

# FINAL REPORT

Title: Accelerating awareness, understanding, and adoption of wildland fire science information

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## Table of Contents

List of Tables	i
List of Figures	i
List of Abbreviations and Acronyms	ii
Keywords	iii
Acknowledgements	iii
Abstract	1
Objectives	2
Background	2
Materials and Methods	5
Results and Discussion	6
Conclusions	19
Literature Cited	19
Appendix A: Contact Information for Key Project Personnel	A1
Appendix B: List of Completed/Planned Scientific/Technical Publications/Science Delivery Products	A1

### List of Tables

Table 1. Recent airborne field studies	4
Table 2. Observational specifications	13
Table 3. Priority VOC	16

### List of Figures

Figure 1. Vertical sampling of downwind smoke plume.	9
Figure 2. Ground-based smoke emissions diagram for hypothetical burn plot	10
Figure 3. Sampling scales and measurements platforms of smoke and emissions	12

## List of Abbreviations and Acronyms

AGL	above ground level
BB	biomass burning
BBOP	Biomass Burning Observation Project
BC	black carbon, also called soot
CAMx	Comprehensive Air Quality Model with extensions
CH <sub>3</sub> CN	Acetonitrile
CH <sub>4</sub>	Methane
CMAQ	Community Multiscale Air Quality Model
CO	carbon monoxide
CO <sub>2</sub>	carbon dioxide
SERDP	Strategic Environmental Research and Development Program
DOE	Department of Energy
FASMEE	Fire and Smoke Model Evaluation Experiment
HCN	hydrogen cyanide
HNO <sub>3</sub>	nitric acid
HONO	nitrous acid
JFSP	Joint Fire Science Program
MCE	modified combustion efficiency
MIP	mobile instrument package
ML	mobile laboratory
N <sub>2</sub> O	nitrous oxide
NAAQS	National Ambient Air Quality Standards
NH <sub>3</sub>	ammonia
NO <sub>x</sub>	nitrogen oxides (sum of NO and NO <sub>2</sub> )
O <sub>3</sub>	ozone
OH	hydroxyl radical
PAN	peroxyacetyl nitrate
PM	particulate matter, also referred to as aerosol
PM <sub>2.5</sub>	fine particulate matter, aerodynamic diameter < 2.5 microns
POA	primary organic aerosol
RXCADRE	Prescribed Fire Combustion and Atmospheric Dynamics Research Experiment
SCREAM	South Carolina Regional Emissions and Aging Measurements
SEAC4RS	Studies of Emissions and Atmospheric Composition, Clouds and Climate Coupling by Regional Surveys
SIP	sub-canopy instrument package
SOA	secondary organic aerosol
UAS	unmanned aircraft system
VOC	volatile organic compounds
WRF-Chem	Weather Research and Forecasting model coupled with Chemistry

## **Keywords**

Smoke, fire, wildland fire, biomass burning, emissions, atmospheric chemistry, air quality, FASMEE, emission factors, smoke impacts, emission inventories

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## **Abstract**

Smoke from wildland fires has a significant impact on public health and transportation safety and presents a serious complication for air regulators seeking to design effective and efficient emission control strategies to meet and maintain air quality standards. Wildland fires produce numerous hazardous air pollutants and criteria pollutants (fine particulate matter, carbon monoxide, nitrogen oxides, ozone, and particulate lead) which are regulated under the Clean Air Act's National Ambient Air Quality Standards. Addressing the substantial public health, regulatory, and transportation safety impacts of smoke from wildland fires requires a significantly improved understanding smoke production, dispersion, and chemistry that may be used to evaluate, improve, and develop smoke modeling systems. The Fire and Smoke Model Evaluation Experiment (FASMEE) is a comprehensive research effort to improve the scientific understanding of wildland fire behavior, plume rise, and smoke dispersion, and smoke chemistry. FASMEE is a large-scale interagency effort to identify the critical measurements necessary to improve operational wildland fire and smoke prediction systems, collect observations through a coordinated field campaign, and utilize them to advance science and modeling capabilities. This project has developed the Smoke Emissions, Chemistry, and Transport Observational Study Plan for the FASMEE project.

The study plan identifies key science questions which must be addressed to develop improved smoke models for protecting public health and transportation safety and for designing effective air pollution control strategies. A comprehensive inventory of the field observations required to address these key science questions has been assembled. Sampling strategies, platforms, and measurement methods and instrument technology have been carefully considered to design a field measurement plan that satisfies the observational requirements defined by the key science questions. The study plan combines ground-based (mobile and fixed location), tower, and airborne platforms to comprehensively characterize smoke from the source to distances of 30 km downwind and throughout its vertical depth, over the duration of the FASMEE prescribed fires.

Emission factors will be measured for the lofted plume and the extended duration residual smoldering, which is not entrained in the convective plume, and can have significant local impacts. Downwind measurements of the plume by an aircraft with a suite of chemistry instruments will provide the observations needed to fill critical gaps in the current knowledge of smoke chemistry and develop improved chemical reaction mechanisms for air quality models. Measurements from tall towers and vertical profiles by aircraft will characterize the vertical distribution of density, a necessary observation for the proper evaluation of plume models.

## Objectives

The objective of Fire and Smoke Model Evaluation Experiment (FASMEE) is to provide observational data necessary to evaluate and advance operationally used fire and smoke modeling systems and their underlying scientific understanding. This project responds to FASMEE Task Statement 4 – Smoke emissions, chemistry, and transport. This project has addressed Task Statement 4 by achieving two objectives:

Objective 1: Identify key science questions and knowledge gaps that must be addressed to provide improved smoke models to land and air quality managers.

Objective 2: Design of a comprehensive observational study plan which provides the measurements of smoke emissions, chemistry, and transport necessary to answer the key science questions, narrow critical knowledge gaps, and develop and evaluate improved smoke modeling systems.

## Background

### Societal impacts of smoke

Land managers and air regulators rely on smoke modeling systems to address the societal impacts of wildland fire. Smoke from wildland fires can pose a significant threat to public health and transportation safety. Fires are also a major and highly variable source fine particulate matter (PM<sub>2.5</sub>, particles with an aerodynamic diameter < 2.5 μm), ozone (O<sub>3</sub>), carbon monoxide (CO), and nitrogen oxides (NO<sub>x</sub> = NO + NO<sub>2</sub>) (Jaffe et al., 2013; Jaffe and Wigder, 2012; Urbanski et al., 2011; Wiedinmyer et al., 2011) which are criteria air pollutants regulated under the Clean Air Act through the National Ambient Air Quality Standards (NAAQS). Wildland fires are also an important sources of methane (CH<sub>4</sub>) and light absorbing carbonaceous aerosols which are potent short-lived climate forcers.

Wildland fire smoke is a significant threat to public health. Exposure to wildfire smoke has been associated with increases in respiratory morbidity, cardiovascular morbidity, and mortality (Fisk and Chan, 2017; Liu et al., 2015; Williamson et al., 2016). Large wildfire events can cause severe pollution episodes with substantial impacts on public health. (Kochi et al., 2012) estimated that the 14 day, 750,000 acre wildfire outbreak in southern California in 2003 led to 133 excess cardiorespiratory-related deaths with total mortality related costs of roughly \$1 billion. Health impacts are not limited to intense outbreaks in proximity to large populations, like the 2003 southern California outbreak. Much less severe wildfire episodes have been causally linked to hospital patient counts at communities 200 – 300 miles downwind (Moeltner et al., 2013).

Accurate forecasting of acute or extended duration smoke events will enable air quality managers and public health officials to confidently initiate mitigation efforts and improve public response. Relatively simple mitigation actions of limiting outdoor activity and continuously operating the fans of forced air heating and air conditioning systems upgraded with a high efficiency filters may have tremendous benefits for sensitive groups, such as the elderly, young children, and people with

respiratory conditions. For example, (Fisk and Chan, 2017) estimate that this simple intervention, focused on the elderly population, would have reduced excess cardiorespiratory deaths by ~40 during the 14 day, 2003 southern California fire. In addition to mitigation and forecasting, the epidemiology of wildfire smoke exposure would benefit from more accurate smoke models because the concentration of pollutants that populations experience is a significant uncertainty in many epidemiological studies.

The air quality impact of smoke from wildfires also presents significant challenges to air regulators' efforts to meet NAAQS and improve visibility in National Parks and Wilderness Areas as required under the federal Regional Haze Rule. State and regional air regulators need improved smoke modeling systems to accurately quantify the contribution of wildfires to air pollution and thereby enable the design of control strategies for anthropogenic pollution sources that are effective and efficient in achieving and maintaining air quality standards.

The societal impacts of smoke depend directly on the atmospheric concentrations and properties of the gases and aerosols that result from wildland fires. The concentrations of PM<sub>2.5</sub> and O<sub>3</sub> have direct effects on public health. The chemical composition and morphology of aerosols determines their potential role in climate forcing through light absorption and scattering and cloud formation and precipitation processes. Ultimately, improving smoke models comes down to providing tools that accurately simulate the atmospheric concentrations and properties of the gases and aerosols produced by wildland fires at locations near the source to 1000+ km downwind. The observational study designed in this project considers three processes that must be better understood to achieve this goal - emissions, atmospheric transport, and chemistry (the evolution of the chemical composition of the smoke, gases and aerosols, during transport from the source). Emissions, atmospheric transport, and chemistry are end processes of fire and they obviously depend on the properties, phenomena, and processes being addressed in the other FASMEE disciplines. The amount, type, assemblage, and condition of fuels burned (Task Statement 1 – Fuels and consumption) and the combustion conditions (Task Statement 2 – Fire behavior and energy) determine the mass and composition of fresh emissions. The shape and size of fuel particles, fuel packing, and moisture content all influence the relative mix of flaming and smoldering combustion, processes that produce very different emission profiles. For example, increasing the bulk density, depth, and/or moisture content of a conifer forest litter layer favors smoldering combustion. Differences in the chemical composition of fuel components, such as nitrogen content, also influence emission profiles. Plume dynamics and the interaction of the convective plume with the ambient atmosphere and the terrain (Task Statement 3 – Plume development and meteorology) determines the vertical distribution of smoke at the source, which is a key determinant in subsequent smoke transport and dispersion.

## State of the science

Fresh smoke is a complex mixture of gases and particulate matter (PM, or aerosol. PM<sub>2.5</sub> is the subset of PM with an aerodynamic diameter < 2.5 μm). Over 400 gases, including carbon dioxide (CO<sub>2</sub>), CO, CH<sub>4</sub>, volatile organic compounds (VOC), and NO<sub>x</sub> are present in fresh fire emissions (Gilman et al., 2015; Hatch et al., 2015; Urbanski, 2014). PM in fresh smoke is mostly small particles (PM<sub>2.5</sub>) which are primary organic aerosol (POA) and soot (graphitic carbon that strongly absorbs sunlight and is often referred to as black carbon (BC)) with minor fractions of inorganic components such as potassium, sodium, nitrate, ammonium, sulfate, and chloride (Gilman et al., 2015; Hatch et al., 2015; Urbanski, 2014). Over the past decade, comprehensive laboratory and field experiments (Table 1) have significantly increased our knowledge of the composition (Urbanski, 2014; Yokelson et al., 2013) and processing of wildland fire emissions (Alvarado et al., 2015; Forrister et al., 2015; May et al., 2015). The most recent field campaigns (SEAC4RS and BBOP, Table 1) are just beginning to publish results and while they will eventually provide additional datasets for characterizing emissions and smoke chemistry, significant knowledge gaps will remain. With the exception of RxCADRE (Table 1) (Ottmar et al., 2016), previous field studies lacked the comprehensive fuels, fire behavior, and meteorological measurements that will be obtained in FASMEE. The pollutants emitted and their intensity depend on the relative mix of flaming and smoldering combustion. Knowledge of the fuels consumed (types, conditions, and amounts) and relative importance of flaming and smoldering combustion are critical for developing fuel-type specific emission factors that can be applied to different fuel and combustion conditions. This specificity in fuel types and combustion phases is also needed for the fuel consumption models used to manage burns and predict wildfire emissions such as CONSUME (<https://www.fs.fed.us/pnw/fera/research/smoke/consume/>) and FOFEM (<https://www.firelab.org/project/fofem>).

Table 1. Recent airborne field studies

Acronym	Campaign Name	Year	Location	Sponsor
	Advanced Chemical Measurements of Smoke from Prescribed Burns	2009 2010	California, Arizona, North Carolina	DoD-SERDP
	Airborne and Lidar measurements of smoke plume rise, emissions, and dispersion	2009 2010 2011	Montana, Idaho, Utah, Washington	JFSP
SCREAM		2011	South Carolina	DoD-SERDP JFSP
RXCADRE		2012	Florida	JFSP
BBOP	Biomass Burning Observation Project	2012	Washington	DOE
SEAC4RS	Studies of Emissions and Atmospheric Composition, Clouds and Climate Coupling by Regional Surveys	2013	Western US	NASA

Fully characterizing emissions requires sampling of both the plume and un-lofted emissions from residual smoldering. Of the many smoke emission studies conducted in the US (Table 1), comprehensive ground measurements of emissions were lacking for all but a few of the burns studied during the SCREAM study and those burns were limited to light understory fuels in the southeast. These fires are not a suitable proxy for wildfires in forests which typically involve moderate to heavy ground fuels and canopy fuels. Currently there are few observational datasets of emissions from forest fires in moderate to heavy surface fuels or canopy fuels. Those that do exist have significant deficiencies: limited chemical speciation of emissions, only cursory fuels information, and no measurements of un-lofted smoke. Concurrent measurements of the convective smoke plume and un-lofted smoke from residual smoldering combustion are needed to characterize the composition and emission intensities associated with fires in fuels typical of wildfire conditions, especially those in the western US.

The chemical and physical processing of smoke plumes is another research area in great need of additional observational datasets. The formation mechanisms for secondary species ( $O_3$  and secondary organic aerosol (SOA)) and what environmental and chemical conditions control their relative importance are not understood (Alvarado et al., 2015; Jaffe and Wigder, 2012). Individual fire plumes can have very different behavior,  $O_3$  production can be highly variable and particle mass has been observed to both increase and decrease (Akagi et al., 2013; Alvarado et al., 2015; Jaffe and Wigder, 2012; May et al., 2014). Comprehensive measurements of the chemical composition and environmental conditions of smoke plumes during the early stages of aging are needed to identify the processes governing  $O_3$  and SOA formation in biomass smoke.

The magnitude and ratios of emissions from wildland fires vary greatly depending on fire size, fuel characteristics, combustion efficiency, and meteorological conditions (Akagi et al., 2011; Urbanski, 2014). Downwind chemical production of  $O_3$  and PM from fires is very complex, highly variable, and often difficult to predict (Alvarado et al., 2015; Jaffe and Wigder, 2012). Typically, 3-D photochemical grid models such as the Weather Research and Forecasting (WRF) model coupled with Chemistry (WRF-Chem), the Community Multiscale Air Quality Model (CMAQ), or Comprehensive Air Quality Model with extensions (CAMx) are used to estimate local to continental scale  $O_3$ , PM, and haze for scientific and regulatory assessments. Field data from specific and well characterized wildland fires are critically important to improve emissions estimation approaches, and for assessing plume transport and chemical evolution in photochemical transport models. This will enhance confidence in fire predictive capabilities to support future scientific and regulatory assessments related to fire impacts on local to continental scale  $O_3$ , PM, haze, climate, and air toxics.

## **Material and Methods**

This study plan was developed in collaboration with the FASMEE Task 1 (Fuels and consumption), Task 2 (Fire behavior and energy), and Task 3 (Plume development and meteorology) Discipline Leads, the FASMEE Modeling Leads, and the FASMEE Leadership Team. The project PI also engaged in extensive consultations with numerous researchers who are

experts in the field of in-situ atmospheric chemistry and biomass burning emission measurements. These consultations included several informal, in-person side meetings at the Second International Smoke Symposium and the American Geophysical Union Fall Meeting. The project PI also consulted several with air quality and atmospheric chemistry modelers beyond the FASMEE Modeling Leads to ensure a diverse, comprehensive and thorough understanding of modeling needs was accounted for in the Smoke Emission, Chemistry, and Transport Observational Study Plan.

## Results and Discussion

The results of this project are the identification of key science questions, a comprehensive observational study design with a detailed set of required observations and specifications to inform the FASMEE Phase 2 Funding Opportunity Notice.

### Key science questions

The smoke emissions, chemistry, and transport observational plan is designed to address five key science questions:

1. Composition of fresh emissions
  - *Are fire average emission factors for FASMEE Southeastern Campaign fires similar to those measured in recent experiments in the Southeast which sampled emissions from understory burns in light fuels? What are the emission factors for VOC, NO<sub>x</sub>, and PM for moderate- to high-intensity fires in heavy forest fuels in the West?*
2. Lofted and un-lofted emissions
  - *What are the differences between un-lofted and lofted emissions? Can these differences be attributed to specific fuel and fire properties (spread rate, intensity, area of active fire, plume dimension)? Is it possible to parameterize the partitioning of total fuel consumption between the un-lofted and lofted portions based on general knowledge of fuels involved and fire properties?*
3. Plume height, emissions, and fire-radiative power / fire intensity
  - *Can fire-radiative power (Fire Behavior and Energy Observational Study Plan; satellite observations) serve as a reliable predictor of plume height, combustion efficiency, or gas/particulate emissions?*
4. Parameterization of rapid near-source changes in emissions
  - *As fresh emissions mix with the ambient environment they undergo rapid changes including gas and aerosol reactions, particle formation/evaporation, and dilution.*

*These changes can be dramatic over distances from the source that are sub-grid-scale for most atmospheric-chemistry modeling applications. Intensive sampling of ambient meteorology and the chemical composition of the plume from the source to downwind distances of 30 km will support development of methods for parameterizing grid-scale fire emissions.*

5. Elucidation of gas and aerosol phase chemistry in the near-source plume

- *Current air quality and atmospheric chemistry models do not capture the processes that can lead to significant formation of ozone and the formation or loss of organic aerosol in the first few hours after emissions. Detailed chemical and meteorological measurements within plumes and of the plume environments are needed to develop and validate photochemical and aerosol mechanisms to address questions such as:*
  - a. *What causes high ozone observed in many fresh plumes?*
  - b. *What mechanism leads to the formation or loss of organic aerosol within smoke plumes?*
  - c. *What is the impact of smoke aerosol on photolysis rates within smoke plumes?*

In addition to these key science questions, the observational plan provides a strong focus on sub-canopy emissions for the life cycle of the fire. Several large-scale laboratory studies, including the recent NOAA FIREX study, have provided a rich body of emission measurements. Laboratory studies allow researchers to use a vast array of advanced atmospheric chemistry instrumentation and analytical methods to provide the most thorough characterization possible for fresh smoke. It is not feasible to deploy such a large suite of complex instrumentation in the field, so many of the laboratory measurements must be extrapolated to fires in natural environment for use in smoke modeling. However, recent fieldwork (Akagi et al., 2013; May et al., 2015) suggests that smoke can undergo rapid but highly variable chemical changes as the smoke cools, and it is diluted with ambient air as it is lofted from the point of emission to the level of neutral buoyancy. An improved understanding of these chemical processes is needed to confidently apply the large body of existing laboratory measurements in smoke models to the field. The smoke measurements obtained from towers erected inside the burn units will provide valuable measurements of nascent smoke as it is forming and being entrained into the convective plume. Comparing the tower measurements with coincident measurements of the lofted plume obtained from the manned aircraft will provide the observations needed understand the complex chemical transformations of fresh smoke and thereby provide a pathway for applying the wealth of laboratory measurements in smoke models to real-world situations.

Residual smoldering of coarse woody debris, duff / organic soils, and litter layers produces a mixture of emissions that is very different from that observed in the lofted plume (Akagi et al., 2013, 2014). Quantifying the composition and intensity of smoke produced by residual smoldering

is critical for addressing public health impacts (especially local and nocturnal smoke exposure), transportation safety, and nuisance smoke. To date there is only one detailed field study of smoke emissions from residual smoldering (Akagi et al., 2014). This SERDP-supported effort measured residual smoldering emissions from three pine-understory prescribed fires in South Carolina. However, the fuel loadings were light and the residual smoldering was limited, so this study is not a good proxy for wildfires or prescribed fires with moderate or heavy fuel loading. The study also lacked the detailed fuels and fire behavior measurements that are integral to FASMEE. The coincident fuels and fire behavior observations will enable the development of much needed quantitative models for residual smoldering emissions.

### **Smoke emissions, chemistry and transport observational study plan**

Smoke and emissions measurements will be collected in the following subtasks, organized by vertical sampling range:

- Lofted plume (manned aircraft)
- Intermediate-level smoke (UAS or aerostat)
- Sub-canopy smoke (sub-canopy instrumentation packages and towers)

#### **Lofted-plume**

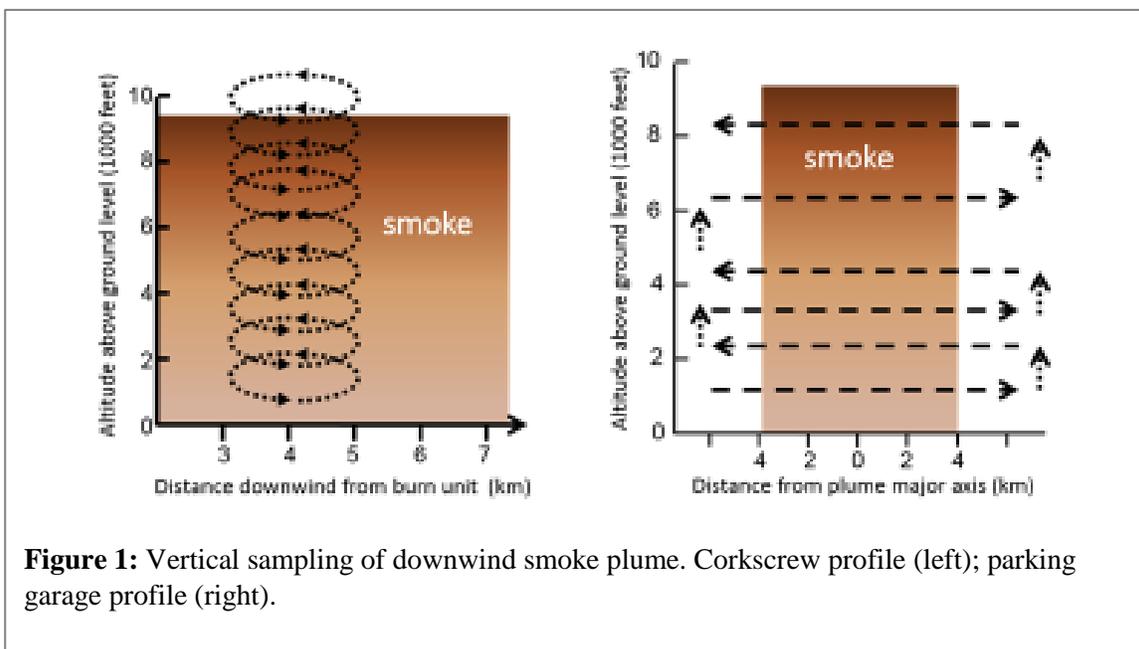
Airborne chemical measurements from a manned aircraft are required to adequately sample the emissions in the lofted plume and to characterize the chemical processing of the emissions as the plume mixes with the ambient atmosphere and is transported downwind of the source. The atmospheric chemistry and meteorology observations required for the lofted plume are listed in Table 2. The airborne flight profiles will provide intensive horizontal and vertical sampling of the near-field smoke plume (~30 km from source). The sampling strategies include:

- Across plume tracks at multiple altitudes probing the plume from near the source to ~30 km downwind;
- Along-plume major-axis (direction of transport) at approximate altitude of maximum plume density from near the source to ~30 km downwind to provide pseudo-Lagrangian observations;
- Vertical profile from 500 feet above ground level (AGL) to above the plume top immediately down wind of the source and a few locations further downwind (Figure 1).

The flight profiles will sample fresh emissions, smoke vertical profile near the source, and the spatial distribution of smoke downwind of the fire. Fresh smoke samples taken near the source will be used to calculate emission factors. The vertical profiles of PM and CO concentrations and

meteorological variables are intended for the evaluation of plume-rise models and algorithms used to vertically distribute fire emissions in atmospheric chemistry models. Aviation safety dictates a minimum flight altitude of 500 feet AGL while sampling smoke, setting the lower limits of flight profiles. The upper limits of vertical plume sampling will depend on the fire energetics, plume dynamics, and ambient meteorological conditions. Hypothetical prescribed burns in the Southwestern Campaign may occur at an elevation of around 10,000 feet. Allowing for a plume rise of ~13,000 feet would require an aircraft with an operational (i.e., with full science payload) ceiling of 23,000 feet (density altitude). This is the lowest maximum altitude the manned aircraft should be capable of sampling fires for experiments in the southwest, with a preferred operational ceiling of ~32,000 feet (~10 km). Observations of gas and PM concentrations, meteorology, and solar radiation measured over transport distances of up to 30 km will provide the observations necessary to evaluate gas-phase chemistry and PM models used in atmospheric chemistry models.

There are trade-offs between the parking garage and the corkscrew vertical profiles. The parking garage profiles lack the vertical resolution of the corkscrew profiles. However, the horizontal legs of vertical profiles in the parking garage technique may begin and/or end in background air, and



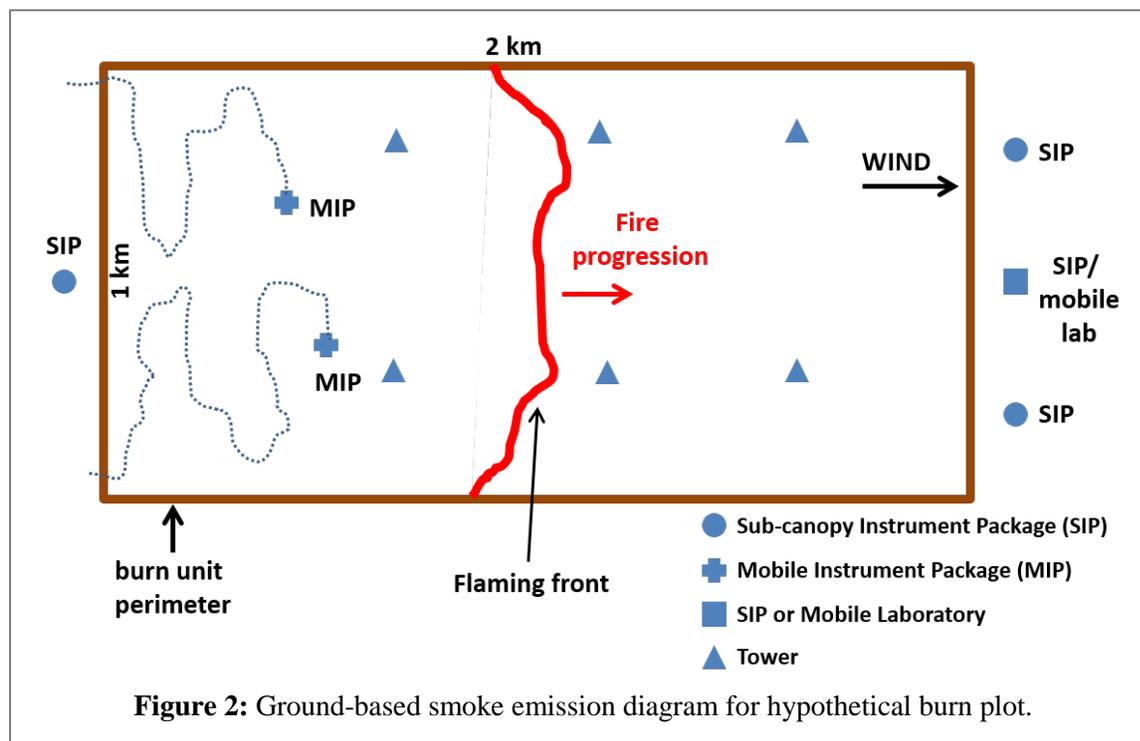
these smoke samples can be used to derive emission factors, if they are near the source where the composition has not been appreciably altered by chemical processing. The horizontal legs of parking garage profiles also provide measurements to evaluate smoke dispersion simulations.

### Intermediate-level Smoke

The primary purpose of the intermediate-level smoke measurements is to monitor fresh emissions while the manned aircraft is sampling downwind. Many of the factors that influence the combustion process (the mix of flaming and smoldering), and the overall chemical composition of

fresh smoke, may vary considerably over the lifetime of a fire. Although the manned aircraft will conduct pseudo-Lagrangian sampling, a continuous near-source measurement of fresh emissions will be critical for interpreting the downwind observations when the source characteristics are changing rapidly. The intermediate-level smoke sampling must provide continuous measurements MCE and short-duration batch samples of PM and key VOC. The secondary purpose of the intermediate level smoke sampling is to measure the vertical distribution of smoke between the canopy and the lowest level of manned aircraft measurements. Two platforms suitable for the intermediate-level smoke sampling are an aerostat or an unmanned aircraft system (UAS). The objectives would be most fully satisfied using a UAS, as its greater mobility would enable sampling of a significantly larger volume of smoke than would an aerostat. If tall towers (i.e. above canopy) are deployed for the Plume Development and Meteorology Discipline measurements, these could also serve as a sampling platform for this subtask.

### Sub-canopy smoke



Sub-canopy sampling will use ground-based platforms to characterize fresh emissions over the life cycle of the burns. Figure 2 depicts the sub-canopy smoke sampling scheme for a hypothetical burn plot. Sub-canopy sampling would use four types of platforms to measure buoyant smoke being entrained into the convective plume, un-lofted smoke (drift smoke), and post-fire-front extended smoldering. The sub-canopy plan includes instrumented towers erected within the burn unit, which will sample smoke forming and entraining into the bottom of buoyant plume and drift smoke. Un-lofted drift smoke will be measured using fixed-site sub-canopy instrument packages (SIP) located immediately downwind of the unit and one SIP located upwind of the burn unit to

monitor background conditions. Figure 2 shows the downwind SIP flanking a possible mobile lab (ML). The ML could be replaced with an additional SIP to conserve cost. The SIP will also operate for an extended duration and sample smoke from extended smoldering that drifts across the sites. The post-fire-front sampling will use one or two mobile instrument packages (MIP; mobile is defined a package that could be carried by two people within the burn unit). The post-fire-front sampling will measure emissions from independently smoldering fuel components (e.g., logs, stumps, and duff mounds). The MIPs would collect grab samples of smoke in canisters to be analyzed for CO<sub>2</sub>, CO, CH<sub>4</sub>, and VOC later in a laboratory. This approach has been employed effectively in the SCREAM field study (Table 1). If tall towers are deployed up and downwind of the unit for plume development and meteorology discipline measurements (FASMEE Task 3), the lower levels of the towers could also serve as SIP sampling platforms.

### **Notes on Airborne Observations (manned aircraft and UAS)**

Airspace will be divided between areas reserved for UAS operations and areas reserved for manned aircraft as shown in Figure 3. All UAS and manned aircraft will need to adhere to well-developed flight plans in accordance with regulations and authorities controlling the airspace.

The temporal scale for airborne observations will vary by measurement method and may depend on air speed of the platform. The spatial scale for airborne observations will depend on the temporal scale and air speed of the platform. For example, a 5-second collection time to fill a canister with a whole air sample is a linear distance of 325 m at an air speed of 65 m/s. The term “whole-air sampling” (WAS) as used here includes three methods: grab, batch, and on-line. In the grab and batch methods, a sample is stored (e.g., in stainless-steel containers, cartridges, or on filters) for later laboratory analysis. In the on-line method, the sample is analyzed in situ upon acquisition (e.g., by FTIR). On-line methods are necessary for gases that are highly reactive, unstable, or prone to losses on container walls (e.g., NO<sub>x</sub> and ammonia (NH<sub>3</sub>)). The grab method attempts to instantaneously collect an air sample both to provide a snapshot of the chemical composition and to limit the linear distance the sample represents. The batch method deliberately collects a sample over some interval, providing a time-integrated sample in the case of ground-based measurements at a fixed location or a spatially integrated sample when collected from an aircraft or UAS.

## Smoke emissions, chemistry, and transport identified observations

Table 2 lists the identified needed measurements for the Smoke Emissions, Chemistry, and Transport discipline, divided by subtask. The FASMEE field campaign provides a unique opportunity to obtain surface, canopy, and upper air measurements of different specific fire events to better constrain the dynamic nature of smoke emissions and the physical and chemical evolution of smoke plumes from fire events of various and complex combustion regimes (smoldering to flaming). These measurements will be especially useful to evaluate and improve three-dimensional modeling systems that estimate both primary pollutant impacts and secondarily formed pollutants with known health and ecosystem effects, on a local to continental scale. Measurements from this field study are expected to lead to improved (1) emission rates for different fuel types, (2) PM, VOC and nitrogen speciation by fire type and phase of combustion, (3) allocation of plumes spatially and temporally, (4) differentiation of smoldering and flaming portions of the fire event, (5) near-fire and downwind chemical evolution, and (6) optical properties of plumes. This field study will also provide valuable information to improve other less anticipated aspects of fire emissions and air quality modeling as work intensifies in this research area.

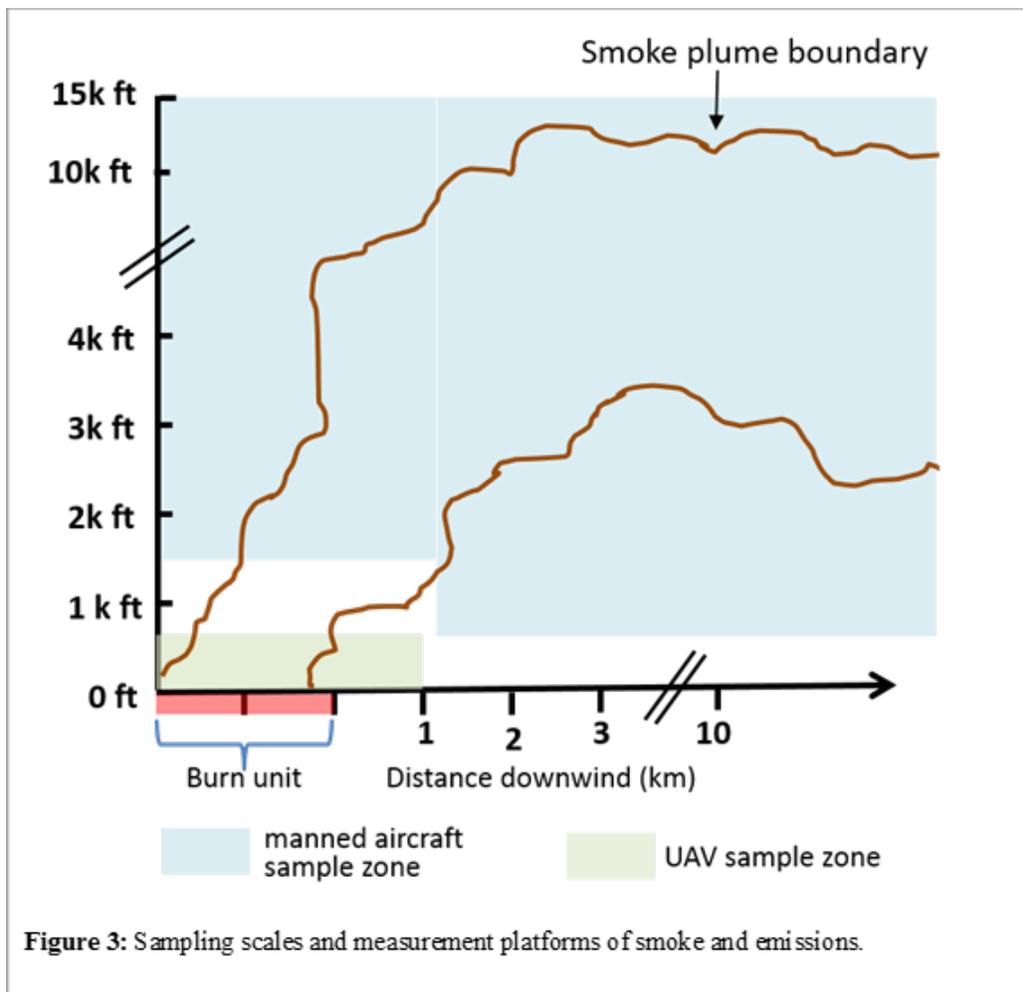


Figure 3: Sampling scales and measurement platforms of smoke and emissions.

**Table 2:** Observational specifications. Priority VOC are listed in Table 3.

Measurement Block	Spatio-temporal	Observation	Additional Specifications*
<b>Lofted Plume</b>			
Carbon	Continuous 2 s	<ul style="list-style-type: none"> <li>• CO</li> <li>• CO<sub>2</sub></li> <li>• CH<sub>4</sub></li> <li>• H<sub>2</sub>O</li> </ul>	<ul style="list-style-type: none"> <li>• 40 ppb (precision)</li> <li>• 100 ppb (precision)</li> <li>• 10 ppb (precision)</li> <li>• 100 ppm (precision)</li> </ul>
Ozone	On-line WAS or Continuous, 10 s	<ul style="list-style-type: none"> <li>• O<sub>3</sub></li> </ul>	<ul style="list-style-type: none"> <li>• 0.2 ppbv/10% (LOD/accuracy)</li> </ul>
Nitrogen containing compounds	On-line WAS or Continuous (Off-line WAS** viable for HCN and CH <sub>3</sub> CN) 10 s	<ul style="list-style-type: none"> <li>• NO</li> <li>• NO<sub>2</sub></li> <li>• NH<sub>3</sub></li> <li>• HONO</li> <li>• PAN</li> <li>• HNO<sub>3</sub></li> <li>• HCN</li> <li>• CH<sub>3</sub>CN</li> </ul>	<ul style="list-style-type: none"> <li>• 1 ppbv/10% (LOD/accuracy)</li> <li>• 0.2 ppbv/10% (LOD/accuracy)</li> <li>• 0.5 ppbv (LOD)</li> <li>• 10 ppbv (LOD)</li> <li>• 10 pptv (LOD)</li> <li>• 25 pptv / 20% (LOD/accuracy)</li> <li>• 0.5 ppbv (LOD)</li> <li>• 0.5 ppbv (LOD)</li> </ul>
VOC	WAS and/or continuous 10 s	<ul style="list-style-type: none"> <li>• Speciated VOC</li> </ul>	
Particulate Matter	Continuous 2 s	<ul style="list-style-type: none"> <li>• Bscat</li> </ul>	<ul style="list-style-type: none"> <li>• 5 1/Mm (precision)</li> </ul>
	Continuous 10 s	<ul style="list-style-type: none"> <li>• PM OM</li> <li>• PM NO<sub>3</sub></li> <li>• PM NH<sub>4</sub></li> <li>• PM SO<sub>4</sub></li> <li>• PM Cl</li> </ul>	<ul style="list-style-type: none"> <li>• 0.40 µg/m<sup>3</sup> (LOD)</li> <li>• 0.07 µg/m<sup>3</sup> (LOD)</li> <li>• 0.25 µg/m<sup>3</sup> (LOD)</li> <li>• 0.05 µg/m<sup>3</sup> (LOD)</li> <li>• 0.05 µg/m<sup>3</sup> (LOD)</li> </ul>
	Continuous 10 s	<ul style="list-style-type: none"> <li>• Refractory PM (BC)</li> </ul>	
	Continuous 2 s	<ul style="list-style-type: none"> <li>• Particle light scattering (e.g., Bscat by nephelometry)</li> </ul>	<ul style="list-style-type: none"> <li>• 5 1/Mm (precision)</li> <li>Measured at 1 or more wavelengths in visible spectrum</li> </ul>
	Continuous 2 s	<ul style="list-style-type: none"> <li>• Particle light absorption coefficients</li> </ul>	Measured at both UV and visible wavelengths
	Continuous 10 s	<ul style="list-style-type: none"> <li>• Size distribution of fine and coarse PM</li> </ul>	
	Continuous 2 s	<ul style="list-style-type: none"> <li>• Size-resolved particle number (0.1–1.0 µm)</li> </ul>	

Measurement Block	Spatio-temporal scales	Observation	Additional Specifications*
<b>Lofted Plume</b>			
Meteorology	Continuous 1 s	<ul style="list-style-type: none"> <li>• Horizontal wind speed</li> <li>• Horizontal wind direction</li> <li>• Vertical wind speed</li> <li>• Temperature</li> <li>• Dew point temperature</li> <li>• Static pressure</li> </ul>	<ul style="list-style-type: none"> <li>• 1 m/s (accuracy)</li> <li>• 5 deg (accuracy)</li> <li>• 0.5 m/s (accuracy)</li> <li>• 0.5 C (accuracy)</li> <li>• 0.5 C (accuracy)</li> <li>• 3 mb (accuracy)</li> </ul>
	Continuous 3 s	<ul style="list-style-type: none"> <li>• Down-welling actinic flux or photolysis frequencies</li> </ul>	
Location	Continuous 1 s	<ul style="list-style-type: none"> <li>• GPS latitude</li> <li>• GPS longitude</li> <li>• GPS altitude</li> <li>• True air speed</li> <li>• Ground speed</li> </ul>	<ul style="list-style-type: none"> <li>• 20 m (accuracy)</li> <li>• 20 m (accuracy)</li> <li>• 20 m (accuracy)</li> <li>• 1 m/s (accuracy)</li> <li>• 4 m/s (accuracy)</li> </ul>
<b>Intermediate Level Smoke</b>			
Carbon	Continuous 30 s	<ul style="list-style-type: none"> <li>• CO</li> <li>• CO<sub>2</sub></li> </ul>	<ul style="list-style-type: none"> <li>• 1 ppm (precision)</li> <li>• 500 ppb (precision)</li> </ul>
Particulate matter	Batch sample ~ 20 min	<ul style="list-style-type: none"> <li>• PM2.5</li> <li>• PMEC</li> <li>• PMOC</li> </ul>	<ul style="list-style-type: none"> <li>• 5 µg/m<sup>3</sup> (precision)</li> </ul>
VOC	Batch sample ~ 20 min	<ul style="list-style-type: none"> <li>• Speciated VOC</li> </ul>	<ul style="list-style-type: none"> <li>• Depends on VOC</li> </ul>
Meteorology	Continuous 2 s	<ul style="list-style-type: none"> <li>• Air temperature</li> <li>• Relative humidity</li> </ul>	<ul style="list-style-type: none"> <li>• 0.5 C (accuracy)</li> <li>• 5% (accuracy)</li> </ul>
Location	Continuous 2 s	<ul style="list-style-type: none"> <li>• Latitude</li> <li>• Longitude</li> <li>• Altitude</li> </ul>	<ul style="list-style-type: none"> <li>• 20 m (accuracy)</li> <li>• 20 m (accuracy)</li> <li>• 10 m (accuracy)</li> </ul>
<b>Sub-canopy smoke</b>			
<b>Sub-canopy Instrument Packages (SIP) and Towers</b>			
Carbon	Continuous 30 s	<ul style="list-style-type: none"> <li>• CO</li> <li>• CO<sub>2</sub></li> </ul>	<ul style="list-style-type: none"> <li>• 1 ppm (precision)</li> <li>• 500 ppb (precision)</li> </ul>
Nitrogen containing compounds	Continuous 60 s	<ul style="list-style-type: none"> <li>• NO</li> <li>• NO<sub>2</sub></li> </ul>	<ul style="list-style-type: none"> <li>• 1 ppb / 5% (LOD/accuracy)</li> <li>• 0.2 ppb / 5% (LOD/accuracy)</li> </ul>
VOC	Batch sample ~ 20 min	<ul style="list-style-type: none"> <li>• Speciated VOC</li> </ul>	
Meteorology	Continuous 5 s	<ul style="list-style-type: none"> <li>• Horizontal wind speed</li> <li>• Horizontal wind direction</li> <li>• Temperature</li> <li>• Relative humidity</li> </ul>	<ul style="list-style-type: none"> <li>• 1 m/s (accuracy)</li> <li>• 5 degree (accuracy)</li> <li>• 0.5 C (accuracy)</li> <li>• 5% (accuracy)</li> </ul>

Measurement Block	Spatio-temporal scales	Observation	Additional Specifications*
<b>Mobile Laboratory (ML)</b>			
<b>The mobile laboratory observations replicate the SIP observations and add continuous VOC sampling, particle speciation, and particle sizing</b>			
Continuous	10 s	<ul style="list-style-type: none"> <li>• Speciated VOC</li> </ul>	
Particulate Matter	Continuous 10 s	<ul style="list-style-type: none"> <li>• PM OM</li> <li>• PM NO<sub>3</sub></li> <li>• PM NH<sub>4</sub></li> <li>• PM SO<sub>4</sub></li> <li>• PM Cl</li> </ul>	<ul style="list-style-type: none"> <li>• 0.40 µg/m<sup>3</sup> (LOD)</li> <li>• 0.07 µg/m<sup>3</sup> (LOD)</li> <li>• 0.25 µg/m<sup>3</sup> (LOD)</li> <li>• 0.05 µg/m<sup>3</sup> (LOD)</li> <li>• 0.05 µg/m<sup>3</sup> (LOD)</li> </ul>
	Continuous 10 s	<ul style="list-style-type: none"> <li>• Refractory PM (BC)</li> </ul>	
	Continuous 10 s	<ul style="list-style-type: none"> <li>• Size distribution of fine and coarse PM</li> </ul>	
	Continuous 10 s	<ul style="list-style-type: none"> <li>• Size resolved particle number (0.1–1.0 µm)</li> </ul>	
<b>Mobile Instrument Platform (MIP) – measurement of emissions residual smoldering</b>			
Carbon	Grab sample	<ul style="list-style-type: none"> <li>• CO</li> <li>• CO<sub>2</sub></li> </ul>	<ul style="list-style-type: none"> <li>• 1 ppm (precision)</li> <li>• 500 ppb (precision)</li> </ul>
VOC	Grab Sample	<ul style="list-style-type: none"> <li>• Speciated VOC</li> </ul>	

\*Desired limit of detection (LOD), precision and accuracy

\*\*WAS = whole air sampling; the listed time resolution for WAS refers to the time required to collect an air sample for analysis. PM OM = organic matter, PM NO<sub>3</sub> = nitrate, PM NO<sub>3</sub> = ammonium, PM SO<sub>4</sub> = sulfate, PM Cl = chloride, PM<sub>2.5</sub> = total particulate matter < 2.5 µm diameter, EC = elemental carbon, OC = organic carbon.

**Table 3: Priority VOC**

Name	Formula	MW <sup>1</sup>		Name	Formula	MW <sup>1</sup>
Ethyne	C <sub>2</sub> H <sub>2</sub>	26		Benzene	C <sub>6</sub> H <sub>6</sub>	78
Hydrogen cyanide	HCN	27		Cyclopentenone	C <sub>5</sub> H <sub>6</sub> O	82
Ethene	C <sub>2</sub> H <sub>4</sub>	28		2-Methylfuran	C <sub>5</sub> H <sub>6</sub> O	82
Ethane	C <sub>2</sub> H <sub>6</sub>	30		Toluene	C <sub>7</sub> H <sub>8</sub>	92
Formaldehyde	HCHO	30		Phenol	C <sub>6</sub> H <sub>6</sub> O	94
Methanol	CH <sub>3</sub> OH	32		2-Furaldehyde	C <sub>5</sub> H <sub>4</sub> O <sub>2</sub>	96
Propyne	C <sub>3</sub> H <sub>4</sub>	40		Styrene	C <sub>8</sub> H <sub>8</sub>	104
Acetonitrile	C <sub>2</sub> H <sub>3</sub> N	41		Ethylbenzene	C <sub>8</sub> H <sub>10</sub>	106
Propene	C <sub>3</sub> H <sub>6</sub> O	42		o-Xylene	C <sub>8</sub> H <sub>10</sub>	106
Isocyanic acid	HNCO	43		Xylenes (m- & p-)	C <sub>8</sub> H <sub>10</sub>	106
Acetaldehyde	C <sub>2</sub> H <sub>4</sub> O	44		Indene	C <sub>9</sub> H <sub>8</sub>	116
Propane	C <sub>3</sub> H <sub>8</sub>	44		Benzofuran	C <sub>8</sub> H <sub>6</sub> O	118
Formic acid	CH <sub>2</sub> O <sub>2</sub>	46		Napthalene	C <sub>10</sub> H <sub>8</sub>	128
1,3-Butadiene	C <sub>4</sub> H <sub>6</sub>	54		Camphene	C <sub>10</sub> H <sub>16</sub>	136
Acrolein	C <sub>3</sub> H <sub>4</sub> O	56		3-Carene	C <sub>10</sub> H <sub>16</sub>	136
1-Butene	C <sub>4</sub> H <sub>8</sub>	56		D-Limonene	C <sub>10</sub> H <sub>16</sub>	136
Acetone	C <sub>3</sub> H <sub>6</sub> O	58		i-Limonene	C <sub>10</sub> H <sub>16</sub>	136
n-Butane	C <sub>4</sub> H <sub>10</sub>	58		Myrcene	C <sub>10</sub> H <sub>16</sub>	136
Propanal	C <sub>3</sub> H <sub>6</sub> O	58		Pinene_alpha	C <sub>10</sub> H <sub>16</sub>	136
Acetic acid	C <sub>2</sub> H <sub>4</sub> O <sub>2</sub>	60		Pinene_beta	C <sub>10</sub> H <sub>16</sub>	136
1,3-Cyclopentadiene	C <sub>5</sub> H <sub>6</sub>	66		γ-Terpinene	C <sub>10</sub> H <sub>16</sub>	136
Cyclopentene	C <sub>5</sub> H <sub>8</sub>	68		Terpinolene	C <sub>10</sub> H <sub>16</sub>	136
Furan	C <sub>4</sub> H <sub>4</sub> O	68		n-Decane	C <sub>10</sub> H <sub>22</sub>	142
Isoprene	C <sub>5</sub> H <sub>8</sub>	68		n-Undecane	C <sub>11</sub> H <sub>24</sub>	156
2-Butanone	C <sub>4</sub> H <sub>8</sub> O	72		Sesquiterpenes	C <sub>15</sub> H <sub>24</sub>	204
Methyl vinyl ketone	C <sub>4</sub> H <sub>8</sub> O	72				

<sup>1</sup>MW = molecular weight (g/mole)

## Measurement justifications

This section justifies the comprehensive measurements of atmospheric chemical composition and atmospheric conditions listed in Table 2. The necessity of these measurements is justified according to measurement blocks: Carbon, VOC, nitrogen-containing compounds, particulate matter, and meteorology

### Carbon

Emission factors are determined using the carbon mass balance method, which requires a near complete accounting of the biomass carbon volatilized in fires (Burling et al., 2010; Yokelson et al., 1999). More than 90% of combusted biomass carbon is released as CO<sub>2</sub>, CO, and CH<sub>4</sub> (Urbanski, 2014), so measurement of these compounds is essential. Modified combustion efficiency (MCE), a widely used measure of the relative mix of flaming and smoldering combustion, is defined as the ratio of emitted CO<sub>2</sub> to the sum of emitted CO<sub>2</sub> and CO. Because the emission factors of many species are correlated with MCE, it is a useful metric for extrapolating emissions factors from one set of combustion conditions to another (Akagi et al., 2011). Furthermore, since CO has a relatively long atmospheric lifetime (~30 days) and a low background concentration, MCE is the primary tracer used to account for dilution when interpreting plume chemistry.

### VOC

VOC and NO<sub>x</sub> are important for their potential to form O<sub>3</sub> and SOA. Photochemical reactions of VOC and NO<sub>x</sub> can lead to O<sub>3</sub> production. The process is highly complex and depends on VOC:NO<sub>x</sub> ratios, the availability of free radicals, such as hydroxyl radical (OH), and the formation of peroxy nitrates. SOA is organic particulate mass formed through a complex series of chemical reactions and physical transformations of organic species. Laboratory investigations have identified hundreds of VOC in fresh smoke (Hatch et al., 2015). In a field experiment, it is not feasible to measure all of the VOC believed present in fresh smoke. Therefore, the list of priority VOC in Table 3 was created based on compounds' OH-reactivity and secondary organic aerosol potential, following (Gilman et al., 2015), potential to form OH via photolysis, and molar fraction of total emitted carbon.

### Nitrogen containing species

Nitrogen (N) is only a trace component of biomass, but N-containing primary emissions and their chemical processing products are important for determining smoke impacts. The dominant N-containing products of biomass burning (BB) are N<sub>2</sub>, NO<sub>x</sub>, nitrous oxide (N<sub>2</sub>O), NH<sub>3</sub>, nitrous acid (HONO), hydrogen cyanide (HCN), and acetonitrile (CH<sub>3</sub>CN). NO<sub>x</sub> are central to atmospheric chemistry (Seinfeld and Pandis 2006). Unlike fossil fuel combustion, biomass burning (BB) temperatures (<1500 °C) are not sufficient to produce thermal NO<sub>x</sub> (produced by high temperature reactions of atmospheric O<sub>2</sub> and N<sub>2</sub>) and the NO<sub>x</sub> BB emissions are derived from fuel N. HONO

and  $\text{HN}_3$  are both primary products of biomass combustion. HONO photolyzes rapidly and can be an important source of OH, the radical species that drives daytime atmospheric chemistry.  $\text{NH}_3$  is an important species in the formation and growth of aerosol and in atmospheric deposition of nitrogen. Gaseous nitric acid ( $\text{HNO}_3$ ) is formed by the  $\text{NO}_2 + \text{OH}$  reaction, an important chain termination step that removes  $\text{NO}_x$  and OH from atmospheric oxidation cycles. Like  $\text{NH}_3$ ,  $\text{HNO}_3$  is important in the formation and growth of aerosol. Thus, measurements of atmospheric  $\text{HNO}_3$  are of tremendous value for understanding both gas phase and aerosol phase chemistry. HCN and  $\text{CH}_3\text{CN}$  (acetonitrile) are primary products of biomass burning. Since there are no other major sources of these gases to the atmosphere, they are commonly used as tracers of biomass burning. As tracers, the concentrations of these gases are used to interpret and quantify the role of fire emissions in atmospheric chemistry downwind, where the plume has mixed with air masses influenced by other sources (e.g., urban pollution or biogenic emissions). Peroxyacetyl nitrate (PAN [ $\text{CH}_3\text{COO}_2\text{NO}_2$ ]), formed by the oxidation of VOC in the presence of  $\text{NO}_x$ , is an important reservoir species for  $\text{NO}_2$ . PAN can reduce  $\text{O}_3$  formation in fresh smoke plumes, but it leads to downwind  $\text{O}_3$  formation when  $\text{NO}_2$  is released when PAN thermally dissociates (Fischer et al., 2014; Gilman et al., 2015).

### **Particulate Matter**

From the perspective of societal impacts—public health, air quality regulations, visibility (both safety and aesthetics), and climate—PM is the most important atmospheric agent produced by wildland fires. These societal impacts depend on many PM properties, such as mass concentration, number concentration, particle size distribution, chemical composition, and morphology. PM in fresh smoke is mostly primary organic aerosol (POA) and BC (i.e., soot or elemental carbon), with minor fractions of potassium, sodium, nitrate, ammonium, sulfate, and chloride (Fischer et al., 2014; Gilman et al., 2015). However, there is great variability in the amount and properties of fresh PM associated with any fuel type or fire behavior. Further, BB PM is a highly dynamic system that changes on time scales of seconds to days through dilution, cooling, coagulation, and chemical processing (Vakkari et al., 2014). POA can evaporate as the fresh smoke plume is diluted with ambient air, reducing the total PM mass (May et al., 2015). However, this loss in organic PM may be countered by the formation of SOA, which is organic mass from the condensation of low-volatility gases produced through complex gas phase chemistry. SOA not only increases PM mass, but it also alters the chemical and optical properties of the PM (Forrister et al., 2015; Liu et al., 2014, 2016). The changes in organic mass from evaporation, condensation, and coagulation lead to changes in the PM size distribution (Sakamoto et al., 2016). To advance our understanding of this complex and dynamic system, the multiple facets of BB PM—mass concentration, number concentration, particle size distribution, and composition—must be carefully observed from the time of emission through the aging processes.

## Conclusions

This project has identified key science questions and knowledge gaps that must be addressed to 1) advance the science of smoke emission, smoke chemistry, and atmospheric chemistry in general, and 2) provide improved smoke models to land and air quality managers. This project has also designed a comprehensive study plan to acquire the smoke emission, chemistry, and transport observations that are essential to address the key science questions, narrow critical knowledge gaps, and develop and evaluate improved smoke modeling systems. The observational study plan, if faithfully executed will provide immediate benefits to land managers and air quality modelers by providing a comprehensive set of emission factors for fires in well characterized moderate to heavy surface fuels and canopy fuels. While these fuel types are representative of many large wildfire events and prescribed fires in the western US, there is currently, there is no comprehensive dataset of emission factors measured in-situ for these fuel types. This study plan immediately addresses this need. The study plan's intensive vertical measurements of smoke concentration and meteorology, near the source and downwind, when combined with the observations of fire energetics (FASMEE Task 2) and the plume development and meteorology (FASMEE Task 3) will provide the comprehensive dataset that is necessary to evaluate and develop the plume models that are critical for forecasting smoke impacts. The comprehensive measurements of the evolution of smoke composition from the source to 30 km downwind will provide valuable datasets for evaluating and improving the chemical mechanisms currently used for simulating O<sub>3</sub> and aerosol. The fuels measurements (Task 1) and observations of fire energetics (Task 2) will assist researchers, model developers, and model end-users to extrapolate the FASMEE findings to a broader range of fire types and fire behavior.

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## **Appendix B: List of Completed/Planned Scientific/Technical Publications/Science Delivery Products**

The Smoke Emissions, Chemistry, and Transport Observational Study Plan presented in this document will be used by the FASMEE Leadership Team to develop the FASMEE Study Plan and inform the Funding Opportunity Notice.