009) to several thousand meters (aircraft based, e.g. Urbanski, Yokelson et al. 2007b). PM can be sampled real-time, as with light scattering analyzers (Ward and Hardy 1984), or on filters, and gas is usually collected with "grab samples" during the same time period that PM is sampled (Ward and Hardy 1984, Urbanski et al. 2009). Assumptions of the method include 1) the relative concentrations of measured PM and gas species proportionally represent quantities emitted, i.e., there has been no differential diffusion or transport between PM and gases following combustion, 2) the PM and gases are well mixed throughout the convection column, such that measurements at a particular location within the column are representative of the fire, and 3) carbon in the fuel is released in direct proportion to the carbon in the emissions (Ward and Hardy 1984).

The fact that PM EF changes significantly with phase of combustion at a given location presents a challenge for estimating an overall EF for the entire combustion process. Calculation of an overall EF is generally approached in one of four ways: 1) assume that measured PM and CO_2 provide an unbiased representation of that emitted during the entire combustion process, as is typically done for high-altitude measurements (Yokelson et al. 2007b); 2) estimate separate EFs for each phase of combustion, then estimate how much fuel is consumed by each phase to calculate a weighted EF (Ward and Hardy 1989); 3) estimate EF for each of multiple short time segments during the fire while measuring vertical flux of PM and CO_2, then weight EF according to the vertical flux (representing rate of consumption) during each time segment (typically measured using towers; Ward and Hardy 1984, Urbanski et al. 2009); and 4) estimate EF at multiple locations vertically integrated throughout the plume (Andreae and Merlet 2004).

1. What are the greatest sources of uncertainty in current estimates of PM emission factors?

Accounting for the smoldering combustion emission source

An important source of uncertainly in estimation of PM emission factors (EFs) relates to how much of the total combustion process is incorporated in EF estimates, i.e., whether the relative "source strength" of flaming versus smoldering combustion is adequately represented in a total fire or "event based" estimate of PM EF. Given that measurements of PM and gases for EF estimation have been taken within the smoke plume (vertical convection column) of the fire at widely varying elevations, it is possible that not necessarily all emissions are incorporated into the plume at a given vertical location of measurement. More specifically, emissions from smoldering combustion following the passage of the flaming front beneath the measurement location may not be fully represented in the plume, as they are produced by low intensity combustion resulting in relatively low temperature gases and a weak convection column, making the emissions more susceptible lateral dispersion relative to vertical transport (Curcio et al., Mickler et al.). Such weak convection currents may also fail to fully entrain emitted PM and allow differential diffusion of gases and PM, contradicting the assumption of thorough mixing of emitted species in the plume (Hsieh et al.), discussed further below. Given the much higher PM EF of smoldering combustion compared to flaming combustion, its underestimation would have a disproportionately large influence on estimates of event-based PM EFs.

It was suggested that the adequacy of current methods of estimating PM EFs depends on the application. For the purpose of estimating broad scale impacts of fire emissions for national emissions inventories, the emissions of interest are those that are injected high enough into the atmosphere to be carried by trade winds and have a long enough suspension time to influence regional air quality monitoring. In that case, measurements made by aircraft and on high towers should be appropriate for fires dominated by flaming combustion and measured while the fire is still active (Urbanski et al.). However, a full account of PM emissions is expected of EPA inventories, regardless of source, for reports to Congress and other stakeholders (Rao). Also, measurement of near-surface smoldering combustion may be needed for assessing health impacts to humans near the fire and for accounting for greenhouse gas emissions (Mickler et al., Alvarado et al.). Measuring vertical flux of gases and PM during flaming versus smoldering phases of combustion using towers (e.g., the FASS system) presumably incorporates a greater amount of emissions from smoldering combustion than measurements taken at high altitudes. However, these measurements also assume that all emissions of interest vertically intersect the sampling location, which might still result in underestimation of the source strength of residual smoldering. These concerns are naturally highest for fires dominated by smoldering combustion, such as fuel beds composed primarily of coarse woody debris (Alvarado et al.) or organic soil (Curcio et al., Mickler et al.). Surprisingly, it seems that there are no published PM EFs for organic soil combustion, although measurements using conventional tower methods show burns to have very high event-based PM EFs (Mickler et al.). Estimation of residual smoldering combustion was listed as a needed area of improvement for the FEPS system (Alvarado).

Although the smoldering combustion source strength may be underrepresented in certain estimates of PM EF, some evidence was presented that suggests smoldering combustion products could result in the overestimation of PM EFs if measured too close to the ground. Samples collected immediately above flames or smoldering fuel during prescribed burns in southern pine forests (Robertson et al.) showed $PM_{2.5}$ EFs to be much higher than predicted by the typical relationship between $PM_{2.5}$ EF and MCE determined from measurements taken from towers or aircraft (Urbanski et al.). Similarly, research presented by Mickler et al. showed that most (though not all) experimental burns in a southern pine forest had highly elevated $PM_{2.5}$ EF relative to MCE using PM measurements taken approximately 2 m above the ground. These results are also consistent with published measurements of PM EFs at multiple heights along a tower, where the lowest elevation showed the highest $PM_{2.5}$ EF (Ward et al. 1983).

A possible explanation is that air being measured at low elevations during fires is "contaminated" by residual PM from which combustion-emitted CO_2 and CO has differentially diffused. Such airborne PM might accumulate near the ground because 1) it has a low intensity (smoldering) combustion source resulting in low gas temperature, weak convection, high local residence time relative to rate of gas diffusion, and possibly reduced mixing, or 2) the residual PM is a heavier fraction than that vertically entrained in the convection column. Evidence for differential diffusion was presented by Hsieh et al., where measurements of $PM_{2.5}$ and gases were measured inside and just outside the plume of an experimental fire (wood burning in a barrel) using the same method as Robertson et al. above. The relationship between $PM_{2.5}$ EF and MCE was similar to that previously published directly within the plume, but $PM_{2.5}$ EF was extremely elevated relative to MCE just outside the plume, indicating an accumulation of residual PM following differential diffusion of CO_2 and CO. Other experiments in the field by Hsieh et al. have indicated elevated PM within recently burned areas after CO_2 has returned to ambient (pre-fire) levels. Such differential diffusion might partially explain the observation of higher $PM_{2.5}$ EFs estimates in the field than in the laboratory using the same fuels (Urbanski et al., Yano et al.). Further experimentation will probably be required to test these concepts and improve $PM_{2.5}$ EF estimates for specific applications.

Assumptions of the excess concentration method

As discussed in the overview, the "mass balance" or "excess concentration" method of estimating the amount of CO_2 released through combustion depends on the assumption that the concentration of ambient CO_2 relative to other gases is the same between ambient air and air in the fire plume. Work by Hsieh et al. has sought to test this assumption empirically by using the carbon isotope signature of ambient versus fuel C to more directly differentiate ambient versus combustion-produced CO_2. Estimates of combustion-emitted CO_2 using this method correlated well with those using the excess concentration method, although the excess concentration method was shown to overestimate combustion-emitted CO_2 by an average of about 11% and underestimate $PM_{2.5}$ EF by an average of about 6 %. The percentage is generally lower for smoldering combustion because of relatively high concentrations of CO emitted, all of which is assumed to be from the fuel. Thus, any inaccuracy in the excess concentration method is minimized by the low ambient CO_2 concentration relative to that of combustion-emitted CO_2. The reason for this systematic difference between the two methods of measurement is not yet known.

Environmental and temporal influences on PM EF

$PM_{2.5}$ EF was shown to respond strongly to different North American forest cover types, increasing from forests in the southeastern U.S. to southwestern U.S. to the northern Rockies (Urbanski et al.). It also increases from grasslands and chaparral to southeastern evergreen shrublands to conifer forests (Urbanski et al.). Correspondingly, specific PM EFs are typically applied to a particular general fuel bed or habitat cover type for purposes of emissions estimation. However, PM EFs can be influenced by more fine scale and temporally varying factors, including fuel loading, fuel composition, fuel structure, and fuel moisture type, which can be strongly related to time since a given land use change event (e.g., fire, logging) and season of burn (Alvarado et al., Goodrick et al., Ottmar et al., Robertson et al.). There has been relatively little work aimed at determining the range of EFs associated with such specific conditions. For example, it was noted in the discussion that all published estimates of $PM_{2.5}$ EF in southern pine forests to date have been made in the dormant season, although some currently planned research initiatives will compare dormant and growing season fire (Ottmar, Urbanski). One limitation is that fuel moisture of live fuels is currently not as well modeled as other fuels, although efforts to improve models for seasonal variation in fuel moisture and consumption are ongoing (Curcio, Gillam).

Presented research showed PM EFs in frequently burned southern pine forests to be positively related to the growing season, fuel moisture, relative humidity, and percent live herbaceous vegetation, and negatively related to time since previous fire and fine dead fuel accumulation (Mickler, Robertson). PM EF probably responds most strongly to fraction of the fine fuel load composed of live herbaceous vegetation, which corresponds primarily to fuel moisture (Robertson, Urbanski), although fuel chemistry may also play an important role (Goodrick).

2. What are some new or underutilized approaches that could be taken to reduce the uncertainties in PM EF estimation, and what resources are available to support such research?

Defining PM EFs

There appears to be a need for some clarification of what a given calculation of PM EF represents. For example, an EF for $PM_{2.5}$ vertically translocated by the convection column during active fire spread should be specified as such and not necessarily presumed to be a full event-based EF, especially if a relatively large proportion of fuel consumption is through smoldering rather than flaming combustion (Curcio et al., Hsieh et al., Mickler et al., Robertson et al., Urbanski et al.). New models may need to be developed for predicting PM concentrations near the surface within or near the burned area. Mickler et al. are working on such models to predict PM concentrations within forest stands for use in the BlueSky framework. Such developments might also improve smoke dispersion models such as FEPS.

Methods of estimating PM EFs

It was suggested that predictable relationship between $PM_{2.5}$ EF and MCE might allow the calculation of EF based on measurements of MCE alone (Robertson et al., Urbanski et al.), which requires only the measurement of CO_2 and CO emitted from the fire. This approach has the advantage of not having to assume that the PM and gases have remained well mixed since being emitted, which seems to be a questionable assumption where there are low-temperature (smoldering) emission sources and the possibility of differential diffusion, as discussed above.

An alternative approach is to use the thermogram of PM generated by Multi-elemental Scanning Thermal Analysis (MESTA) technology to determine what portion of PM is ambient versus combustion-emitted for comparison with emitted CO_2 to estimate the EF (Hsieh et al.). This approach also allows differentiation of PM emitted by flaming versus smoldering combustion for further refinement of PM EF estimates under conditions dominated by one combustion phase or another.

The carbon isotope method of distinguishing combustion-emitted versus ambient CO_2 was also presented (Hsieh et al.). This method has the advantage of not having to assume that the relative concentration of ambient CO_2 in the fire plume is the same as that measured under ambient conditions. However, the method also depends on the assumption of a fixed carbon isotope signature for the fuels combusted, but preliminary tests on a wide variety of fuel types in the southeastern U.S. Coastal Plain show that the isotopic signature of natural fuels have very low variance (Hsieh et al.).

Measurement technology

The most widely used, tower-based Fire Atmosphere Sampling System (FASS) was presented and described (Urbanski et al.). FASS collects gas and PM using a sampler mounted on a tower, through which the sampled air is piped downward to a below-ground collection and analysis system. CO_2 and CO are measured both continuously and stored in canisters for later analysis, and PM is collected on fiberglass filters. Three-D anemometers record wind speed and rate of vertical convection. Samples are taken during three periods representing mostly flaming, transitional, and mostly smoldering combustion phases to produce a weighted, event-based PM EF (Urbanski et al.).

Eddy flux towers have also recently been used (Mickler et al.), in which the 3-D flux of air, heat, H_2O, CO, CO_2, CH_4, NO_x, NH_3, and N_2O is measured in real time during fires, allowing source characterization (e.g., flaming versus smoldering combustion) as well as fire front turbulence and heat in close proximity to the source.

Airborne platforms were also presented (Gullet et al., Urbanski et al.). Urbanski et al. presented systems carried by airplanes capable of real-time measurement of $PM_{2.5}$, CO_2, CO, CH_4, and other gases and pollutants. Gullet et al. presented the use of an Aerostat balloon to lift a light-weight system that collects real-time samples of CO_2, CO, SVOC, $PM_{2.5}$ and PM_{10}, and other species, has a 3D anemometer and GPS system, and which transmits data to the ground in real time. This unmanned system is useful for application in inhospitable environments in which manned flights are too dangerous, and thus it has been used during the burning of spilled oil (Gullet et al.).

PM and gas samples have also been taken at the tip of the flame during flaming combustion and directly above smoldering combustion sources using a hand-held sampling tube from which gas and PM are transported a short distance to an open-air sampling location (Hsieh et al., Robertson et al.). There $PM_{2.5}$ is sampled using a fiberglass filter sampler and CO_2 and CO are collected in "grab bags" for analysis of gas concentration and carbon isotope ratios, which in turn is used to fractionate ambient versus fire-emitted CO_2.

Measurement of Additional PM EFs

Estimation of PM EFs for an increasing number of fire conditions will be essential for improving emissions inventories. Thus, developers of large-scale emission inventories are actively seeking and collecting new EF estimates to improve regional emissions calculations. For example, the Western Regional Air Partnership is collecting new EFs for development of the Deterministic and Empirical Assessment of Smoke's Contribution to Ozone (DEASCO3) platform designed to replace the Fire Emissions Tracking System (FETS) (Moore et al.). Also, EPA is collecting new EFs, including those for various hazardous air pollutants (HAPs), for incorporation into the Fire Emissions Production Simulator (FEPS) program and as part of the BlueSky emission calculation framework (Rao et al.). More specifically, EPA is searching for PM EFs for specific crop residues to improve its estimates of emissions from agricultural burning (Rao et al.). Also, event-based PM EFs for the full range of seasonal conditions are needed, as discussed above. A recent meeting of the Department of Defense Strategic Environmental Research and Development Program (SERDP) compiled EFs from a wide range of sources (Rao).

3. How can emission factor estimates be better utilized in emission calculation tools and frameworks?

Application of EFs according to specific burn conditions

As PM EFs are calculated for an increasing number of specific conditions ad fuel types, they should be used to improve the accuracy of emissions models for specific regions, fuel types, and conditions. For example, currently the First Order Fire Emission Model (FOFEM) applies one $PM_{2.5}$ EF for all flaming combustion and one for all smoldering combustion, and some proportion of the two is use according to fuel type without regard to fuel moisture, fuel live or dead status, bulk density, or other variables which appear to influence EF (Mickler et al., Robertson et al., Urbanski et al.). Consume still uses PM EFs published in the 1980s, because they are broken down by flaming and smoldering combustion, whereas most of the newer estimates are event-based from samples at high altitudes (Ottmar). Additions of more specific PM EFs to such models would be facilitated by development of models predicting EC and associated EFs for varying fuel conditions. These tools play a key role development of national emissions inventories, including development of EPA's NEI, such that any improvements have broad implications (Rao).

4. How important is the improvement of emission factor estimation in comparison to other sources of uncertainty in wildland fire emissions inventories?

There was a fairly broad consensus that improving the accuracy of PM EF calculations was less critical than improving estimates of area burned (especially by prescribed fires in the southeastern U.S.), fuel loads, and fuel consumption (e.g., Alvarado, Curcio, Gillam, Mickler, Moore, Ottmar). Also, it was pointed out that use of the correct EF requires knowledge of what fuel type is being burned. However, the presentation by Yano et al. suggested that the EF estimate contributes more uncertainty to emissions estimates than the fuel load estimate. More specifically, use of varying sources of $PM_{2.5}$ EFs for the same fuel type resulted in 25% uncertainty in $PM_{2.5}$ emissions estimates, compared to a 20% uncertainty from fuel load estimation using photo series and 12% using Consume 3.0 default fuel loads. Variance in estimates of burned area was not considered in the analysis, although it was thought by some to be the largest source of error.

The model Daysmoke, which predicts PM concentrations over time at a given distance from the fire, was found to be very sensitive to the PM EF used based on measurements of southern pine forests at Eglin Air Force Base, Florida (Yano et al.). Standard deviation of $PM_{2.5}$ concentration predictions generated by use of different EF sources was generally greater than the grand mean. In general, there was a linear relationship between variance in the PM EF input and a PM concentration predicted downwind (Yano et al.).

Research by Hsieh et al. suggests that the current method of estimating PM EFs (excess concentration or mass balance method) systematically overestimates fire CO_2 by 11% and underestimates EF-$PM_{2.5}$ by 7%. However, these errors are presumably relatively small compared to the uncertainty regarding which PM EF estimates are most appropriately applied under given fuel and fire conditions.

5. What are the critical information gaps in wildland fire PM emission inventories currently needed for policy and decision making at the state and federal levels?

As considered above, there is remains considerable uncertainty in each of the steps required to develop PM emission inventories, including calculation of area burned, fuel load, fuel consumption, emission factors, and transport of emissions, as well as the partitioning of monitored PM according to source.

Burned area

Several workshop participants suggested that improving estimates of burned area is the greatest of all needs for improving PM emissions inventories. Information on burned area comes from a wide range of data sources which each have particular sources of error. EPA prefers to use information provided by state agencies, such as authorized prescribed fires and state agency incident reports, but most states do not provide such data (Rao et al.). In lieu of state data, the EPA National Emissions Inventory (NEI) depends on remote sensing estimates of burned area through the Hazard Mapping System (HMS), which utilizes 1 km^2 resolution MODIS satellite data. These data are reconciled with fire incident reports (ICS-209s) using the SmartFire2 framework (Rao et al.). However, the coarse resolution of MODIS, which makes it suitable for large, multiple-day fires, limits its application for and apparently underestimates small, short-duration prescribed burns that are common in the southeastern U.S. (Tian, Zeng), although merging fire counts from the Terra and Aqua MODIS satellites improves the quality of burned area estimates (Zeng et al.). The ideal approach is to have available and reconcile both "bottom-up" data collected by state and local entities and remote sources of data for developing emissions inventories (Rao).

The Monitoring Trends in Burn Severity (MTBS) program uses 30 m resolution Landsat data for relatively refined estimates of burned area and severity for individual burns. MTBS data are increasingly used by the Western Regional Air Partnership (WRAP) program in addition to MODIS for calculation of burn severity as part of its emissions inventory (Moore et l.). Although MTBS coverage is continually increasing, it so far has been largely limited to fires >500 acres occurring on public land and documented by federal incident reports, thus excluding most prescribed burns in the southeastern U.S. There are also limitations to using Landsat data because of its low flyover frequency and availability of clear images relative to rate of "green up" following fire, especially in the southeastern U.S. (Robertson, Tian).

Bottom-up reporting of burned area has long been desired by state and federal agencies. Although ICS-209 incident reports are required for wildfires and large prescribed fires on federal lands, they are not collected for other burns, including the large number on private forest, range, and agricultural lands. It was agreed that the success of such a program would depend on the degree to which the participants see the collected data as ultimately being beneficial to them (Carver, Moore). Perhaps an example to emulate is the voluntary reporting of emissions by oil and gas companies, because they wanted to be accurately represented in emissions inventories (Moore). However, there is some resistance for burners to provide information, especially in the western U.S. Perhaps the case could be made through the prescribed fire councils, as is currently being pursued by EPA (Gillam). Other groups that could be helpful include the Southern Group of State Foresters and the American Society of Foresters. However, a practical limitation is that burners themselves may not be certain about the exact area that they burned, which would use require GPS to be accurate, although estimates would be better than what we have now. FETS (Fire Emissions Tracking System), which is being replaced by DEASCO3, may become the national standard reporting system for fires (Curcio, Gillam, Goodrick, Moore). Implementation of such standards may be pushed forward in the future by federal mandates demanding better reporting (Gillam).

At the state level, prescribed burn authorizations (burn permits) are increasingly being used in part to estimate area burned. However, these estimates probably overpredict burned area because there is no check to determine whether or not the area authorized to burn was actually burned, managers often request authorization for more acreage than they intend to burn, and burn units are rarely 100% burned because of unburnable areas (Robertson). In Georgia, a comparison of burned area data based on Georgia Forestry Commission burn permits and wildfire records and military bases fire records versus EPA remote sensing-derived data showed large discrepancies (up to 29%) in estimated burned area. However, the discrepancy was season-specific, with burned area overestimated by EPA in the summer and fall and underestimated in the winter (Tian et al., Zeng et al.), in part due to MODIS less efficiently detecting fires in the growing season (Zeng et al.). It was suggested that authorization data could be calibrated by intensive study of a subset of burns through remote sensing or GPS, to determine the relationship between burn authorizations and actual area burned (Robertson). This approach could be widely applied as states begin to centralize their burn authorization data, as Florida has done and Georgia is near doing (Gillam, Tian). There is also a need for more calibration between satellite reflectance data and burn perimeters measured on the ground with GPS, as relatively little such work has been done so far. However, there are plans to calibrate MODIS with ground measurements in the southeastern U.S. (Tian). Using remote sensing is also challenging because of forest cover in many areas where there are surface fires (Tian).

To date, estimates of area burned by agricultural prescribed fire have had a particularly high level of uncertainty. Finding sources of data for agricultural area burned is currently a high priority of EPA for development of the NEI (Rao et al.) and of WRAP for development of regional emissions inventories, including development of the DEASCO3 emissions projection platform (Moore et al.).

Fuel loads and characterization

Ottmar et al. presented an overview of surface fuel estimation using Natural Fuel Photo Series, which provide photos and corresponding fuel load characterization for a nearly exhaustive list of common vegetation types in the U.S. Photo series can be very useful in lieu of quantified data in particular locations, but they are limited by their oblique view, which can be misleading for cover conditions, fuel bed height, and litter, apart from not being applicable to ground fuels. The photoseries are now available digitally. Yano et al. found that photoseries overestimated fuel load by 20% on Eglin Air Force Base, Florida.

Ottmar et al. also reviewed the Fuel Characteristic Classification System (FCCS), which provides fairly fine scale fuel cover class coverage for the entire U.S. and is used in several national emissions calculation systems. FCCS fuel bed properties can be modified for particular conditions, including season and certain change events, such as fire, logging, and fuel treatments. So far, change events have been primarily developed for forest types with long disturbance return intervals, but more work is needed for high fire frequency cover types such as southeastern U.S. pine forests, where fuel bed conditions rapidly respond to time since disturbance. New FCCS fuelbeds are continually being added and mapped to cover a wider range of potential fuel conditions. FCCS output provides the input for common models predicting fire hazard, fire behavior, and emissions (Ottmar et al.).

While a great deal of past and current work has focused on characterization of surface fuels, very little has been done to map ground (organic soil) fuels. It is evident that this is a tremendous need. Ideally, organic fuel maps and should be added to the National Fire Danger Rating System. A challenge to ground fuel mapping is the inability to use conventional remote sensing algorithms, although the scheduled launch of SMAP satellites with ground penetrating radar may help with this effort (Curcio et al.).

Fuel consumption and emissions

In addition to the need to map ground fuels, there is a great need to develop models for ground fuel availability to predict associated ground fuel consumption. Case studies show stunning amounts of fuel consumption associated with organic soil consumption, including a total of 9.1 Tg C in the Evans Road Fire in North Carolina (Mickler et al.) and 384 tons per acre in the Edna Buck Fire in (Curcio et al.). Such fuel consumption is not predictable using conventional surface fuel maps and fuel consumption models designed for spreading surface fires. On the other hand, fuel consumption models and individuals tasked with estimating fuel consumption often assume that 100% of existing organic fuel is consumed, which is also generally not correct (Curcio).

Curcio et al. presented the Estimated Smoldering Potential (ESP) system, "An operational tool for fire practitioners to quantify the availability of ground fuels and their potential contribution to fire emissions." ESP involves a matrix of monitoring sites that track depth-specific organic fuel moisture for use in a fuel availability algorithm. This kind of system is needed to replace or supplement the currently often used Keetch-Byrum Drought Index (part of NFDRS), which can underestimate the potential for organic soil to combust. Water level is not a good indicator of ESP, or fire danger, as fuels can smolder down into saturated organic soil. ESP takes into account the response of smoldering potential to fuel moisture content and percent mineral content. Currently, ESP Fire Danger Stations are deployed in North Carolina, and it is being considered for broader use by the National Wildfire Coordinating Group Smoke Committee. Other needs include developing ESP algorithms for other regional organic soils and linking the system to ground penetrating radar estimates of soil moisture from the scheduled SMAP satellite (Curcio et al.).

Alvarado et al. presented recent advances in modeling both organic soil and coarse woody debris fuel consumption. Coarse woody debris, similar to organic fuel, can continue to burn by smoldering combustion long after the flaming front has passed and may contribute large amounts of previously unmodeled emissions. Combustion models developed from empirical field and laboratory studies in the tropics are unique in that they consider the rate of advancement of a smoldering combustion front through large coarse woody debris particles (e.g., logs using the "cigarette" model) for calculation of rate of combustion. Combustion was influenced by time of day, wood chemical and physical properties, location relative to the ground, and decomposition stage. Moisture had a relatively weak effect as moisture is driven off by the advancing smoldering front. Results are intended for improvement of the FEPS 1.1 emissions production and transport model (Alvarado et al.).

There is also a need for a more standardized system for reporting on approximately how much fuel was actually burned after a fire event, to be included in the ICS-209 federal incident situation reports (Curcio). Some fires do not have Fire Effects Monitoring Officers (FEMOs) as they should, and some of these are not well trained for their technical task (Curcio, Sullivan). Fires that last several days often have gaps in the necessary ICS-209 reporting, even though these reports are used by the SmartFire platform for validating satellite data for EPA emissions inventories (Curcio, Rao).

Transport of Emissions

Development of models to better predict emissions transport remains a great need, as reflected in efforts by various research groups to improve existing models. A research group associated with Alvarado et al. is evaluating a model for plume rise development to be incorporated into the CATT-BRA climate and weather model, which was created by the *Instituto Nacional de Pesquisas Espaciais* (National Institute for Space Research, INPE) in Brazil. As noted above, Yano et al. calibrated downwind PM concentrations predicted by Daysmoke according to the PM EF used for calculating emissions. Preliminary work by Mickler et al. showed that predicted emissions transport varies significantly between use of subcanopy versus above-canopy inputs for windspeed and temperature, necessitating development of new models for subcanopy smoke dispersion for use in the U.S. Forest Service BlueSky emissions framework.

Emissions Source Partitioning

Determining the source of pollutants and their chemical components is an important aspect of air quality assessment. EPA uses the data repository system called SPECIATE (http://www.epa.gov/ttnchie1/software/speciate/index.html) to provide speciation profiles (chemical content) of PM and other pollutants from specific sources, which can be used to calculate the probable source of measured pollutants (Rao et al.). Certain PM species act as "smoke markers" indicating wildland fire (natural fuel biomass combustion) as their source. Some of the most common smoke markers are the fraction of organic carbon (OC), levoglucosan, and potassium, which are compared to fractions in freshly burned biomass to determine the relative source strength of biomass combustion, including wildfires and prescribed burns (Sullivan et al.). However, an important limiting factor is the variability in the concentration of these substances in the fuel combusted, as well as rates of release under different fire conditions, including wildfires versus prescribed fires. Prescribed fires tend to produce higher concentrations of smoke markers, in part because of the predominance of flaming relative to smoldering combustion. Thus, PM suspected to be from wildfires versus prescribed fires needs to be analyzed separately, or the relative contribution of each needs to be estimated (Sullivan et al.). One suggestion is to not rely on potassium and levoglucosan alone, but rather a broader range of markers, which might include OC, galactosan, arabinose, and resin acids (Balachandran et al., Sullivan et al.). OC is most reliable in rural areas where it is less confounded by fossil fuel emission sources (Rao). Carbon monoxide (CO) has also been used as a tracer to validate V-smoke.

Another approach (discussed above) is the use of MESTA, which provides thermograms of PM showing the relative proportions of C, N, and S released from a sample with increasing temperature (Hsieh et al.). This method may be subject to the same limitation as smoke markers, i.e., there is variation in thermogram signatures among biomass combustion samples, but this has not yet been empirically tested. Preliminary research suggests that MESTA thermograms are fairly robust among burning conditions, at least relative to other sources of PM such as fossil fuels (Hsieh et al.).

The geographic distribution of ambient PM species, including particulate OC, levoglucosan, acrolein, and other markers, could be compared with the geographic distribution of wildland fires for validation of emissions estimates (Rao). Regional air quality models such as CMAQ and CAMx could be used to conduct case study sensitivity runs to test the goodness of fit between estimates based on ambient species and other sources emission information (Rao).

6. What collaborations need to be pursued to improve research and validation of PM emission estimates?

7. What efforts should be made to better validate and calibrate PM emissions inventories?

These questions are addressed together, as collaboration and validation are closely related. These question struck the participants as difficult to answer, since there is need for collaboration and validation on a wide range of research efforts among scientists focused on a particular step of the process of predicting emissions (area burned, fuel loads, fuel consumption, EFs, emission transport) as well as among scientists working on different steps. Collaboration is also needed among research scientists, air quality specialists, and policy makers. There are many barriers to collaboration, including varying sources of funding, differing agency and organizational goals, information proprietorship, limits on travel funding, and limited time to interact with other people and programs.

On the other hand, fire emissions measurement by its nature is interdisciplinary in that the final product relies on the integration of multiple analytical steps, thus demanding collaboration to improve and validate emissions estimates. In addition to serving as a collaborative forum itself, this workshop revealed encouraging trends in collaboration among organizations and individuals represented. An excellent example is the Prescribed Fire Combustion and Atmospheric Dynamics Research Experiment (RxCADRE), which is a series of gatherings of fire scientists using the most recent technology to measure a wide range of variables on the same prescribed fires, including fuel loading, fuel consumption, fire behavior, emissions, and emissions transport and atmospheric dynamics. The list of participating state and federal agencies, universities, and non-profit research organizations too long to list here, and several of the workshop presentations reported results from RxCADRE burns (Gullet et al., Ottmar et al., Sullivan et al., Urbanski et al., Yano et al). A similar collaborative effort is being made by the Western Regional Air Partnership (WRAP) in development of the DEASCO3 Project, which is gathering a large number of federal, state, and private entities to examine case studies to validate sources of information for improving emissions inventories in the western states (Moore et al.). Researchers at the Georgia Department of Natural Resources are working closely with Georgia Institute of Technology to validate and improve emissions inventories for the state (Tian et al., Zeng et al.). The Fire and Environmental Research Applications (FERA) team, producing nationally used applications such as Consume and FCCS, is a collaboration of the U.S. Forest Service and University of Washington. These and other collaborations presented involved leveraging of multiple sources of funding, including Joint Fire Sciences Program, Forest Service National Fire Plan, National Science Foundation, EPA, Strategic Environmental Research and Development Program, state forestry agencies, and others.

While these collaborations are all within the U.S., the presentation by Alvarado et al. showcased the viability of international collaboration, in that case among FERA (U.S.) and Brazilian government and university researchers. Associated research was also conducted in Mexico with plans for collaboration with European Union combustion modelers. Foreign research teams are actively developing models that could be considered for application or validation in the U.S., such as the CATT-BRA emissions transport model developed in Brazil (Alvarado et al.).

A repeated theme among the workshop presentations was the fairly high variation in estimates and predictions of parameters contributing to emissions estimates among various models, databases, and sources of information, even when applied to the same fire event or fuel cover type. Such variation was identified in estimates of area burned (Moore et al., Tian et al., Zeng et al.), fuel load and fuel consumption (Curcio et al., Goodrick et al., Mickler et al., Ottmar et al., Yano et al.), $PM_{2.5}$ EFs (Alvarado et al., Hsieh et al., Mickler et al., Robertson et al., Yano et al.), emissions transport (Alvarado et al., Mickler et al., Yano et al.), and chemistry of PM providing smoke markers (Balachandran et al., Sullivan et al.).

Generally speaking, such sources of variation arise from either differences in 1) sources of empirical data used as input to models or 2) differences in the theoretical algorithms used to process input, although these are also usually based on empirical data. Thus, it is ideal to build empirical databases using data from a wide range of sources to 1) provide a common and comprehensive dataset for validation of existing models and 2) improve or develop new models based on the comprehensive data. An example of this approach is the Smoke and Emissions Model Intercomparison Project (SEMIP) developed through funding by the Joint Fire Sciences Program (Goodrick et al.). Continued funding, staffing, and use of SEMIP will provide a valuable contribution to PM emissions modeling and reduction in model error. Similar validation and reconciliation efforts are being made by the DEASCO3 project, the SmartFire and BlueSky emissions frameworks, WebFIRE, and the Interagency Fuels Treatment Decision Support System (IFT-DSS). However, a limitation to this approach is that contributions are to a large degree voluntary, such that there is still much more information available than what is in these databases. Practically, it needs to be someone's job to search for and collect data from literature and from scientists and to provide the needed database management and quality control. Such positions, although clearly very important, appear to be understaffed or underfunded.

Acknowledgments

Many thanks are owed to those who made the workshop a success, including Kaye Gainey for assistance in organizing the workshop and summary materials, Rick Gillam of EPA for providing the workshop venue, Glynnis Bugna for assistance with logistics, Yuch Ping Hsieh for guidance and support, and the workshop participants who have been generous with their time and suggestions. Funding was provided by National Science Foundation grant AGS-962970.

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APPENDIX 1 – PRESENTERS* AND PARTICIPANTS

Ernesto Alvarado*
University of Washington, School of Environmental and Forest Sciences

Siv Balachandran*
Georgia Institute of Technology, School of Civil and Environmental Engineering

James Boyland
Georgian Department of Natural Resources, Environmental Protection Division, Planning and Regulatory Development Unit

Glynnis Bugna
Florida A&M University

Vince Carver
U.S. Fish and Wildlife Service, Pocosin Lakes National Wildlife Refuge

Gary Curcio*
North Carolina Department of Natural Resources, Division of Forest Resources, Fire Environment Branch

Scott Davis
U.S. Environmental Protection Agency, Region 4, Air Planning Branch

Dave Frederick
Southern Group of State Foresters

Rick Gillam
U.S. Environmental Protection Agency, Region 4, Air Quality Monitoring

Scott Goodrick*
U.S. Forest Service Southern Research Station, Fire Research Laboratory, Center for Disturbance Science

Brian Gullet*
U.S. Environmental Protection Agency, Office of Research and Development, National Risk Management Laboratory, Air Pollution Prevention and Control Division, Air Pollution Technology Branch

Yuch Ping Hsieh*
Florida A&M University

Michael Kemme
U.S. Army Corps of Engineers, Construction Engineering Research Laboratory

Kim Byeong
Georgia Department of Natural Resources, Environmental Protection Division, Air Protection Branch

Matthew Mavco
Air Sciences Inc.

Robert Mickler*
Alion Science and Technology Corp.

Tom Moore*
Western Governors' Association, Western Regional Air Partnership, Air Quality Program, Cooperative Institute for Research in the Atmosphere, Colorado State University

Roger Ottmar*
U.S. Forest Service Pacific Northwest Research Station, Pacific Wildland Fire Sciences Laboratory

Tesh Rao*
U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Emissions Inventory and Analysis Group

Kevin Robertson*
Tall Timbers Research Station and Land Conservancy

Ted Russell
Georgia Institute of Technology, School of Civil and Environmental Engineering

Chuck Sams
U.S. Forest Service Region 9 Air Quality Program

Daniel Stratton
U.S. Forest Service Region 8 Air Quality Program

Amy Sullivan*
Colorado State University, Department of Atmospheric Sciences, Atmospheric Chemistry/Air Quality Program

Di Tian*
Georgia Department of Natural Resources, Environmental Protection Division, Air Protection Branch, Planning and Support

Shawn Urbanski*
U.S. Forest Service Rocky Mountain Research Station, Missoula Fire Sciences Laboratory, Fire, Fuel, and Smoke Science Program

Aiko Yano*
Georgia Institute of Technology, School of Civil and Environmental Engineering

Tao Zeng*
Georgia Institute of Technology, School of Earth and Atmospheric Sciences

APPENDIX 2 - AGENDA

February 7, 2012

8:00-8:10 Welcome and overview. *Dr. Kevin Robertson*, Tall Timbers Research Station and Land Conservancy, Fire Ecology Program.

8:10-8:30 Exploring uncertainty in modeling wildland fire smoke impacts. *Dr. Scott Goodrick*, U.S. Forest Service Southern Research Station, Fire Research Laboratory, Center for Disturbance Science.

8:30-8:50 Uncertainties in southeastern U.S. prescribed fire emissions and their impact on predicting smoke dispersions. *Aiko Yano*, Georgia Institute of Technology, School of Civil and Environmental Engineering.

8:50-9:10 Some critical elements affecting the accuracy of PM emission factor determination in forest fires. *Dr. Yuch Ping Hsieh*, Florida A&M University, Wetlands Research Program.

9:10-9:30 Fire environment effects on $PM_{2.5}$ emission factors and validation of previous estimates in southern U.S. pine-grasslands. *Dr. Kevin Robertson*, Tall Timbers Research Station and Land Conservancy.

9:30-9:50 Field measurements of PM2.5 emission factors for prescribed burning and wildfires. *Dr. Shawn Urbanski*, U.S. Forest Service Rocky Mountain Research Station, Missoula Fire Sciences Laboratory, Fire, Fuel, and Smoke Science Program.

9:50-10:20 BREAK

10:20-10:40 The role of smoldering combustion on smoke emissions. *Dr. Ernesto Alvarado*, School of Environmental and Forest Sciences, University of Washington, Seattle.

10:40-11:00 Investigation of smoke marker ratios from controlled laboratory burns vs. wildfires and prescribed burns. *Dr. Amy Sullivan*, Colorado State University, Department of Atmospheric Sciences, Atmospheric Chemistry/Air Quality Program.

11:00-11:20 Emission sampling from forest fires with an aerostat-lofted instrument platform. *Dr. Brian Gullet*, U.S. Environmental Protection Agency, Office of Research and Development, National Risk Management Laboratory, Air Pollution Prevention and Control Division, Air Pollution Technology Branch.

11:20-11:40 Emissions from a prescribed fire in southern Georgia. *Siv Balachandran*, Georgia Institute of Technology, School of Civil and Environmental Engineering.

11:40-12:00 Advances in characterizing fuels and consumption for inventory of wildland fire emissions. *Dr. Roger Ottmar*, U.S. Forest Service Pacific Northwest Research Station, Pacific Wildland Fire Sciences Laboratory.

12:00-1:00 LUNCH

1:00-1:20 EPA's National Emissions Inventory (NEI), with a focus on biomass burning estimates. *Dr. Tesh Rao*, U.S. Environmental Protection Agency, Emissions Inventory and Analysis Group.

1:20-1:40 North Carolina prescribed fire and wildland fire emissions on longleaf pine sites on the Piedmont sandhills and pocossins forests and organic soils on the Coastal Plain. *Robert Mickler*, Alion Science and Technology.

1:40-2:00 DEASCO3 Emission Inventory Methodology for SIP-grade Planning. *Tom Moore*, Western Governor’s Association, Western Regional Air Partnership, Air Quality Program, Cooperative Institute for Research in the Atmosphere, Colorado State University.

2:00-2:20 Review of emissions inventories for wildland fires in Georgia. *Dr. Di Tian*, Georgia Department of Natural Resources, Environmental Protection Division, Air Protection Branch, Planning and Support.

2:20-2:40 Estimated Smoldering Potential - a fire management tool that can advance smoke management programs and data for emissions inventory. *Gary Curcio*, North Carolina Division of Forest Resources, Fire Environment Branch.

2:40-3:00 Large fire emissions in summer over the southeastern U.S.: Satellite measurements and modeling analysis. *Dr. Tao Zeng*, Georgia Institute of Technology, School of Earth and Atmospheric Sciences.

3:00-3:30 BREAK

3:30-5:30 Discussion focused on following questions (*Kevin Robertson, Moderator*):

1) What are the greatest sources of uncertainty in current estimates of PM emission factors?
2) What are some new or underutilized approaches that could be taken to reduce the uncertainties, and what resources are available to support such research?
3) How can emission factor estimates be better utilized in emission calculation tools and frameworks?
4) How important is the improvement of emission factor estimation in comparison to other sources of uncertainty in wildland fire emissions inventories ?
5) What are the critical information gaps in wildland fire PM emission inventories currently needed for policy and decision making at the state and federal levels?

6) What collaborations need to be pursued to improve research and validation of PM emission estimates?
7) What efforts should be made to better validate and calibrate PM emissions inventories?

APPENDIX 3 - ABSTRACTS

The role of smoldering combustion on smoke emissions

Alvarado, Ernesto.

University of Washington, School of Environmental and Forest Sciences

Smoldering combustion is an important phase of combustion of wildland fuel combustion. This combustion phase produces a large amount of emissions over long time affecting communities and firefighters. Also, because smoldering combustion is a slow process, it affects soil nutrients, roots and seed bank due to much longer heat residence time. The incomplete nature of the process makes smoldering combustion and important source of CO. Also, compared to flaming, smoldering combustion exposes the soil to higher average temperatures, altering important properties on the mineral soil.

Smoldering usually follows the flaming phase of biomass combustion. The flaming period provides energy for heating the biomass, which in turn releases combustible gases (volatiles) leaving a charred layer that advances as the pyrolysis wave goes inward. When the flux of volatiles can no longer sustain gas phase reactions, in the vicinity of the biomass, oxygen can reach the charred heated surface initiating heterogeneous oxidative reactions (smoldering).

Some of the smoldering modeling work has been conducted through numerical and experimental modeling, as well as field studies. This presentation will give an overview of smoldering modeling to predict smoldering front propagation and emissions based on an assumption of a porous biomass structure. Some results from simulating smoldering combustion propagation and emissions, as well as from field and laboratory observations, are presented and discussed.

Estimated Smoldering Potential - a fire management tool that can advance smoke management programs and data for emissions inventory

Curcio[1]*, Gary M., Jim Reardon[2], Tim Howell[3]

[1]IPAFES, and Division of Forest Resources Fire Environment Branch
[2]US Forest Service, Rocky Mountain Research Station, Missoula Fire Sciences Laboratory
[3]North Carolina Forest Service, Asheville, NC

The effective advancement of the North Carolina (NC) Smoke Management Program is dependent on the integration of old and new science and the use of fire management tools. This dynamic flexibility is necessary to meet the combined pressures of controlled burning, regulatory requirements, increasing complexity of NC’s air-sheds and the need for better emissions inventory data. Many NC’s natural resource land management agencies are planning to increase controlled burning at a time when air quality standards are changing with the intent of improving air quality for human health.

Increasing burning opportunities or maintenance of existing prescribed burning programs are dependent on better, finer scale tools and real time web based database that can provide timely information that support burning decisions. Estimated Smoldering Potential (ESP) in Organic Soils and the National Fire Danger System provide insight on burning conditions. These models then provide input for fire emission productivity model whereby emissions can be estimated. With use of these new tools, fire practitioners can populate real time web based emission database using the best known and evolving science.

Exploring uncertainty in modeling wildland fire smoke impacts

Goodrick, Scott.

U.S. Forest Service Southern Research Station, Fire Resarch Laboratory, Center for Disturbance Science

Periodic fire is an important part of many ecosystems. Unfortunately, the smoke from such fires can have serious health impacts on the people living in and around such ecosystems, leading to the need to consider wildland fire along with other pollutant sources in air quality regulations. The effective inclusion of fire emissions in air quality policies requires that emissions from wildland fires be quantified. However, calculating the emissions from a single wildland fire involves numerous estimations, each subject to considerable uncertainty. The first step, estimating the available fuel load is subject to substantial uncertainty as there are a number of methods available for estimating fuel load. However, the fuel bed changes through time and has considerable spatial heterogeneity not captured by any of the available tools. Estimates of fuel moisture content and fuel consumption are also uncertain as moisture values are rarely measured on burn units with any degree of rigor. Instead, fuel moisture estimates derived from local weather observations are substituted. Even the final step in the emission process, converting consumed fuel to an amount of pollutant emitted has its own uncertainties related to the fuel type, time of year, and fire intensity. Uncertainty is and will continue to be an important aspect wildliand fire emissions estimates for the foreseeable future.

Advances in Characterizing Fuels and Consumption for Inventory of Wildland Fire Emissions

Ottmar, Roger D.

Pacific Wildland Fire Sciences Laboratory, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station

Whether you are concerned with particulate matter, carbon monoxide, carbon dioxide, nitrogen oxide or hydrocarbons, all smoke components from wildland fires are generated from the incomplete combustion of fuel. The amount of smoke produced can be derived from knowledge of area burned, fuel loading, fuel consumption, and pollutant-specific emission factors. Multiplying a pollutant-specific emission factor (lbs/ton) by the fuel consumed, and

adding the time variable to the emission production and fuel consumption equations results in emission and heat release rates that allow the use of smoke dispersion models. The Fire and Environmental Research Applications team (FERA) of the Pacific Wildland Fire Sciences Laboratory has developed a suite of tools to characterize fuelbeds, and estimate the amount of fuel consumed during a wildland fire. These variables are the two most critical variables used with particulate matter emissions factors to estimate emissions from wildland fire. The tools include the Fuel Characertistic Classification System, Digital Photo Series, Consume, and the Pile Calculator.

Fuel Characteristic Classification System - FCCS is a user-friendly software program that allows users to access fuelbeds from a nation-wide library or create their own custom fuelbeds. FCCS fuelbeds were compiled from published literature, fuels photo series, fuels data sets and expert opinion. Users can modify FCCS fuelbeds to create a set of customized fuelbeds representing any scale of interest. A LANDFIRE Fuel Characteristic Classification System fuelbed map for the continental United States and Alaska has been completed. The website for the FCCS is http://www.fs.fed.us/pnw/fera/fccs/.

Digital Photo Series - The Digital Photo Series contains searchable data and images for the nearly 400 sites contained in the Natural Fuels Photo Series, representing fuels in a wide range of ecosystems throughout the United States. Each entry includes a site description, species composition, fuel loading and arrangement, and overstory composition and structure. This information can be used for planning fuels treatments or other management actions and as inputs to fire behavior and fire effects models and applications. The Digital Photo Series is available online at http://depts.washington.edu/nwfire/dps/.

Consume - Consume is a user-friendly software application for estimating fuel consumption and emissions produced. Land managers and researchers input fuel characteristics, length of ignition, fuel conditions, and meteorological attributes; Consume then calculates fuel consumption and emissions by combustion phase. Consume is designed to import data directly from the Fuel Characteristic Classification System (FCCS), and its output is formatted to feed other models and provide usable reports for burn plan preparation and smoke management requirements. Consume can be used for all forest, shrub and grasslands in North America. The Consume 3_0 website is http://www.fs.fed.us/pnw/fera/research/smoke/consume/index.shtml

Pile Calculator - The pile calculator is a user-friendly web-based tool that enables land managers to accurately assess biomass, fuel consumption, and emissions generated from the burning of conifer, hardwood or shrub machine and hand piled material. Land managers can use this tool to accurately and efficiently estimate the biomass of piled fuels as well as target the best time for igniting the piles to meet air quality regulations. The hand-pile calculator can be found on-line at: http://depts.washington.edu/nwfire/piles/.

Environmental Protection Agency's (EPA) National Emissions Inventory (NEI), with a focus on biomass burning estimates

Rao, Tesh.

U.S. Environmental Protection Agency, Emissions Inventory and Analysis Group

Development of the 2008 National Emissions Inventory (NEI) will be discussed. Specific focus will be placed on methods that the U.S. Environmental Protection Agency (EPA) uses to estimate biomass burning (wildfires, prescribed fires, and agricultural fires) emissions.

Details will be provided on State-submitted fire emissions information as well as how chemical speciation of PM2.5 emissions is done in the EPA inventories. Next steps for the 2011 inventory cycle will be outlined for the biomass burning sector.

Investigation of Smoke Marker Ratios from Controlled Laboratory Burns vs. Wildfires and Prescribed Burns

Sullivan[1], A.P., S.M. Kreidenweis[1], B.A. Schichtel[2], and J.L. Collett, Jr.[1]

[1]Colorado State University, Department of Atmospheric Science
[2]National Park Service/CIRA, Colorado State University

One of the main sources of organic carbon (OC) aerosols is biomass burning. Therefore, it is important to be able to determine the contribution of biomass burning to the total OC concentration. The most common method employed to make this determination is through the use of smoke marker measurements. The key to making a smoke marker measurement is knowing the ratio of the smoke marker to the total OC concentration at the source. However, there is still much uncertainty in these ratios, especially for biomass burning emissions from wildfires and prescribed burning. Therefore, the goal of this work is to try to better understand smoke marker ratios at the source for this type of burning. Comparisons of samples collected from multiple wildfires across the U.S. and six sets of prescribed burns will be made to source samples collected at the Fire Science Lab in Missoula, MT from the FLAME (Fire Laboratory at Missoula Experiment) studies. Smoke markers such as levoglucosan, galactosan, and potassium will be discussed. How sampling location, fuel type, and burning conditions affect these ratios will also be presented.

Review of Emissions Inventories for Wildland Fires in Georgia

Tian[1, 2], Di, Tao Zeng[1, 2], James Boylan[1]

[1]Georgia Department of Natural Resources, Environmental Protection Division
[2]School of Earth and Atmospheric Sciences, Georgia Institute of Technology

Wildland fires are a major contributor to particulate matter in Georgia. Their emissions vary with fuel and meteorological conditions, and burning techniques, though these factors are usually not considered in the current fire emission inventory development due to lack of data. The first detailed wildland fire emissions inventory for Georgia is developed as part of the Visibility Improvement State and Tribal Association of the Southeast 2002 inventory (VISTAS, http://www.metro4-sesarm.org/vistas/SesarmRHR.htm). The wildland fire emissions inventory are calculated as the product of the amount of biomass consumed and the associated emission factors (ratios of the mass of pollutants emitted per unit biomass on a dry basis). The amount of biomass consumed is estimated from burned area records obtained by surveying state and federal agencies. Such records are location-specific for wildfires and by county for prescribed burning. Varying fuel consumption and emissions factors by fuel types are used for wildfires, and state-wide average fuel consumption and emissions factors are used for prescribed burning. The same method has been used to develop 2005 and 2008 wildland fire emissions inventories by Georgia Environmental Protection Division, which have been submitted to the U.S. Environmental Protection Agency as required by Air Emissions Reporting Requirements (AERR) Rule. Another similar wildland fire emissions inventory is developed as part of Southeastern Modeling Analysis and Planning (SEMAP) 2007 emissions inventory. These wildland fire emissions inventories in the four different years are compared. The SEMAP 2007 and AERR 2008 inventories are further compared with SMARTFIRE 2007 and 2008 estimates based on satellite data, respectively. Suggestions for future wildland fire emissions inventory development are provided.

Reference:
Tian, D., Y. Hu, Y. Wang, J.W. Boylan, M. Zheng, and A.G. Russell (2009). Assessment of biomass burning emissions and their impacts on urban and regional PM2.5: a Georgia case study. Environmental Science and Technology, 43 (2), 299-305.

Field Measurements of $PM_{2.5}$ Emission Factors for Prescribed Burning and Wildfires

Urbanski, Shawn, Wei Min Hao, and Stephen Baker

U.S. Forest Service, Rocky Mountain Research Station, Missoula Fire Sciences Laboratory

We report airborne and tower-based measurements of emission factors for $PM_{2.5}$ ($EF_{PM2.5}$) and several trace gases (EF_X, where X = CO_2, CO, CH_4, C_2H_6, C_2H_4, C_2H_2, C_3H_8, or C_3H_6) made throughout the contiguous United States on prescribed fires and wildfires. EF were measured for a wide range of vegetation commonly managed by prescribed burning in the southeast (pocosin, palmetto, sawgrass, wiregrass, pine forest), southwest (chaparral, mixed

conifer forest), and interior mountain west (Ponderosa pine / Douglas fir forest). EFs were also measured for 10 wildfires occurring in conifer forests of the mountain west (Montana, Idaho, Oregon, and Utah). The relationship of $EF_{PM2.5}$ to fuel type, fuel moisture, fire type (prescribed or wild), and combustion efficiency is examined. Our $EF_{PM2.5}$ are compared to previously published values and we provide 'best estimate' $EF_{PM2.5}$ for prescribed burning and wildfires according to vegetation type and region.

Uncertainties in southeastern US prescribed fire emissions and their impact on predicting smoke dispersions

Aika, Yano[1], Roger Ottmar[2], Scott Goodrick[3], Yongqiang Liu[3], Brian Gullett[4] and Talat Odman[1]

[1]Georgia Institute of Technology, School of Civil and Environmental Engineering
[2]U.S. Forest Service, Pacific Northwest Research Station
[3]U.S. Forest Service, Southern Research Station
[4]U.S. Environmental Protection Agency, Office of Research and Development

Responsible practice of Prescribed Burning (PB) requires accurate predictions of smoke and air quality impacts. Several modeling tools are available for use in PB management today. Models predict how much smoke or pollutant emissions a burn will produce, how high the smoke plume will rise, how it will disperse under current meteorological condition, where it will be transported, and whether the pollutants it contains would burden air quality in urban areas. All of these model predictions are subject to certain degree of uncertainty. This presentation will focus emission related uncertainties. Emissions are estimated from fuel loads, the fraction of the fuels that would combust under actual field conditions, and the amount of pollutants emitted by burning each fuel type involved.

The Prescribed Fire Combustion and Atmospheric Dynamics Research Experiment (Rx-CADRE) conducted at Eglin Air Force Base near Niceville, Florida between 4-12 of February 2011. Three burns during this study period provided a unique opportunity to evaluate the uncertainties in emissions and their impacts on smoke dispersion predictions. Comparison of measured fuel loads to photo series estimations provided insight to uncertainty levels introduced by the photo series approach. Similarly, comparing fuel consumption estimated by CONSUME to actual amounts of fuel consumed, based on the difference of pre- and post-burn amounts, showed the uncertainty in consumption estimates. Variability in emission factors can be estimated by comparing emissions measured by tethered aerostat against emissions per unit mass of fuel consumed from laboratory and other field studies. Finally, the effect of emission uncertainties to dispersion predictions by Daysmoke will be presented.

Large fire emissions in summer over the southeastern US: Satellite measurements and modeling analysis

Zeng[1, 2], Tao, Yuhang Wang[2], and Di Tian[1]

[1]Georgia Department of Natural Resources, Environmental Protection Division
[2]School of Earth and Atmospheric Sciences, Georgia Institute of Technology

Fire count products from the MODIS instruments onboard the Terra and Aqua satellites are compared to the bottom-up fire inventory in 2002 in the southeastern United States. Data from both satellites are available only in the second half of the year. The correlation between Terra MODIS fire counts with the bottom-up inventory is moderate (0.57). We extend the Aqua fire data using the relationship between Terra and Aqua MODIS fire products from 2003 to 2006. The correlation between combined satellite products and the bottom-up inventory is improved (r=0.76). Consistent springtime fire maximum are shown in both bottom-up and satellite-based datasets in the southeastern US. The major discrepancy is that the satellite observed fire count peak in summer 2002 is not found in the bottom-up inventory. Examination of satellite observations for the following 4 years reveals that the summer peak of fire counts in 2002 are substantially more significant than the other years. To further examine the satellite observations, we apply model simulations to quantify the effects of fire emissions in the summer. A new fire emission inventory is therefore constructed by incorporating the satellite fire-count data trend into the bottom-up inventory. The model results with the original and the updated fire inventories are evaluated using surface observations. The additional fire emissions help reconcile the model underestimate of summertime carbonaceous aerosol loading in the southeastern United States. Further analysis of MODIS aerosol optical depth (AOD) indicates that fire pixels in the Southeast have higher AODs (by 27%) when fires were indicated by the satellite fire count products.