Fire and Smoke Model Evaluation Experiment (FASMEE)

Study Plan

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EXECUTIVE SUMMARY

This document presents the study plan for the Fire and Smoke Model Evaluation Experiment (FASMEE). FASMEE is a large-scale interagency effort to (1) identify the critical measurements necessary to improve operational wildland fire and smoke prediction systems, (2) collect observations through a coordinated field campaign, and (3) use these measures and observations to advance science and modeling capabilities. FASMEE is aimed at operational modeling systems in use today as well as the next generation of modeling systems expected to become operationally useful in the next 5 to 10 years.

The overall goal of FASMEE is to:

- *Evaluate and advance operationally applicable fire and smoke modeling systems and their underlying scientific models and frameworks.*

The overarching science question for FASMEE is:

- *How do fuels, fire behavior, fire energy, and meteorology influence the dynamics of near-source plumes and the long-range transport of smoke and its chemical evolution?*

FASMEE is partitioned into three phases:

- Phase 1—The analysis and planning process to review and assess the current state of fire-plume-smoke modeling and scientific understanding to determine the critical needs and realistic pathways to addressing these needs.
- Phase 2—Implementation of a set of field campaigns to be completed over 2019-2022 to collect data valuable for model evaluation and improvement.
- Future Improvements—Identified set of analyses and improvements to models based on the data collected in Phase 2, to begin if appropriate funding sources are identified.

Phase 2 recommendations emphasize measurements of high-volume smoke production from burning in heavy fuels that produce multiple plume cores and significant vertical plume development. The FASMEE field campaigns will include data collection, archiving, and preliminary model development using the observational data. Multiple agencies and universities and hundreds of scientists will participate making it substantially larger than the Prescribed Fire Combustion Atmospheric Dynamics Research Experiment (RxCADRE) completed in 2012. FASMEE has the potential to significantly influence the fields of fuels, fire behavior, plume dynamics, and smoke

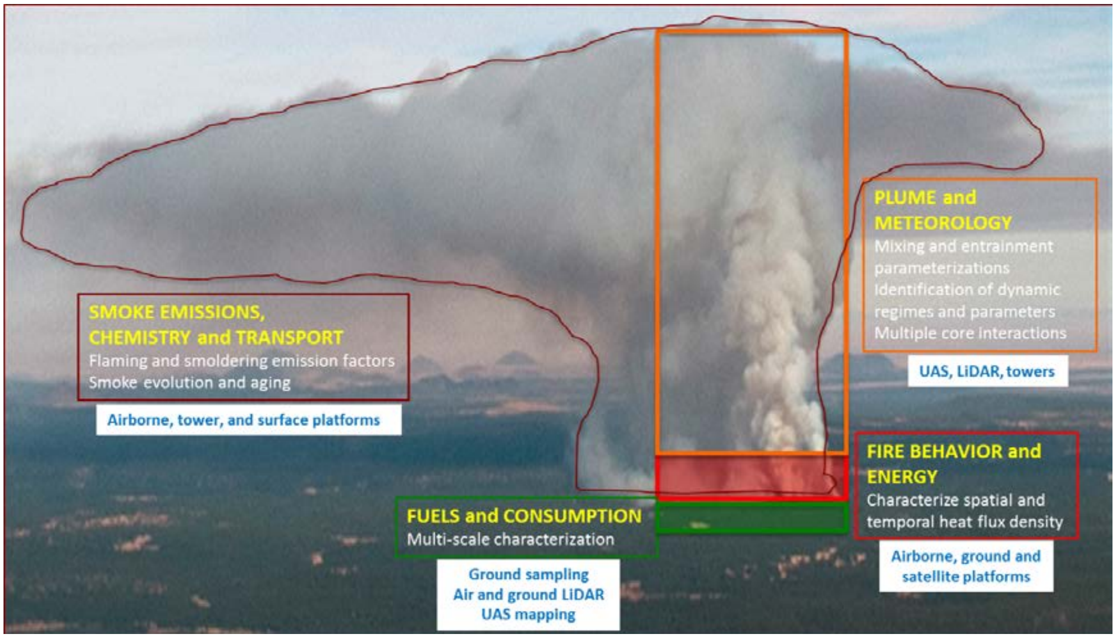

Figure ES-1: Graphic representation of the FASMEE project. (Figure 3-1 of Study Plan)

chemistry for years to come. The field campaign will provide a robust, integrated baseline dataset to not only evaluate fire models but also leverage data from other scientists and agencies to address additional questions. Furthermore, wildland vegetation and fuels, fire behavior, and fuel consumption will be characterized and mapped over space and time, allowing immediate fire effects to be co-located and directly related to the characterized fire. Immediate effects include the fire's energy release, plume dynamics, smoke generation, and other effects such as soil heating and tree mortality measurements. Given these fire-plume-smoke-chemistry system linkages, FASMEE has been designed with four discipline areas: (1) FUELS and CONSUMPTION, (2) FIRE BEHAVIOR and ENERGY, (3) PLUME DYNAMICS and METEOROLOGY, and (4) SMOKE EMISSIONS, CHEMISTRY, and TRANSPORT (Figure ES-1).

Based on an analysis of both the types of model and science data needs, the FASMEE Phase 1 Science Team has developed a list of needed burns and measurements. The burns and measurements translate the generalized models and data needs of the science questions into a specified set of achievable field observations. Since limited data exist for characterizing fuels, fire behavior, and smoke plume dynamics associated with wildfires, most needed types of burns are: (1) high-intensity fires, (2) large fires capable of producing significant atmospheric plume dynamics and a substantial downwind smoke plume, and (3) where possible (particularly in the Southwestern Campaign), a simplified ignition to obtain as closely as possible a free-running fire, to avoid the inherent initialization issues in random ignition that does not coalesce into a freely evolving fire.

The FASMEE approach and science plan is developed in coordination with other agency efforts, in particular, the NOAA Fire Influence on Regional and Global Environments Experiment (FIREX) campaign and NASA's FIREChem activity, as well as in consultation with US Environmental Protection Agency and National Science Foundation efforts in fire and smoke research.

To collect critical measurements necessary to improve operational wildland fire and smoke prediction systems, three recommended US field campaigns have been identified in conjunction with federal partners and land management host agencies: (1) Western Wildfire Campaign, with instrumentation focused on rapid-deployment source characterization at plume dominated wildfires with long-range plume transport targeting smoke plume dynamics and chemistry measurements by NOAA and NASA; (2) Southwestern Campaign (Fishlake National Forest/Kaibab Ranger District), with moderate and highly-instrumented planned burns completed on sites with heavy fuel loads, ignited to obtain a high-energy intensity, dynamic plume development; and (3) Southeastern Campaign (Fort Stewart/Savannah River Site), with maximum-instrumented planned burns completed on sites with high fuel loads, ignited to obtain a moderate-energy intensity fire producing long-distance plume transport relevant for smoke management. These three campaigns cover a range of fire intensities that include those relevant to the 12 million acres of prescribed fire annually conducted and for megafires that dominate wildfire emissions.

The FASMEE study plan includes descriptions of detailed command structures, safety plans, incident action plans, and airspace de-confliction plans, as well as site access and logistical staging plans and data management considerations. All plans are subject to the approval and modification by host agencies.

Expected outcomes of FASMEE include:

- *Improved scientific knowledge of the physically coupled fuels–fire–smoke–chemistry system.*
- *Exportable methodologies for measuring fuels for fire spread, fuel consumption, and fire emissions models.*
- *New insight concerning the processes that drive the spatial organization of fire energy and emissions which defines the transition between fires and plumes that impact air quality.*
- *Improvement of existing operational fire and smoke models and the development of new, more advanced models based on the collection of an unprecedented dataset (fuels, fire, meteorological, and smoke plume and chemistry).*

The Joint Fire Science Program (JFSP) is planning to release a Funding Opportunity Notice (FON) in September of 2017 associated with this study plan for Phase 2 activities within field campaigns 2 (Southwestern) and 3 (Southeastern) only. The Western Wildfire Campaign (Campaign 1) is not included in the FON because it will be separately funded by the JFSP, providing valuable data for FASMEE and supporting the FIREX and FIREChem campaigns.

1. OVERVIEW OF FASMEE

This document presents the study plan for the Fire and Smoke Model Evaluation Experiment (FASMEE). FASMEE is an integrative research effort to improve the scientific understanding of wildland fire and smoke. This large-scale interagency effort is focused on the development and evolution of modeling tools serving land and fire management needs. This study plan details the critical measurements necessary to improve operational wildland fire and smoke prediction systems (defined throughout this document as systems used by land management and regulatory agencies for planning and response purposes). FASMEE is aimed at collecting key measurements through a series of coordinated field campaigns that will be made available to evaluate (defined throughout this document as determining model's suitability for a given purpose) and validate (defined throughout this document as quantitative comparison between observed and predicted measurements) operational modeling systems in use today as well as the next generation of modeling systems expected to become operationally useful in the next 5 to 10 years. The overall goal is to advance the underlying scientific understanding of wildland fire and smoke and improve the ability to model these processes for operational support.

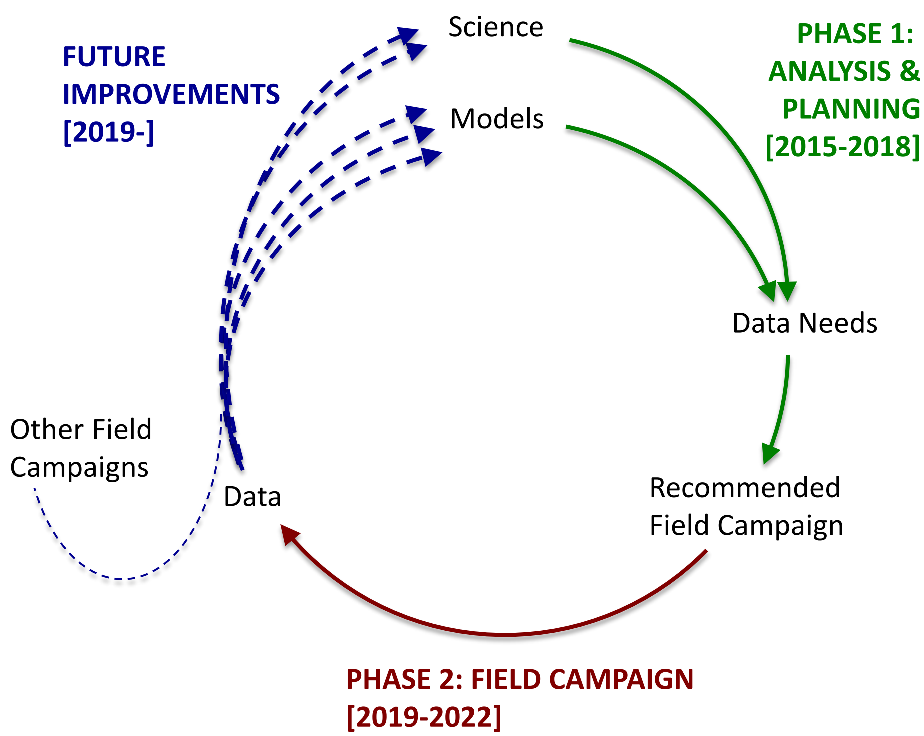

Figure 1-1: FASMEE phases, including planning (Phase 1), observational data collection (Phase 2) and Future Improvements including data analysis and advancement of fire and smoke models (if support and funding becomes available).

FASMEE has two active phases and one suggested phase (Figure 1-1). Phase 1 is the analysis and planning process, for which the science team has reviewed and assessed the current state of fire-plume-smoke modeling and scientific understanding to determine critical needs and realistic pathways to address these measurement needs. Phase 1 began in 2015 and culminates in this study plan and final planning for Phase 2. Phase 2 is a set of field campaigns to collect data that will be completed over 2019–2022. Future improvements would be a suggested set of best measurement practices and a set of analyses and model improvements based on the data collected within Phase 2, and is dependent on identifying future funding sources.

The purpose of this study plan is to present the data needs, burn recommendations, and measurement specifications identified in Phase 1 of FASMEE. As implementation of Phase 2 proceeds, this study plan will serve to guide planning, and it will also be revised and modified by necessity as specific Phase 2 projects are funded and underway. This plan also lays out a roadmap to complete the full circle of connections shown in Figure 1-1, from identifying scientific and modeling needs and data needs, to conducting a field campaign, and anticipating needs for potential analysis and model improvement if funding sources are identified. Indeed, the Phase 2 measurement plan presented here is driven specifically by the scientific analyses and model improvement needs anticipated to be addressed in a final phase.

1.1 BACKGROUND AND MOTIVATION

Fire and smoke models are critical tools for wildland fire decision making and planning. Many models that drive the operational systems in use today, however, are used without adequate validation and evaluation because of the lack of suitable data (Cruz and Alexander 2010 and Alexander and Cruz 2013), and they may not work under specific conditions. Accurate estimates of fire and smoke emissions and dispersion from wildland fires are highly dependent on reliable characterization of many variables: area burned, pre-burn biomass of fuel bed components and condition, fuel consumption by combustion phase, fire behavior, heat release, plume dynamics, meteorology, and smoke chemistry. Improving estimates of plume rise and smoke production and dispersion is fundamentally based on characterizing fire-atmosphere interactions, including wildland fire behavior and plume dynamics. The proposed observational campaigns of the Fire and Smoke Model Evaluation Experiment (FASMEE) have been identified during Phase 1 as a critical need for evaluating operationally used fire and smoke modeling systems and advancing and transitioning newer models and systems into operational use (Cruz and Alexander 2010 and Alexander and Cruz 2013). By directly and indirectly influencing improvements to operational fire and smoke models, results from FASMEE will guide:

- The land management community, through improved models and guidance on their performance, reliability, scope of applicability, and validation;
- The scientific community, through a unique dataset and new understanding of fire, fire effects, emissions, and smoke plumes, chemistry, and transport; and
- The public, through improved fire information and smoke impact warnings.

Area burned, fuel loading (FCCS), fuel consumption (Consume and FOFEM), fire behavior (Behave, FlamMap) smoke transport (HYSPLIT) and dispersion modeling systems span a broad range of complexity (Prichard et al. 2005, Stein et al. 2015, Andrew, 2010; Briggs 1969, 1971, 1972; Achtemeier 2011, Larkin et al. 2010). In general, however, these systems have been simplified to be used in operational applications (e.g., fuel consumption, wildland fire spread and smoke prediction for tactical and strategic planning purposes) and rely on sets of assumptions and algorithms derived from observations and theory.

For example, operational fire and smoke modeling systems use simplified fuel consumption, fire behavior, heat release and plume models that are based on empirical or statistical relationships developed from laboratory, field, and smokestack observations (e.g. Rothermel 1972; Reinhardt et al. 1997; Anderson, 2008; Prichard et al. 2007; Andrews, 2010; Briggs 1969; 1971; 1972). These are the fire behavior, fuel consumption, heat release, and plume models in use today within the fire and smoke operational systems (FlamMap, Behave Plus, Consume, FOFEM, FEPS, V-smoke, Daysmoke, PB Piedmont, BlueSky, WFDSS, IFTDSS). Operational applications require that the models can be executed fast enough to provide usable predictions, and that the data needed for their executions are readily available. For these reasons, mostly simpler systems are used in operational applications. For examples of operational smoke models, see the National Interagency Fire Center webpage for smoke management (https://www.nifc.gov/smoke/smoke_modeling.html).

Complex smoke forecasting approaches explicitly model the physical processes driving buoyancy-induced plume rise and smoke transport. Examples of these weather forecasting models are WRF-SFIRE (Mandel et al. 2011, 2014a), MesoNH-ForeFire (Filippi et al. 2009), and CAWFE (Coen 2013, Coen and Schroeder 2013). In these approaches, simplified fire spread models locate the sources of heat and mass that generate the buoyant plume and smoke (see Appendix B). Other Models in use are weighted toward fire behavior that, in addition to plume rise and smoke generation, explicitly account for the processes of gas-phase combustion and vegetation consumption (e.g., WFDS [Mell et al. 2007] and FIRETEC [Linn et al. 2002]). These fire behavior models require relatively high-resolution computational grid cells (e.g., 1 m), and the resulting high computational demand precludes their routine use on large domains (e.g., greater than approximately 10 ha; see Appendix C).

More complex models explicitly resolve key processes for fire and smoke modeling that must be simplified and parameterized in simpler models. Given improved linkages with complex modeling systems, future operational systems may offer the ability to develop a new generation of models that are both more accurate across a wider array of conditions and are calibrated with fully dynamic models. As the resolution of the weather forecasting models increases, these fire-atmosphere interactions and smoke plumes become explicitly resolvable on fine-model grids. Thanks to improved computational capabilities, operational applications of coupled-fire atmosphere models (e.g., Israeli Matash system based on WRF-SFIRE) are increasingly feasible ("Matash" fire prediction system 2016, Mandel et al. 2014b). New avenues for development have been opened by the recent rapid increase in the resolution of numerical weather prediction products, In the future, implementation of integrated systems such as WRF-SFIRE-CHEM (Kochanski et. al 2015), will be able to resolve fire progression, plume rise, smoke dispersion and chemical transformations in a fully coupled way.

To advance the capabilities of the operational fire and smoke modeling systems in use today, rigorous evaluation, validation, and improvements to models are needed. The performance of both currently used and next generation models need to be assessed and evaluated. This assessment will make it possible to set expectations for how well a model will perform under real-world applications, the level of model uncertainties, and the key sources of these uncertainties that need improvements. For highly intensive, physics-based models, such work can provide the baseline for distilling intermediate-complexity models that may be more computationally efficient in time-critical operational settings.

Currently insufficient observational data exist to facilitate this work, especially in the context of the fire behavior and coupled fire atmosphere models, which require integrated datasets with information about the fuel, energy release, local and fire-induced micrometeorology, and plume dynamics and chemistry. Without such observational data, the accuracy and validity of simplistic or physics-based approaches cannot be fully assessed. Further, known science gaps cannot be addressed, such as relationships between heat release, wind fields, plume dynamics, and feedbacks to wildland fire behavior. In Phase 1, FASMEE identified the most critical observational needs, providing a description of a suite of integrated measurements in forested sites representative of many prescribed burning programs in the southeastern US and increasingly common high-intensity fires in the West.

In Phase 2, FASMEE will undertake the field campaigns, including data collection and archiving and, based on the observational results, begin preliminary model evaluation. As envisioned, it will be a large fire field campaign, with significant potential to advance the fields of fuels, fire behavior, plume dynamics, and smoke chemistry for years to come. The field campaign will provide a robust, integrated baseline dataset that can be used to evaluate fire models and to leverage other data to address additional questions. The Phase 2 observational campaign will provide the knowledge to characterize wildland vegetation and fuels, fire behavior, meteorology, and fuel consumption that will allow researchers to directly relate energy release, plume dynamics, smoke generation, and other immediate fire effects (e.g., soil heating and tree mortality) to the characterized fire.

The Phase 1 Science Team has recommended that subsequent future use of these data for scientific and model evaluation and improvement should move forward if funding sources could be identified. This effort would specifically focus on data analysis and model development, evaluation, and testing. This will require identifying funding sources, but it is highlighted in this study plan as a necessary step to ensure that Phase 2 observational datasets are collected with an explicit vision of how data can later be analyzed and incorporated into evaluating and testing models.

The need for coordinated, cross-discipline observations to support operational fire and smoke modeling has been highlighted in recent synthesis reports, including the JFSP Smoke Science Plan (Riebau and Fox 2010), the Smoke and Emissions Model Intercomparison Project (SEMIP) (Larkin et al. 2012), the Fire and Smoke Model Evaluation workshop and report (Brown et al. 2014), a special session on Wildland Fire Behavior and Smoke (Prichard and Ottmar 2014), the Prescribed Fire Combustion Atmospheric Dynamics Research Experiment (RxCADRE) special issue (Ottmar et al 2016a) and at the 2nd International Smoke Symposium (2016). The FASMEE field campaign is the coordinated multidisciplinary effort that will be conducted on large, operational prescribed fires targeting heavy fuel loads and burned to produce high-intensity fires with developed plumes.

FASMEE was inspired by the successful collaborations within the RxCADRE and direction and guidance from the Joint Fire Science Program (JFSP) Smoke Science Plan and Fire and Smoke Model Evaluation workshop and report. This collaboration led to the JFSP partnering with the Department of Defense, Environmental Security Technology Certification Program (ESTCP) to initiate the FASMEE planning phase (Phase 1).

FASMEE is being undertaken as part of a coordinated group of field campaigns on wildland fire and wildland fire smoke currently being planned, including the National Oceanic and Atmospheric Administration (NOAA) Fire Influence on Regional and Global Environments Experiment (FIREX) experiment (2016 and 2019), the National Aeronautics and Atmospheric Administration (NASA) wildland fire chemistry experiment (FIREChem; anticipated to begin 2019, and fire studies funded by the US Environmental Protection Agency, National Science Foundation, and the US Department of Defense under their Strategic Environmental Research and Development Program (SERDP) projects (Appendix A2). The FIREX and FIREChem campaigns as well as US EPA and NSF research projects are aimed at advancing our understanding of smoke and how it influences the chemistry of the atmosphere. The SERDP projects are designed to improve the understanding of wildland fire combustion processes. It is imperative the larger-scale data collection of FASMEE be closely tied to the SERDP projects and the regional-scale measurements made as part of FIREX, FIREChem, USEPA, and NSF.

Among these campaigns, FASMEE provides a unique perspective in that it specifically addresses all components of characterizing the fuels, fire, and plume development that lead to smoke emissions and injection into the broader atmospheric circulation, as well as near-fire smoke chemistry and plume aging. It also provides expertise in characterizing fuel and fire that does not exist in the NOAA and NASA projects which are atmospheric chemistry directed. See Appendix A for background information and details on coordination with these other federal agency efforts.

1.2 STRUCTURE OF THIS STUDY PLAN

This study plan presents the overall goals (Section 2), science questions, and overall data needs identified by FASMEE (Section 3). A set of needed measurements is presented to address these needs (Section 4), along with specific recommended field campaigns to collect these data (Section 5). Recommended steps for utilizing data from the field campaign are then presented (Section 6). Finally, benefits of this approach are discussed (Section 7).

Attached appendices present the details of the Study Plan: (A) Model Evaluation and Validation, (B) Integration with Other Field Campaigns, (C) Operational Modeling Needs, (D) Recommended Measurements and Justification, (E) Recommended Field Campaigns, (F) Utility of Data – Pathways for Use, (G) Logistics Plans, (H) List of Abbreviations and Acronyms, (I) References, and (J) Acknowledgments.

2. GOALS OF FASMEE

The overall goal of FASMEE is to:

- *Evaluate and advance operationally applicable fire and smoke modeling systems and their underlying scientific models and frameworks.*

To address this goal, the overall objective of FASMEE Phase 2 is to:

- *Collect, reduce, and make available a set of quality-controlled, integrated measurements required to achieve the overall goal.*

Advances in operational fire and smoke modeling are of critical importance to society during this time of rapid climate change and more active fire seasons. Improved smoke prediction systems have implications for firefighter safety and for communities who are at risk of local or regional smoke impacts from wildland fires. It is important not just to predict smoke from fires but also to provide reliable information about the level and chemical composition of smoke to reduce possible health impacts. It is also important to gain a better perspective of fire prone ecosystems where current operational fire models can be appropriately used, with the goal of developing sufficient understanding of fire behavior to enhance their envelope of application. This goal has important implications for tactical and strategic planning for firefighter safety during planned and unplanned wildland fire events.

Central to the FASMEE campaign is obtaining measurements to support a better understanding of plume dynamics and chemistry. Specifically, how do fire-atmosphere interactions combine to produce smoke plumes, how do plume dynamics influence fire behavior, and how can plume dynamics be reliably modeled for smoke dispersion and transport? These dynamics are critical for two reasons: (1) to understand fire behavior, particularly extreme, column-driven fire behavior, which is highly relevant for wildland fire operations and firefighter safety, and (2) to improve our understanding of lofting and chemical transformations of smoke within large plumes that are necessary for predicting smoke composition, transport, and downwind impacts. Of particular interest is how plume dynamics work in high-intensity fires, including stand-replacing crown fire events, and how wildland fire emission chemistry relates to fuels and burning conditions of particular fires, whether prescribed burns or wildfires.

The overarching science question facilitated by the Phase 2 measurement plan is:

- *How do fuels, fire behavior, fire energy, and meteorology combine spatially to determine the development and dynamics of near-source plumes and the long-range transport of smoke and its chemical evolution?*

To address this question, observational measurements of coupled fire-atmosphere dynamics are needed that are integrated over space and time to quantify a complex set of coupled physical phenomena. To meet objectives that define a successful experiment, cross-scale measurements are necessary to adequately resolve the buoyant emissions and moisture source as well as plume development and smoke dispersion from sufficiently large fire events. In recommending a field campaign to meet these needs, FASMEE focuses on the following general approach for Phase 2:

- *To use standard, innovative, and cost efficient field measurement techniques across a range of disciplines to 1) collect observational data necessary to evaluate and advance operational smoke modeling systems and their underlying scientific basis and 2) provide a basis for increasing our understanding of fire behavior in high intensity and plume dominated wildland fires.*

2.1 MEASURES OF SUCCESS

The proposed FASMEE Phase 2 field campaigns will collect, reduce, and archive critical, relevant, and comprehensive observational data of fire, fuels, and smoke over a range of spatial and temporal scales during large-scale field campaigns that can be used to:

- *<u>Test and validate</u> the underlying scientific basis for fire and smoke models.*
- *<u>Evaluate and advance</u> operationally used fire and smoke modeling systems through quantification of key variables, to add capability and efficiency to and to understand their domain of utility and applicability.*
- *<u>Provide observational context</u> for continued fire and smoke model enhancement, including refinement and extension in fire regimes that have not been adequately characterized, including high intensity and complex topography.*

To accomplish Phase 2, these specific steps are needed:

- Improved model parameterizations to enhance both model predictions and the science that serves as the foundation for the models within operational systems. For example, the field measurements will help quantify the processes that drive the spatial organization of fire energy and emissions that defines the transition between fires and plumes and that ultimately determines smoke transport.

- Added capability to the models that will allow for developing the next-generation modeling systems. For example, a key component missing in smoke models is a good understanding of how the combustion environment combines with ambient atmospheric conditions to generate plume-driven fire dynamics.

- Improved quantification and confidence building in operational modeling capabilities leading to improved operational model applications. This in turn improves decision support for operational management.

In the end, FASMEE will be considered a success when the data collected during Phase 2:

- *Improves the science implemented in fire and smoke models.*
- *Provides valuable knowledge that will advance the next-generation modeling systems and operational applications.*
- *Provides information on effective and cost efficient methodologies for measuring fuels for fire spread, fuel consumption, and fire emissions models.*
- *Operational fire and smoke models show demonstrable improvement and better ability to predict wildland fire emissions, plume dynamics, and impacts on air quality.*
- *Ultimately improves decision-support for operational fire and smoke management.*

The FASMEE study plan presented here, to be fine-tuned in Phase 2, lays out a set of needed measurements and recommended activities to achieve success.

3. SCIENCE QUESTIONS AND DATA NEEDS

Based on the goals of FASMEE, a number of specific science questions were identified. Because of the interdisciplinary nature of modeling fire and smoke, these were divided into four discipline areas:

1. Fuels and consumption
2. Fire behavior and energy
3. Plume dynamics and meteorology
4. Smoke emissions, chemistry, and transport

These discipline areas are necessarily integrated and interrelated, and they approximately follow this logical modeling progression: fuels→fire behavior→plume dynamics→smoke chemistry (Figure 3-1; see Appendix C for a discussion of modeling steps).

The core organizational arrangement for FASMEE and the FASMEE Science Team is structured around these four disciplines. This structure is useful to provide the expertise needed to understand each discipline area and to effectively collaborate on a scope of work in which needs, planned work, and analyses interconnect across disciplines.

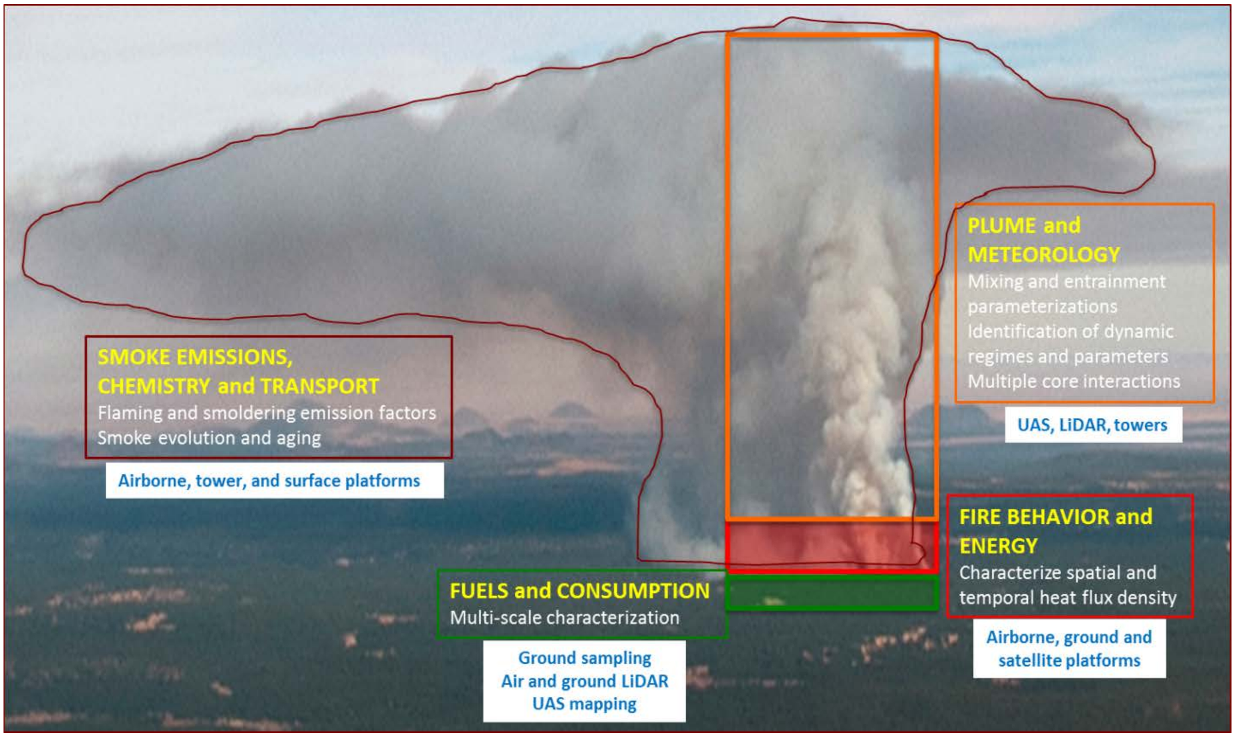

Figure 3-1: Graphic representation of the four FASMEE disciplines.

3.1 SCIENCE QUESTIONS

The overarching science question to be addressed by FASMEE is:

- *How do fuels, fire behavior, fire energy, and meteorology combine spatially to determine the dynamics of near-source plumes and the long-range transport of smoke and its chemical evolution?*

This question was broken down by discipline. Numerous experts in each discipline were consulted through discussions, and an interdisciplinary scientific leadership team was created to identify and organize the science needs, scientific gaps, and needed scientific observations for FASMEE. The resulting sub-questions by discipline are:

Fuels and consumption

- *What are implementable methodologies for measuring fuels and resulting fuel measurements that will improve the use of fire spread models, fuel consumption models, and fire emission production models that are part of current and next generation operational fire and smoke modeling? At what spatial and temporal resolution are the methodologies best developed and applied?*

Fire behavior and energy

- *What processes drive the spatial organization of fire energy and emissions and define the handoff between fires and plumes that ultimately determines smoke transport?*

Plume dynamics and meteorology

- *How does the fire-generated buoyant flow combine with ambient atmospheric conditions to generate near-source plume organization (including plume-driven fire dynamics), number of plume cores and plume entrainment, and vertical distribution of smoke?*

Smoke emissions, chemistry, and transport

- *How do the intensity and composition of fire emissions and the subsequent chemical evolution and transport of emissions depend on fuel characteristics, fire intensity, combustion phase, and atmospheric conditions?*

3.2 DATA NEEDS

Addressing issues within fire and smoke modeling is challenging because of the wide array of spatial and temporal scales involved. Models typically resolve dynamics only above some minimum scale, parameterizing key variables below that scale. Operational prediction models for weather, smoke, and air quality (photochemical) generally run at scales of 1 km or greater, placing the bulk of the fire and plume dynamics into parameterized sub-grid processes. Operational fire growth modeling often occurs at 30-m resolution, but at these scales, models use simplified fire growth or progression schemes that do not fully resolve the complexities inherent in the underlying combustion level dynamics and important fire-atmospheric feedbacks.

An inherent difficulty in coupled fire-atmosphere models is that appropriate scales for modeling the various components markedly differ from each other, because fire dynamics scales are much smaller than atmospheric dynamics scales. Thus, contemporary models of coupled fire and atmosphere dynamics differ considerably in their complexity and how explicitly they treat fire dynamics vs. atmospheric dynamics. Models such as FIRETEC and WFDS, which explicitly model physics-based combustion, cannot routinely model low- to moderate-intensity burns over large areas (i.e., >10 ha) because of limitations in computational capability, even on large-cluster computing systems. Few observations are available of high-intensity, large-fire events where the size and heat fluxes (defined as the sensible heat flux) can overwhelm the atmospheric background and create their own coupled plume dynamics. Of all components of the fire/atmosphere/smoke system, the least observed is the dynamic plume. Although Achtemeier et al.(2012) modeled plumes through organization of plume cores using RxCADRE data, fundamentally, limited observations of the dynamically driven portion of smoke plumes exist that can be used to (1) evaluate and/or validate how well current modeling systems perform and (2) develop new modeling schema.

Simple, operational plume models currently are based on observations of smoke stacks (Figure 3.2) with scaling arguments to derive area and line source equivalents. Observations of wildland fire plumes have either been based on steady-state methodologies or are very limited, such as Light Imaging Detection And Ranging (LiDAR) measurements of the Rim Fire in 2013 (Yates et al. 2016). In the absence of observations, smoke models have either developed tuning schemes to represent the inherently non-steady state, evolving dynamics within the plume as 'plume cores' or 'sub-plumes', or they have relied upon basic fluid dynamics equations without proper evaluation of their application.

The lack of a useable understanding of physical plume dynamics for modeling is a major hurdle for the variety of models seeking to address operational wildfire needs. Plume

Figure 3-2: Pictures of a smokestack (left) and typical wildfire plume (right) showing multiple plumes and other complexity of internal convective dynamics. Much of our understanding of plume dynamics for smoke modeling comes from studies of the idealized smokestack, but real-world fires are much more complex.

structure and dynamics are critical in relation to extreme fire behavior, and these have been cited in several fatality incidents of wildland firefighters since 2011. Predicting plume organization, particularly the entrainment and vertical lofting of smoke, is also critical for all modeling of smoke impacts.

For these reasons, FASMEE has focused its field collection efforts on filling these gaps in our observational database. Critical gaps include (1) the operational need to focus on larger wildfires, their behavior and coarse-scale smoke modeling, (2) the need for better scientific and model understanding of plume dynamics to underpin the next generation of predictive models, and (3) the lack of plume observations in current and past field studies.

FASMEE will produce the first ever spatially and temporally coordinated database of fuels, consumption, fire behavior, atmospheric conditions, plume behavior and structure, and smoke chemistry ever observed on high-intensity fires. In this way, FASMEE will provide an opportunity to develop a deeper understanding of the phenomenological differences between the type of fires most studied to date (smaller, less energy-intense fires) and those fires that are operationally challenging (larger, more energy-intense fires).

4. PRIORITY BURNS AND MEASUREMENTS

Based on an analysis of the needed science data and types of models (see Appendix B), the FASMEE Science Team developed a list of needed burns and measurements. The recommended types of burns and measurements translate the generalized data needs of the science questions and models into a specified set of achievable field observations. These recommendations form the core of the FASMEE Phase 1 planning process.

In Phase 1, experts from disciplines in fuels, fire behavior, meteorology, plume dynamics, and smoke chemistry were brought together to develop the final list of needed burns and measurements. Preliminary modeling was conducted on potential burn sites, and assessments were undertaken to compare data needed for models to run along with model sensitivities and differences (see Appendices B and C).

4.1 TYPES OF BURNS

Across fire and smoke science disciplines represented in Phase 1, a wide range of desired burn types were discussed. For fire behavior modeling issues, different types of burns were needed to resolve fire dynamics and plume dynamics. To resolve fire dynamics, smaller burns with large fireline depth, including a gradient in fuel types and terrain complexity, were desired. For plume dynamics, larger fires capable of producing a signal over the noise of background meteorological conditions were essential. Preferences were narrowed through the science team discussions to prioritize the type of burns desired for FASMEE to: (1) high-intensity fires (sizable surface and crown consumption), (2) large fires capable of producing significant atmospheric plume dynamics and a substantial downwind smoke plume, and (3) where possible (particularly in the Southwestern Campaign), free-running fire (fire behavior not affected by ignition or suppression), to avoid the inherent initialization issues in random ignition that does not coalesce into a freely evolving fire.

4.2 RECOMMENDED MEASUREMENT SUITE

The recommended measurements span the four interrelated disciplines of FASMEE: fuels and consumption, fire behavior and energy, plume dynamics and meteorology, and smoke emissions, chemistry, and transport. Fuel type, condition, and consumption during wildland fire relates to several fire impacts including radiative heating, which provides the energy that drives fire dynamics. Another key factor in fire behavior is local-scale meteorology, which also relates to atmospheric chemistry, dispersion, and transport. Plume dynamics provides the connection between fire behavior and far-field smoke dispersion, because it determines the vertical distribution of the emissions. The quantity and speciation of emissions are determined by the variation in pyrolyzed gases and air participating in the reaction (fire behavior).

To observe the coupled fuels–fire–atmosphere–smoke system, many different instruments and platforms are needed (Figure 4-1). Ground, aircraft (including unmanned aircraft systems [UAS]), and satellite platforms are needed to make the necessary measurements of this system. Specific measurements are generalized by discipline in the sections below, with full details in Appendix C.

4.2.1 Fuels Measurements

Because smoke models require detailed fuel consumption information to predict heat release rate and emissions, any smoke campaign must collect pre- and post-burn fuels information for all combustible material (trees, shrubs, forbs, grasses, coarse and fine woody debris, litter, and duff). The methods for collecting these data will include extensive field sampling linked with LiDAR. Field sampling is the most reliable method for collecting the pre- and post-fire information, but to capture heterogeneous fuel distributions, terrestrial and airborne LiDAR and structure from motion (SfM) methods for complementary point cloud data are also needed.

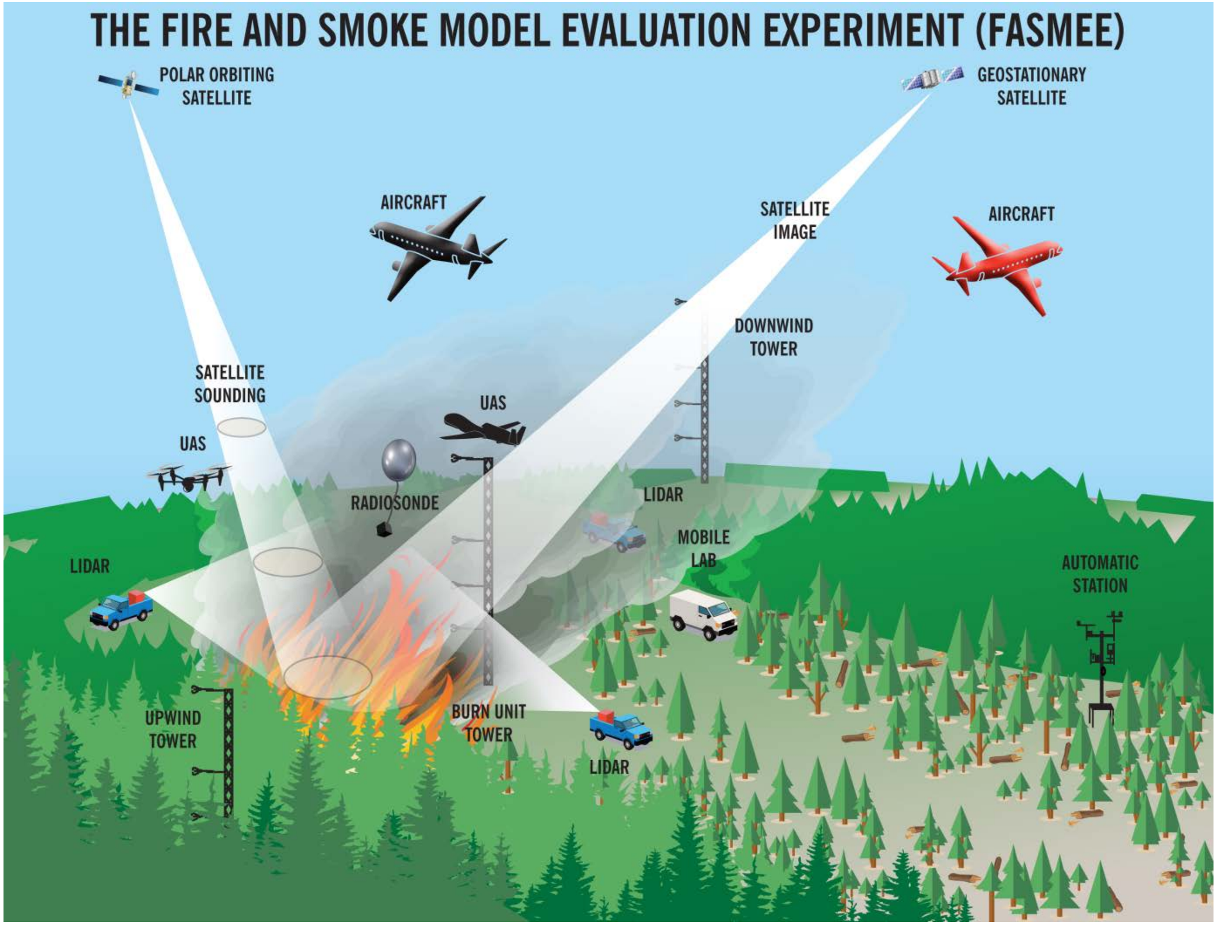

Figure 4-1: Schematic representation of the FASMEE project measurement platforms.

Key measurement variables include fuel load, architecture, composition (type), and moisture. These fuel properties will be measured in Phase 2 using airborne laser scanning (ALS), terrestrial laser scanning (TLS), multi-spectral imagery, thermal IR or microwave imagery, photogrammetry, non-destructive and destructive ground measurements based on inventories, subplots, and transects.

4.2.2 Fire Behavior and Energy Measurements

The Fire Behavior and Energy (FBE) discipline provides the basis for answering key science questions related to the “handoff” of mass and energy between the fire and plume. FBE can also deliver datasets describing heat release in space and time that are required by plume models and provide data for evaluating fire models and key assumptions of smoke models. To achieve these goals requires a combination of remote sensing, coordinated ground measurements, and modeling. Coordinated measurements will be stratified across their expected range of variability within and among fires, and fire heat release will be characterized across spatiotemporal scales. This will allow description of the evolution of structure in fire heat release and plume structure that arises because of the coupling of the fire and the atmosphere.

Key measurements for fire behavior and energy include quantitative fire radiation from satellite, airborne, and tower-based platforms. Other important measurements will include flame-front dimensions spread rates and radiation, flame energy transport, emissions fluxes and combustion efficiency, and emissions partitioning between flaming and smoldering combustion. Fire radiation measurements are needed to derive spread rates, and a combination of data and modeling is needed to derive flame-exit gas temperatures, velocities, and convective fluxes needed in space and through time as inputs to plume models.

4.2.3 Plume Dynamics and Meteorology Measurements

Plume dynamics and meteorology measurements can be organized by four measurement platforms: (1) airborne in situ observations, (2) tower-mounted in situ observations, (3) ground-based in situ observations, and (4) ground-based remote sensing. The atmospheric environment surrounding the burn unit and region is best characterized with a network of surface stations. A network of vertical atmospheric profilers around both the experimental burn unit and outside the experimental region is also critical to quantify both local and mesoscale circulations. Vertical profiles of winds and temperature provide measurements of atmospheric stability and shear of the fire environment, and provide a means of assessing plume dispersion and smoke behavior. To better understand the effect of surface-layer micrometeorology on fire behavior and smoke dispersion, a suite of tall towers (30–50 m) will be placed within the burn unit. These towers can also support other instruments for measurement of fire behavior and energy. Plume rise, entrainment, and fire-atmospheric circulations associated with the plume can be directly measured using a suite of scanning Doppler LiDAR systems (ground and/or aircraft).

Key meteorological variables needed to characterize fire weather conditions and surface meteorology include ambient air temperature, humidity, near-surface wind speed, and wind direction. UAS, radiosondes and LiDAR are needed to observe the plume dynamics and thermodynamics from above the canopy upward to several kilometers.

4.2.4 Smoke Chemistry and Transport Measurements

Direct emissions from biomass burning are a complex mixture of gases and aerosol. The emission factors measured must represent all phases of combustion, including flaming, smoldering and long-term smoldering phases. A comprehensive chemical characterization of smoke emissions requires multiple instruments and techniques employed from both ground-based and airborne measurement platforms. To understand chemical evolution in the smoke plume, detailed precursor and chemical product measurements are needed in the near field to define emission rates of key precursors as well as at different downwind distances (ideally even hundreds of kilometers from the fire source) from a fire extending over a multi-day period. Ground-based emissions measurements include gas emission downwind of the burn, post-fire-front sampling of gas emissions from independently smoldering fuel components, and downwind point sampling of aerosol and gas emissions. Airborne chemical measurements allow researchers to understand chemical evolution in the plume and obtain a more representative smoke sample than is possible using ground-based measurements, because (1) an airborne platform samples a significantly larger volume smoke than any of the ground-based approaches, and (2) the buoyant smoke plume entrains and mixes emissions from a large area. Another advantage of an airborne platform is the ability to bring the instruments to the smoke.

Key measurements for smoke chemistry and transport include particulate matter, carbon, ozone, nitrogen containing compounds, and volatile organic compounds (VOCs) (see Appendix D, Table D-5).

4.3 COMMON COMPONENTS

Any experimentally designed field campaign must address a number of critical common elements, ranging from safety and data quality. Ensuring safety throughout the project requires strict command structures, incident action plans, and aircraft safety plans, as well as site access and logistical staging plans. Ensuring data quality includes quality assurance, archiving, and documentation, as well as data cross-compatibility among the different measurements and platforms. In particular, measurements must be synchronized across time and space. This is especially critical for high-temporal resolution measurements of the fire and plume, where failure will jeopardize the end-product usability. See Appendix F for details.

5. RECOMMENDED FIELD CAMPAIGNS

Guided by these data needs and science questions, an extensive search for field campaign opportunities was undertaken, including sites across the US and Canada. Three campaigns were selected, based on:

- Ability to meet identified needs and requirements for burns and measurements;
- Interested host agency partners;
- Initial cost estimates;
- Geographic balance, with an emphasis on high-intensity fires typical of wildfires in the western US and prescribed underburns in pine forests of the southeastern US with heavier surface fuel accumulations;
- Unique field campaign opportunities unlikely to be repeated in the near future.

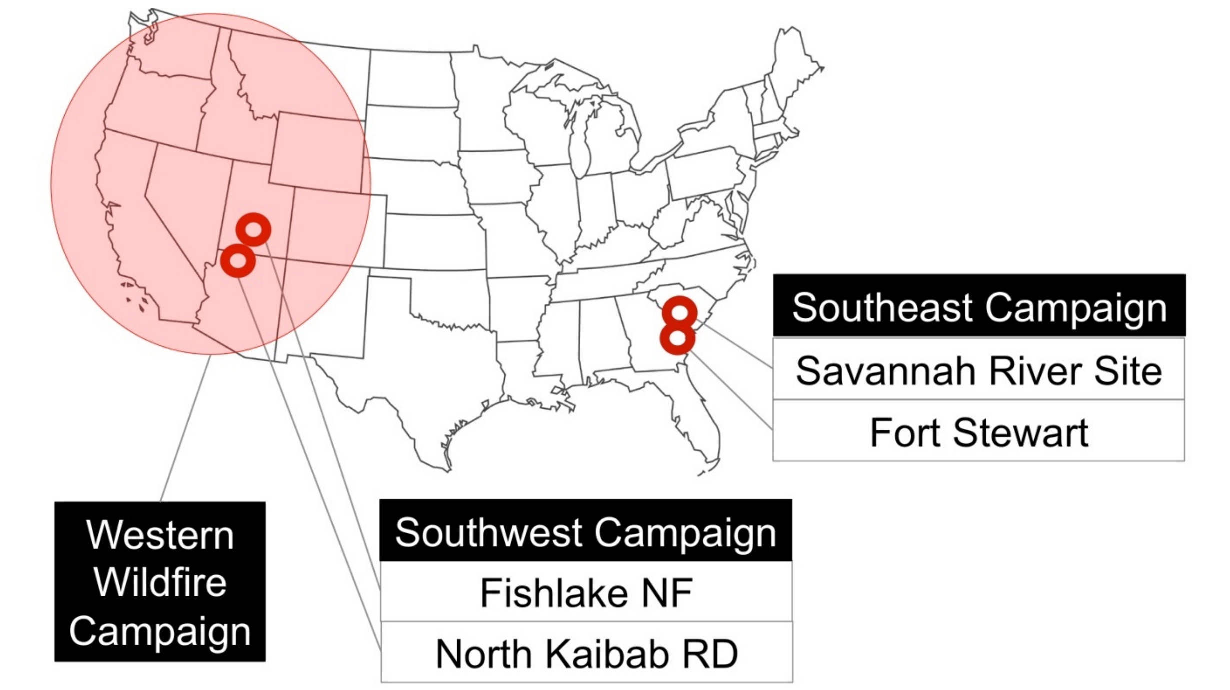

Figure 5-1: FASMEE-recommended field campaign sites. The Western Wildfire Campaign will target active wildfires with rapid-deployment source characterization in the western United States (shaded red circle) and is not part of the 2017 FON. The Southwestern Campaign will target prescribed burn sites at Fishlake National Forest and/or North Kaibab Ranger District. The Southeastern campaign will target prescribed burn sites at Fort Stewart and/or the Savannah River Site.

The three recommended field campaigns in likely implementation order are:

1. **Western Wildfire Campaign (will not be part of the 2017 FON)**
   Western US wildfires with rapid-deployment source characterization.
2. **Southwestern Campaign**
   Moderately and highly instrumented prescribed burns in dense mixed conifer-aspen forests, ignited for a high-intensity, stand-replacement fire.
3. **Southeastern Campaign**
   Highly instrumented prescribed underburns completed in managed pine forests with heavy surface fuel loads, ignited for a moderate-intensity fire.

FASMEE Phase 1 identified several potential field locations meeting similar heavy fuel load requirements and burn requirements that could be considered for further studies. Each campaign is described below and is shown in Figure 5-1.

5.1 WESTERN WILDFIRE CAMPAIGN 2019

The Western Wildfire Campaign is a rapid-deployment campaign aimed at characterizing western wildfires with the potential of dynamic plume development with long-range smoke transport from July through September 2019. This campaign is encouraged because it presents a unique opportunity for smoke chemistry measurements. During this period, the NOAA P-3, the NASA DC-8, and the NSF C-130 large aircraft are all expected to be available and dedicated to smoke and atmospheric chemistry measurements. This campaign offers an unprecedented opportunity to advance the understanding of smoke chemistry, aging, and transport.

A strong source characterization component is necessary for the related campaigns. Working collaboratively with NOAA, NASA and NSF, FASMEE has identified a subset of identified measurements that can be rapidly deployed. These measurements will focus primarily on fuels and consumption information. Depending on funding availability, they may also include aircraft and ground-based remote sensing of fire energy and plume dynamics. See Appendix D for details.

The fires targeted by this campaign will be those measured by smoke chemistry aircraft. Because these aircraft are capable of extremely long ranges, the supplementary measurements recommended here will likely focus on the most significant (strongest and longest lasting) wildfire plumes being measured. The targeted fires will be identified based on availability of fuel data maps and cooperation of Incident Command in conjunction with the joint FIREX, FIREChem, and NSF campaigns. Information on fires that can be best characterized will be transmitted to the respective agency campaign for incorporation into flight planning.

Benefits to the overall FASMEE goals from this specific field campaign are significant, especially if aircraft measurements of fire energy and LiDAR sensing are included. Coordination with the FIREX and FIREChem campaigns offers a rare opportunity to link aircraft smoke and satellite fire measurements with the characterization of the fire and plume dynamics. This campaign will also provide a better understanding of the dynamics controlling near-source plumes and the resulting chemical composition, aging, and transport of smoke through measurements and observations of fuel, fire behavior, fire energy and meteorology.

Benefits to FASMEE increase when the Western Wildfire Campaign is considered in combination with the proposed Southwestern Campaign. The FASMEE Southwestern Campaign will include highly instrumented prescribed fires and provide coordinated, high-resolution measurements of fire-atmosphere interactions. Together with the Western Wildfire Campaign, the Southwestern Campaign measurements would maximize the total data collected for the western US. It would also provide enough data to assure FASMEE success even if the planned southwestern prescribed burns are cancelled.

5.2 SOUTHWESTERN CAMPAIGN 2019-2021

The southwestern campaign will target prescribed burn conditions completed under heavy surface loads and high intensity fire that will produce a dynamic long-range plume relevant for smoke management. The goal is to highly instrument the site to represent the spectrum of fuel, fire behavior, and plume dynamics that are difficult to sample on large wildfires.

Sites for the Southwestern Campaign have been identified as Fishlake National Forest (NF) in Utah and the North Kaibab Ranger District (RD) of the North Kaibab National Forest in Arizona because of their high fuel loadings, large plot sizes, and histories of prescribed burning.

Fishlake NF has initiated a large planned burn campaign to reestablish the aspen stands in the mixed conifer forests, using planned stand replacement fire (Figure 5-2). Fishlake NF is one of a handful of forests in the United States that regularly uses stand replacement fires; six large planned burns were accomplished in June 2016 using a Type I Incident Command team to administer the activities. Fishlake NF has been surveyed with aerial LiDAR, providing an excellent vegetation/fuel map that FASMEE can use to enhance the characterization of the fuel layer. The identified research sites on the Fishlake NF range from 20 to 400+ ha. In the proposed large unit, terrain is steep and highly dissected, with small draws and canyons. The small units are less steep and more uniform with easy access. Fuels for all sites are mixed conifer and aspen forests with insect and disease damage following decades of fire exclusion. These sites are targeted for planned stand replacement fire by the host agency. Overall fuel loadings are high, with a range of 45-370

Mg/ha. Planned ignition will be by helicopter, producing a simplified ignition to obtain as close as possible a free-running uphill fire. Timing for the Fishlake NF burns is best in the spring (typically May and June), but is also possible during late summer and fall (September through November). Planned burns in the Southwestern Campaign are always subject to weather, fire personnel and resource availability, and budgetary constraints related to prescribed fire costs and over-all hosting of the FASMEE project.

Figure 5-2: Stand replacement prescribed burn on Fishlake National Forest on June 6, 2016 (top); typical fuels at Fishlake: mixed conifer and aspen with insect and disease damage (bottom).

North Kaibab RD is unique in that it has a strong fuels program and has established hundreds of permanent forest inventory and fuel plots throughout both ponderosa pine and mixed conifer forests, including existing LiDAR for much of the forest. The forest inventory and fuels data are available to FASMEE and will supplement the data collection planned for improving the representation of the fuels. Identified research sites are over 500 ha and are relatively flat, with small, intermittent stream channels dissecting the area. An established road network allows easy access to all sites. Two general fuel bed types are associated with the identified sites. The lower-elevation sites are ponderosa forests, and the higher-elevation sites are mixed conifer and aspen forests, similar to the Fishlake NF sites. Overall fuel loadings are relatively low in the ponderosa pine area, (range = 20-100 Mg/ha), while the mixed conifer is much higher (40-220 Mg/ha). Planned ignition will be by helicopter using a plastic sphere dispenser providing a simplified ignition and buring across multiple days. For example, 33% of the prescribed burn area will be ignited and allowed to burn during the first 24 hours with the remaining 67% ignited each of the two following days. The ponderosa pine sites are targeted for a low-intensity underburn with minor tree torching expected. The mixed conifer sites will be ignited under conditions where a mixed severity fire will be obtained, resulting in a higher intensity fire with torching of trees expected in pockets. The North Kaibab RD burns will occur only in the late summer or fall (late August-November). As with the Fishlake NF sites, these planned burns are subject to weather, fire personnel and resource availability, and budgetary constraints conducting the prescribed burns and hosting the project.

5.3 SOUTHEASTERN CAMPAIGN 2021-2022

Fort Stewart in Georgia and the Savannah River Site in South Carolina have been identified as sites for the Southeastern Campaign because of their large plot sizes, smoke management relevancy, increased burn opportunities, prescribed burning history, and willingness to delay burning until a higher than average fuel load build-up occurs. Furthermore, the intensity, ignition type, topography and atmospheric conditions will differ from the western campaigns providing FASMEE with a range of fire intensities and plume characteristics. Fort Stewart's prescribed burn program rivals most military facilities and federal agencies within the southeastern United States in annual area burned, and it has jurisdiction over the airspace, allowing easier application of unmanned aircraft as instrument platforms. The Savannah River site also regularly conducts large burns in a completely secure facility with access to decades of high quality meteorological data. At both southeastern sites, the climatology and amount of burning completed makes it much more probable that the prescribed burns will be conducted within a necessary timeframe to meet FASMEE objectives.

Identified research sites on Fort Stewart range from 200 to 250 ha. The terrain is generally flat with a good road network and easy access. Fuels for the identified sites are plantation-established longleaf/slash pine forests that have not been burned for 4 to 6 years, resulting in fuel loads of greater than 30 Mg/ha (Figure 5-3). Ignition will be by helicopter, resulting in a low to moderate surface fire that will reduce fuel loads with minimal impact to the longleaf and slash pine forest. Timing for the Fort Stewart burns will be between December and the end of April, possibly capturing both a dormant and growing season burn. Since the research sites are on a military installation, the resource availability and budget constraints are less of a concern than for the Southwestern Campaign; furthermore, weather constraints are looser in the Southeast.

For the Savannah River site, identified research sites are over 250 ha and are relatively flat with easy access. Fuels for the identified sites are plantation-established longleaf/loblolly pine forests that have not been burned for 4 to 6 years. These sites have been thinned, with logging debris on the ground resulting in surface fuel loads of 40-90 Mg/ha. Planned ignition will be by helicopter dispersing ignitable spheres, resulting in low- to moderate-

Figure 5-3: Prescribed burn at Fort Stewart [February, 2016] (top); typical fuels—4 to 6 year rough—at Fort Stewart (bottom).

intensity fire with little or no tree torching. As with the Fort Stewart site, timing for the Savannah River site burns will be between December and the end of April possibly capturing both a dormant and growing season burn. The Southeastern Campaign is subject to weather, fire personnel and resource availability, and budgetary constraints, but to a much lesser extent than the Southwestern Campaign.

5.4 OTHER FIELD CAMPAIGN OPPORTUNITES

The concept of FASMEE and plans laid out in this Study Plan have value beyond the three currently planned field campaigns. The measurement capabilities and methods developed and implemented in FASMEE Phase 1 and 2 can serve as examples for data collection at other sites as fire and smoke modeling mature. During Phase 1, the FASMEE Leadership identified other potential field locations meeting similar heavy fuel load requirements and burn requirements that could be considered after the Phase 2 western wild fire, Southwest and Southeast campaigns described above are completed. For example, in Phase 1 we identified:

- Blow-down timber in boreal mixedwoods of central Canada where prescribed/ experimental burns are on-going.
- Lodgepole pine forest prescribed fires are on-going across the Northern Rockies of Canada.
- Black spruce forests of Alaska prescribed fires with large fuel loads.
- Smaller prescribed burns near rural communities in the Pacific Northwest.
- Extensive opportunities in Southestern pine forests for fuels reduction

These additional sites would be considered only after FASMEE Phase 2 is complete. These sites would address the data needs and science questions identified in the FASMEE project and would fulfill the general criteria of desired heavy fuel loading and high energy high intensity fires.

6. THE NEXT GENERATION OF FIRE AND SMOKE MODELS

The proposed field campaigns will contribute to scientific understanding and modeling capabilities relevant to coupled fire-atmosphere dynamics (Figure 6-1). The next generation of fire and smoke models are defined here as those models and frameworks that improve or replace current operational models.

The goal of FASMEE is to collect integrated datasets that can be used to evaluate and advance fire and smoke modeling systems applicable to operational support. Current operational systems are relatively simple and may not benefit from all the FASMEE observations. However, future operational modeling systems will rely on more advanced modeling of fire and smoke derived from systems currently used in fire and smoke research. These include physics-based, coupled fire-atmosphere models. Although such systems are likely to be too computationally expensive for operational applications for the foreseeable future, they can be distilled into simpler systems and/or used to train simpler models, therefore they will benefit the simplified models currently employed in incident operations.

Currently in testing are nested modeling systems, which have an interior high-resolution model which more fully resolves critical processes such as fire-atmosphere interactions leading to plumes, and an exterior coarse-resolution model that provides broader context,

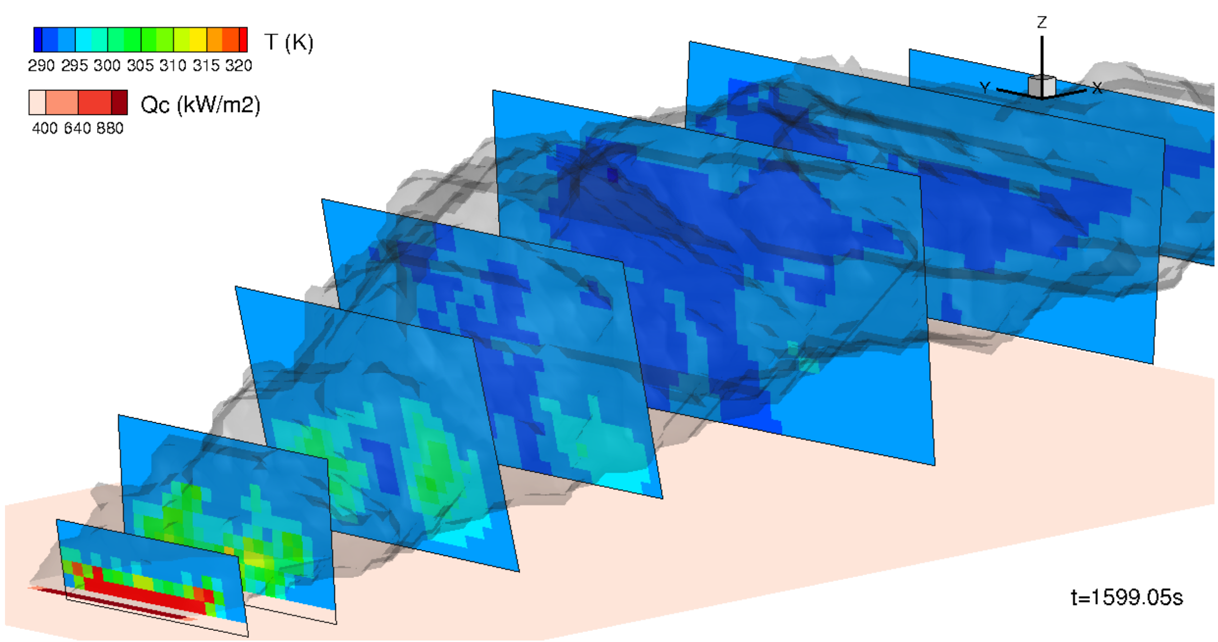

Figure 6-1: Example of smoke plume modeled using a coupled fire-atmosphere model. A line source is used and cross-sectional planes are shown; the planes are orthogonal to the centerline plume motion at each point downwind.

such as smoke transport and dispersion. An example is the WRF-SFIRE-CHEM modeling system shown in Figure 6-2. Such systems are in use in other fields, such as the National Institute of Standards and Technology (NIST) ALOFT modeling system for burning oil slicks in the ocean. FASMEE is designed to provide an additional observational basis for such systems to speed their transition and adoption to operational use.

The FASMEE data can and should be used to directly assess and address modeling capabilities and the best scientific knowledge by addressing the following questions:

(1) What is the atmospheric response to fire heat flux?

A central component of the observations identified for the fully instrumented FASMEE burns is the capture of the heat-release rate and its duration in areas of active flaming. This component allows for post-campaign modeling analyses where the heat generated by the fire within the modeling system is prescribed (i.e., neither combustion nor fire spread need to be modeled; see the "burner" method in Appendix E.6.1); the response of the atmosphere to this perturbation can be compared directly against observations. This approach, if measurements sufficiently support it, will provide plume-rise simulations without the need to model fire spread.

(2) How best and how well can fire behavior models predict the overall fire progression?

The observations from, and broad characterization of, the high-intensity fires planned for FASMEE will help the fire community to address the challenges of determining the

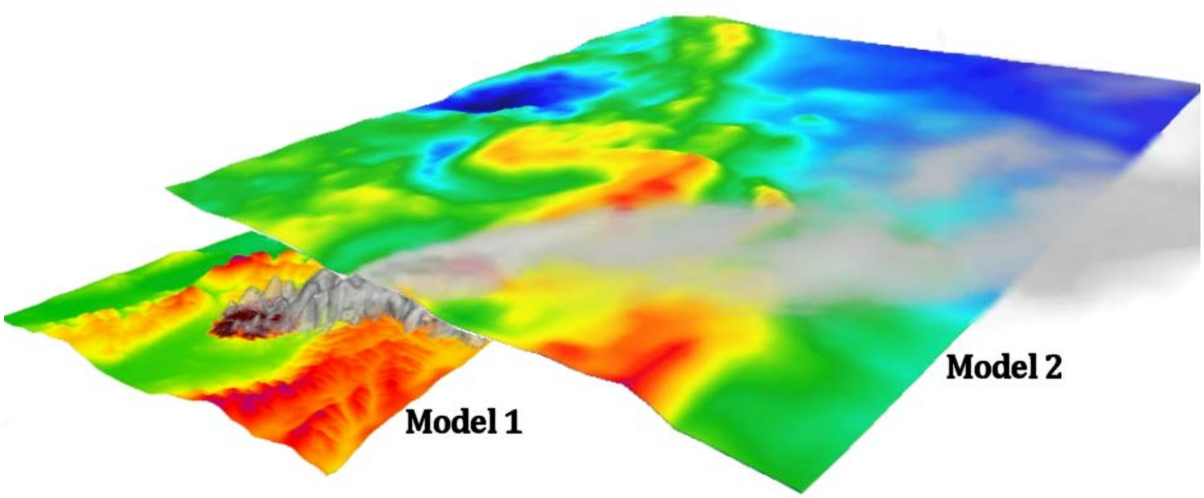

Figure 6-2: Example of how an explicit fire and plume model (Model 1) can drive a coarser-scale air quality/smoke chemistry model (Model 2). Model 1 has a small (kilometers), high-resolution (tens of meters) grid that acts as input to the larger (hundreds of kilometers), coarser (kilometer) grid. In this way, the plume is explicitly captured and "handed off" to the broader air quality model.

applicability of fire behavior models of all complexities for large and intense fires. Pending advances in computing power, the larger proposed experimental burns might be too demanding on existing computational resources for full physics-based fire behavior models that explicitly model combustion. Furthermore, the characterization of the environment (winds and fuels) might be insufficient to adequately constrain fire behavior models in general for robust validation or calibration. However, assessing the overall pattern of fire progression is of value, because it adds to understanding of how such high-intensity fires behave and couple with the atmosphere around them. Of particular interest will be the comparison of initialization and parameterizations of fire progression models between the larger and smaller FASMEE burns, and between the western sites (Western and Southwestern Campaigns) and the eastern sites (Southeastern Campaign). Since the large fires planned for the FASMEE project will have characteristics comparable to wildfires, they present an opportunity to learn how to bridge the gap between fine scale research models and methods that can be put into practice as part of the larger model.

(3) How can coupled fire-atmosphere models predict plume rise and vertical plume structure?

As a corollary to (1), the fire-atmosphere models will be examined in their coupled mode. This is the mode that will be used in future operational systems, because predictions of both fire growth and plume structure are needed in such applications. Because full physics-based systems are probably too computationally costly for operational use, a major component of this effort will be to examine different versions of derived simpler approximation schemes (e.g., WFDS-Level Set and WRF-SFIRE) and their configurations to determine best practices for future prediction systems.

(4) How can complex, explicit coupled fire models be used to improve the current operational use of simpler fire behavior and plume models?

Although the fundamental science governing atmospheric transport and dispersion is fairly well established, in most wildland fire smoke models, the evolution of strongly buoyant plumes such as a smoke plume is poorly described. For example, some simple smoke models use average heat fluxes over a large section of the burned area during different fire stages, which would affect modeling of rapidly-varying, small-scale, and eddy structure of smoke plume and entrainment. The next generation of operational applicable systems is expected to improve modeling of fire and plume dynamics by better understanding variability in heat flux across the burn. Forest vegetation can also have important effects on boundary- and surface-layer structure by altering turbulent kinetic energy and turbulent heat and momentum fluxes. These, in turn, affect the local and within-canopy transport and diffusion of smoke from wildland fires, particularly low-intensity surface fires. The next generation of complex, explicit, coupled fire models will help to address the effects of these interactions, ultimately improving fire behavior and smoke model components in currently used operational modeling systems.

(5) How can critical plume structure be modeled by spatially and temporally resolved fuels and fire dynamics?

Current fuel and smoke modeling is used to provide estimates of bulk heat release and emissions that is needed by several operational systems used for modeling smoke plume and air quality including Daysmoke. The next-generation of coupled models will provide high-resolution spatial distribution and temporal dynamics of fuels and fire products to improve modeling of complex smoke structure. For example, multiple plume updrafts are one of the important plume-structure features caused by fuel and emissions heterogeneity. Multiple plumes not only increase the horizontal heterogeneity of smoke, but also change the heat flux, thereby modifying smoke plume rise and vertical distribution. The formation and evolution of multiple smoke updrafts are related to fuels and fire dynamics, including the ignition patterns and progression, fuel consumption, fire spread, and intensity. These fuels and fire dynamics determine how the individual fire cells develop and merge into separate smoke plumes. The next generation of coupled fire and smoke models will be able to capture fuel heterogeneity and temporarily varying fire processes to provide information for determining the number of multiple updrafts. How well these processes are simulated by operational models (which operate under the constraint of faster than real-time simulations) is a major challenge to be addressed.

(6) How can fuel structure and fuel structure variability be captured on an operational basis to enable better fire, plume, and smoke modeling?

The next-generation fuels characterization will use a range of traditional, field-based measures combined with remotely sensed datasets to provide three-dimensional mapping and characterization of fuels. Coupling traditional measurements with remotely sensed datasets allows for scaling up observations from fine-scale inputs to physics-based models to coarse-scale fuels characterization required by smoke models (e.g., WRF–FIRE, Daysmoke). Hierarchical sampling across a range of spatial scales also provides an important sensitivity analysis of what scale of observations is needed for models of interest. The next-generation models will operate on a range of spatial scales, from physics-based models at the sub-centimeter scale of combustion (for research-focused simulations), to much coarser grids that are sufficient to represent large-fire behavior and for operational focused simulations.

(7) How can the smoke chemistry in photochemical model chemistry kernels be improved?

The complex photochemistry in a fresh smoke plume can cause large changes in O_3 and organic aerosol concentrations within minutes of emission. The wildland fire measurements for FAMSEE will provide comprehensive chemical characterizations of the fresh smoke and its rapid chemical evolution within the first hour following emission. These observations can be used to evaluate and improve atmospheric chemistry models, improving understanding of smoke chemistry and the ability to forecast the effect of fires on air quality and climate.

(8) How can the representation of emissions in models be improved?

Strategies for controlling or reducing smoke emissions (often termed emission reduction techniques) require an accurate representation of the emission composition and intensity associated with different combustion phases and fuel components. The combination of comprehensive fuel, fire behavior, and multi-platform emission measurements over the lifetime of the fire events will provide unique datasets for developing emission factors specific to combustion phase and fuel component, which in turn can be applied to widely used smoke management tools such as CONSUME and FOFEM. Furthermore, NOAA's FIREX 2016 experiments conducted at the US Forest Service Firelab in Missoula, MT measured emissions released from a variety of western and southeastern US fuel types. These laboratory measurements will provide the ability to compare these data with data collected from the FASMEE western wildfire, southwestern and southeastern campaigns.

7. CONCLUSIONS: EXPECTED OUTCOMES AND BENEFITS

7.1 EXPECTED OUTCOMES

The expected outcomes from the FASMEE project include:

- Improved scientific knowledge of the physically coupled fuels–fire–smoke–chemistry system.
- Exportable methodologies for measuring fuels for fire spread, fuel consumption, and fire emissions models.
- New insight concerning the processes that drive the spatial organization of fire energy and emissions which defines the transition between fires and plumes that impact air quality.
- Improvement of existing operational fire and smoke models and the development of new, more advanced models based on the collection of an unprecedented dataset (fuels, fire, meteorological, and smoke plume and chemistry).

7.2 VALUE FOR ASSESSMENT AND ADVANCEMENT OF CURRENT OPERATIONAL FIRE AND SMOKE MODELING

Operational fire models including characterizing fuels, estimating fuel consumption, and predicting fire behavior and heat release rely on relatively simple physics and empirically based coefficients. These software tools currently in use today are the drivers of the smoke model prediction systems and will use the data collected during FASMEE to assess and advance these models. Smoke modeling predicts the spatial and temporal distribution of particulates and gases resulting from combustion during wildland fires. The model predictions of fine particulates, O_3, and other pollutant concentrations can be used to assess public health impacts, transportation safety, and other regulatory impacts and risks. Smoke models are important for quantifying the contribution of wildland fires to regional air pollution. They thus support the development of effective strategies to improve and maintain air quality. Modeling systems (e.g., FIRETEC, WFDS, WRF-SFIRE, MesoNH-ForeFire, Daysmoke, and the Bluesky framework) attempt to quantitatively predict smoke. Modeling systems such as WRF-SFIRE and CMAQ provide quantitative estimates of smoke particulate concentration and trace gases. The significant knowledge gaps in smoke modeling include (1) how the composition and intensity of emissions varies with fuel characteristics and fire behavior, (2) how fire-generated buoyant flow combines with ambient atmospheric conditions to develop smoke plumes, and (3) the post-emission chemical processes that can rapidly cause large changes in the concentrations of fine particulate matter and O_3. The only means to satisfactorily address these gaps is through sufficient measurements of area burned, fuels, fuels consumed, fire behavior, fire generated heat, and smoke production, transport, and evolution, which can then be used to test model parameterizations and evaluate the results.

The FASMEE-recommended measurement suite is designed to collect data for the critical factors in the production, transport, and chemical evolution of smoke. Phase 2 recommendations emphasize measurements of high-volume smoke production from burning in heavy fuels that produce multiple plume cores and significant vertical plume development. The mass of smoke produced and the plume dynamics will mimic those of a robust wildfire, producing a plume sufficiently concentrated to observe photochemical evolution and atmospheric transport similar to that of wildfires. The resulting data can be applied to nearly any modeling system with a smoke prediction component.

7.3 BENEFIT TO FIRE AND SMOKE MANAGEMENT COMMUNITY

The recommended measurement suite planned for FASMEE provides quantitative information for improvements and development of many coupled fire-atmosphere models and will provide critical datasets for developing the next generation of operational models of fire and smoke. For models currently used for research-based analyses of fire, FASMEE will provide uniquely integrated and comprehensive datasets to advance our understanding of the complex fire-atmosphere system. Integrated measurements from the FASMEE campaign will enable evaluations of (1) how well specific models perform under real-world applications, (2) the level of model uncertainties, and (3) what key sources of these uncertainties need improvements. Observation-based phenomenological characterization can help to assess whether intermediate-complexity and physics-based models are capturing coupled fire atmosphere behavior that is critical to the simulation of high-intensity fires in complex terrain.

7.4 BROADER IMPACT TO DECISION MAKERS AND SOCIETY

Many sources for smoke information are now available to managers, including both web-based and downloadable models and datasets. These include simple screening tools, ventilation indices, web-based systems, real-time smoke forecasts and daily atmospheric chemistry modeling. These resources are commonly used to help mitigate smoke impacts, which can be numerous. Smoke from wildfires has been associated with increased physician and emergency room visits, hospital admissions, and mortality. Illnesses attributed to smoke exposure can also result in absenteeism from work and school, affecting economic productivity and educational achievement respectively. FASMEE aims to provide data to improve publicly available information generated from smoke models for the benefits of protecting public health and welfare through more accurate smoke predictions and warnings.

The scope and design of the FASMEE field experiments allows for interagency collaboration and partnering. For example, agency programs that focus on air quality could use similar methods as recommended for the Phase 2 measurement campaign to characterize fuels, fire behavior, and plume dynamics.

FASMEE will serve as a training opportunity for investigators in the earlier stages of their careers to observe and participate in large research burns that involve close coordination among managers, researchers, and operations communities. In the same way that the research outcomes of FASMEE will benefit research support to fire management in the coming decades, the experience provided to early-career personnel involved in FASMEE will benefit the research community's ability to plan, coordinate, and conduct ambitious projects in other areas of fire science well into the future.

7.5 BROADER IMPACT TO OTHER DISCIPLINES

Data from the FASMEE burns also will provide a large set of fuels characteristics and fire behavior measurements for use by other disciplines. For example, ecological measurements pre- and post-burn could be made in the context of knowing in detail the fire environment and burning conditions that can be associated with fire effects and ecological impacts. Documentation of FASMEE burns will include spatiotemporal mapping of fuels, fuel consumption, fire behavior, and plume development to facilitate broad use of the datasets collected in the completed campaigns.

An additional benefit of FASMEE to other disciplines related to fire behavior and smoke modeling is its potential to serve research interests within fire ecology. FASMEE's single greatest benefit to fire ecology is the advance planning of large prescribed burns, providing a chance to conduct detailed studies on fire effects. Depending on their focus, these studies may benefit from the additional insights provided by the data from the FASMEE discipline areas. For example, studies of tree mortality would naturally be improved by the detailed data on fire behavior and energy. Furthermore, the United States Geological Survey (USGS) Forest and Rangeland Ecosystem Science Center (FRESC) studies of soil and erosion would benefit from the detailed pre- and post-fuel characterization and energy release over time. Although FASMEE will not provide the resources to assist with or participate in such studies, the FASMEE leadership team and investigators have expressed a desire to cooperate with interested non-FASMEE teams in conducting work that will not interfere with FASMEE logistics or add personnel or complexity during the burns themselves.

APPENDIX A: MODEL EVALUATION AND VALIDATION

With the growing complexity of wildland fire management issues, managers rely heavily on operational fire and smoke model predictions and simulations to assist in critical wildland fire decision making. Although these models and modeling frameworks are crucial for wildland fire planning purposes, they have not been evaluated and validated or advanced through further development because of the lack of suitable, integrated datasets. Since both fire and smoke modeling is intrinsically tied to accurate characterization of fuels, fuel consumption, fire dynamics, and meteorology, a set of consistent and co-located measures for evaluation and validation of both operational and physics based modeling systems is needed. In the context of this study plan, model evaluation, validation and development are defined as follows:

Model evaluation – evaluation of a model's suitability for a given purpose, including quantitative comparisons between observed and predicted observations.

Model validation – quantitative comparison between observed and predicted observations that provides end-users some understanding of the confidence associated with model predictions.

Model development – design, implementation and evaluation of a model to improve/advance its capabilities for wildland fire applications.

The Fire and Smoke Model Evaluation Experiment (FASMEE) will provide novel and critical observational data necessary to evaluate and validate operational fire and smoke modeling systems that are currently in operational use (Table A-1). The data will also provide opportunities to improve and advance the scientific underpinnings of these models. Recent reviews including the JFSP Smoke Science Plan (Riebau and Fox 2010), the Smoke and Emissions Model Intercomparison Project (Larkin et al. 2012) and evaluation of crown fire modeling approaches (Cruz and Alexander 2010, Alexander and Cruz 2012) conclude that improvements to wildland fire behavior and smoke prediction will require comprehensive datasets that capture sources of uncertainty. To date, few datasets are available to evaluate uncertainty across the chain of models required to predict wildland fire spread, fuel consumption, plume dynamics and smoke chemistry and dispersion (Cruz et al. 2003).

Fuels and consumption are key inputs for all fire and smoke models, and FASMEE Phase 2 will tailor its sampling design to the most data-intensive models. This will ensure that minimum observational requirements for fuels and consumption will satisfy the entire range of fire and smoke models -- from relatively simple operational models currently in use such as BehavePlus (Andrews et al. 2005), FlamMap, Consume (Prichard et al. 2007) and FOFEM (Reinhardt 1997), to complex, physics-based models such as WRF-SFIRE-

CHEM (Mandel et al 2011, 2014a), WFDS (Mell 2007, 2009) and FIRETEC (Linn et al. 2002, 2005). Table A-2 provides a list of both operational and physics based coupled fire-atmosphere models and atmospheric models that can be evaluated with FASMEE datasets.

Fire behavior observations including fire depth, flame length, rate of spread and heat flux will be spatially resolved and therefore can be evaluated in the context of spatially mapped, 3-D fuels and consumption and the smoke that is produced. These integrated fuel consumption, fire behavior and emissions observations will be used to evaluate the full set of current operational models contained within Interagency Fuel Treatment Decision Support System (IFTDSS) and the Wildland Fire Decision Support System (WFDSS). These datasets will also be available to develop the next-generation of operational fire and smoke models. Over the next decade, coordinated measurements will be used to not only test and improve computationally intensive models such as coupled-fire atmosphere dynamics models (e.g., FIRETEC and WFDS) but will also result in improvements to operational models. It is extremely likely that computationally-intensive models will be used to calibrate faster, operational models of fire behavior, fuel consumption and smoke production that have yet to be developed. This hybrid approach will not be possible without integrated, multi-scaled datasets such as the one proposed in this study plan.

A compelling example of next-generation model refinement is the implementation of the STANDFIRE module within IFTDSS. The IFTDSS framework was originally developed to provide a web-based system for fuel treatment planning that employed common operational fire and fuel consumption models based on the Rothermel spread model and empirical observations of fuel consumption and emissions from prescribed burns. Recently, STANDFIRE (Parsons et al. 2016), was developed as a module within IFT-DSS to support creation of 3D fuels from tree list data developed within the Forest Vegetation Simulator and to run FIRETEC and WFDS to evaluate consequences of forest thinning and fuel reduction treatments on predicted fire behavior. Both programs, IFTDSS and the STANDFIRE module, are still under development and will benefit from FASMEE evaluation datasets.

Table A-1: Operational fire models currently in use for wildland fire management in the United States that can be evaluated with FASMEE datasets (See Appendix H for acronyms). Platforms and decision support systems or other applications that house specific models are presented in the "Applications" column. Additional information on datasets can be found in Appendix D.

Model	Description	Applications	FASMEE datasets	Reference
BehavePlus	Primary modeling capabilities include surface fire spread and intensity, crown fire spread and intensity, safety zone size, size of point source fire, fire containment, spotting distance, crown scorch height, tree mortality, wind adjustment factors, and probability of ignition.	Desktop FFE-FVS Fire Family Plus IFTDSS module WFDSS module	Spread rate; Fire intensity	Andrews et al. (2005) https://www.firelab.org/project/behaveplus
Consume	Consume predicts consumption and emissions by combustion phase and fuelbed category. Consume imports data from the Fuel Characteristic Classification System (FCCS) and accommodates the complexity of fuelbed data entered in the FCCS.	Desktop BlueSky Fuel and Fire Tools IFTDSS	Consumption by category: flaming, smoldering and long-term smoldering combustion	Prichard et al. (2007)
DaySmoke	Smoke transport and dispersion model developed for prescribed burn planning in the southeastern United States.	Desktop	Plume rise; short-term smoke transport	Achtemeier et al. (2006) Liu et al. (2008)
FARSITE	The Fire Area Simulator (FARSITE) spatially and temporally simulates fire spread and behavior under heterogeneous conditions. Incorporates existing fire behavior models of surface fire spread, crown fire spread, spotting (Albini 1979), point source fire acceleration (Forestry Canada Fire Danger Group 1992), and fuel moisture (Nelson 2000).	Desktop WFDSS	Spread rate; Fire area & perimeter	Stratton (2006)
FireFamily Plus (FFP)	Fire climatology and occurrence program that summarizes and analyzes weather observations, associate weather with local fire occurrence data, and computes fire danger indices based on the National Fire Danger Rating System (NFDRS) and the Canadian Forest Fire Danger Rating System.	Desktop	Meteorological observations	Bradshaw and McCormick (2000)

Model	Description	Applications	FASMEE datasets	Reference
First Order Fire Effects Model (FOFEM)	Computer program for predicting tree mortality, fuel consumption, smoke production, and soil heating caused by prescribed fire or wildfire.	Desktop (v 6.3.1) IFTDSS module	Consumption by category; soil heating	https://www.firelab.org/project/fofem
Fire Simulation Model (FireSim) Fire Spread Probability (FSPro)	Geospatial probabilistic models that predicts fire growth, and are designed to support long-term decision-making (more than 5 days).	Desktop WFDSS module	Fire area; perimeter	http://wfdss.usgs.gov/wfdss/pdfs/FSPro.pdf
FlamMap	Fire behavior mapping and analysis program that computes potential fire behavior characteristics (spread rate, flame length, fireline intensity, etc.). Relies on the Rothermel spread model for surface fire behavior and Van Wagner crown fire equations.	Desktop IFTDSS module WFDSS module	Spread rate, fireline intensity	Finney (2006) Stratton (2006) Van Wagner (1977)
WindNinja	Computes spatially varying wind fields for wildland fire application.	WFDSS module	Gridded wind fields	Forthofer et al. (2014a,b)
HYSPLIT	Computes simple air parcel trajectories, as well as complex transport, dispersion, chemical transformation, and deposition simulations.	Web-based BlueSky module Many atmospheric modeling systems	Smoke dispersion	http://www.arl.noaa.gov/HYSPLIT_info.php Stein et al. (2015)
CALPUFF	Non-steady-state meteorological and air quality modeling system. The model has not been used to assess the long range transport of pollutants and their impacts.	Desktop	Meteorology observations; plume rise, smoke dispersion	http://www.src.com
CMAQ	Eulerian chemical transport model treating all emission sources, transport, chemical transformation, and deposition processes to estimate O_3, speciated $PM_{2.5}$, and toxics.	Multi-node unix-based computer system	Meteorology, plume rise, smoke dispersion, smoke chemistry	https://www.epa.gov/cmaq
VSmoke	Simple smoke dispersion model to estimate prescribed fire impacts	Web-based Desktop	Plume rise, smoke dispersion	http://weather.gfc.state.ga.us/GoogleVsmoke/vsmoke-Good2.html https://webcam.srs.fs.fed.us/tools/vsmoke/download.shtml

Table A-2: Coupled fire-atmosphere models and atmospheric models that can be evaluated with FASMEE datasets (See Appendix H for acronyms). Platforms and decision support systems or other applications that house specific models are presented in the "Applications" column. Additional information on datasets can be found in Appendix D.

Model	**Description**	**Applications**	**FASMEE datasets**	**References**
CAWFE	Coupled Atmosphere-Wildland Fire-Environment (CAWFE) is a coupled weather - wildland fire computational model developed at the National Center for Atmospheric Research with contributions from the U.S.D.A. Forest Service Missoula Fire Laboratory and U.S.D.A. Forest Service Riverside Fire Laboratory. The modeling system couples the Clark-Hall numerical weather prediction model with a wildland fire behavior model such that simulated atmospheric winds directed the speed and direction of the wildland fire, which burns through wildland fuels, releasing heat and water vapor that in turn alter the atmospheric winds in the vicinity of the fire, thus feeding back on the fire behavior.	NCAR Simulation model (Janice Coen)	Meteorological observations; gridded fire behavior observations; plume dynamics	Clark, T. L., Coen, J. L., Latham, D., 2004: Description of a coupled atmosphere-fire model. International Journal of Wildland Fire, 13, 49-63. http://www.openwfm.org/wiki/CAWFE
FIRETEC	HIGRAD/FIRETEC is a physics-based, 3-D computer code designed to simulate the constantly changing, interactive relationship between fire and its environment. It does so by representing the coupled interaction between fire, fuels, atmosphere, and topography on a landscape scale (100s or 1000s of meters). HIGRAD is a computational fluid-dynamics model that represents airflow and its adjustments to terrain, different types of fuel (vegetation), and the fire itself. FIRETEC combines physics models that represent combustion, heat transfer, aerodynamic drag and turbulence.	Simulation Model, Los Alamos National Laboratory STANDFIRE (under development)	Meteorological observations, gridded fire behavior and radiative energy observations, plume dynamics, fuel combustion	Linn et al. 2002, 2005 https://www.frames.gov/partner-sites/firetec/firetec-home/
MesoNH/ ForeFire	Mesoscale non-hydrostatic model that is multiscaled from large-scale synoptic to small scale (large eddy) atmospheric dynamics. Is coupled with a surface model (SURFEX) to represent surface atmospheric interaction in addition to chemistry and lighting modules. ForeFire is a tracer-based fire model. This modeling suite was developed by the French fire research community (Laboratoire d'Aérologie and CNRM).	Desktop (unix)	Meteorological observations, plume dynamics	Berger et al. 2016 http://mesonh.aero.obs-mip.fr/mesonh53

Model	Description	Applications	FASMEE datasets	References
Vesta	Large-scale, cell-based wildland fire simulator developed within the Fire Paradox project (European).	Desktop	Gridded fire behavior and fire radiative energy observations	http://www.mtda.fr/vesta
WFDS	An extension of NIST's structural Fire Dynamics Simulator (FDS) to fuels that include vegetation. WFDS uses computational fluid dynamics methods to solve the governing equations for buoyant flow, heat transfer, combustion, and the thermal degradation of vegetative fuels. The solution method makes use of large eddy simulation techniques to solve the gas-phase equations on computational grids that are too coarse to directly resolve the detailed physical phenomena.	Desktop (unix) STANDFIRE (under development)	Meteorological observations, gridded fire behavior and radiative energy observations, plume dynamics, fuel combustion	Mell 2007, 2009
WRF-SFIRE (Spread FIRE model)	Stand-alone spread fire model that uses the Weather Research and Forecasting (WRF) model to simulate and predict atmospheric dynamics and fire spread.	High performance computing cluster	Meteorological observations, gridded fire behavior observations, plume dynamics	Mandel et al 2011, 2014 http://www.openwfm.org/wiki/WRF-SFIRE

APPENDIX B: INTEGRATION WITH OTHER FIELD CAMPAIGNS

B.1 INTEGRATION WITH FIREX / FIRECHEM

The FASMEE science plan is developed in coordination with other smoke research investments within the U.S. federal government, in particular, 1) the NOAA Fire Influence on Regional and Global Environments Experiment (FIREX) campaign, and 2) NASA's FIREChem activity. These two programs along with the U.S. EPA Community Multiscale Air Quality (CMAQ) model development activities and a National Science Foundation project have developed explicit ties to FASMEE, which have been established through agency coordination calls during 2016 and in a statement of intent drawn up from these discussions: http://www.fasmee.net.

The FIREX campaign is an initiative aimed at improving the understanding of smoke chemistry. FIREX has multiple components, with the major field campaign involving the NOAA WP-3D aircraft to sample smoke opportunistically from western wildfires in the July-September 2019 timeframe during Phase 2. NASA's Tropospheric Chemistry Program is in the planning phase of a similar air campaign, FIREChem, which is designed to complement the FIREX and FASMEE efforts. During the 2019 FIREX campaign as part of the Western Wildfire Campaign, NASA has reserved its large platform DC8 aircraft for supplemental smoke chemistry measurements, as well as ground-based mobile laboratories using in situ sampling and remote sensing to measure upwind and downwind of natural and agricultural fires. The timing of FIREX and FIREChem airborne sampling overlaps with FASMEE for the 2019 fire season; thus, efforts are under way to work with these campaigns to leverage capabilities and collect datasets to fulfill the suite of project objectives from all three efforts.

An important distinguishing feature of FASMEE is the full characterization of not only smoke plume composition but also the characteristics that generate smoke (Figure B-1). FIREX/FIREChem are collecting data within their expertise focused on smoke chemistry and plume characteristics. To address key questions about the effect of North American wildland fires on air quality and climate, plume sampling integrated with ground-based source characterizations are needed to interpret FIREX/FIREChem data. By combining forces and using the strengths of each group, valuable measurement collections will be available to all activities and enhance the value of FASMEE for smoke model improvement.

To assist in the Phase 2 2019 Western Wildfire Campaign, FASMEE plans to develop approaches for advising FIREX/FIREChem on wildfires to sample and rapidly deploy teams to characterize the fire environment of fires flown by FIREX/FIREChem. FASMEE

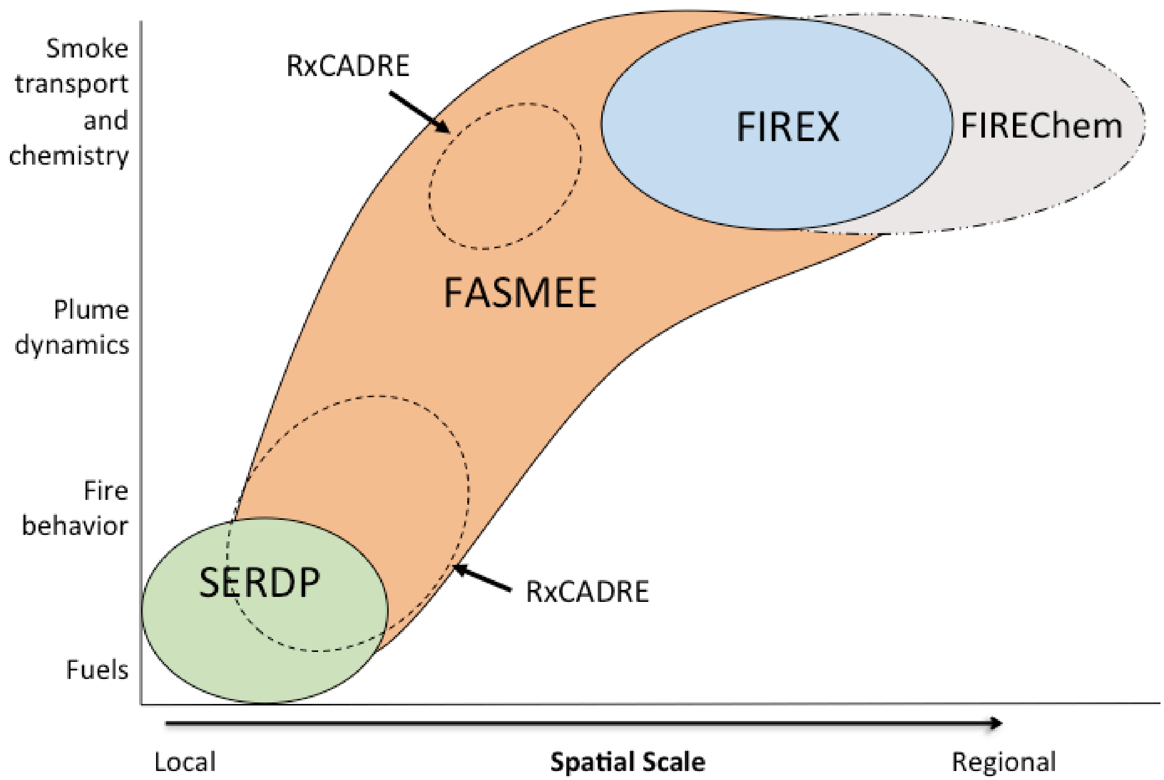

Figure B-1: Conceptual diagram showing the spatial scale (x-axis) and discipline focus (y-axis) of proposed fire and smoke field campaigns.

deployment to the 2019 FIREX/FIREChem-sampled wildfires will allow measurement crews to test approaches and evaluate protocols, making the main FASMEE experiments more valuable to all campaigns, thus enhancing the data available to achieve the goals of FASMEE, FIREX and FIREChem. FIREX/FIREChem airborne resources will be made available August 15-September 15 in 2019 to sample the planned FASMEE prescribed fires in the Southwestern Campaign. Additionally, the FIREX and FIREChem teams have expressed interest in assisting with airborne resources in 2021-2022 for the Southeastern Campaign. Appendix D outlines the rapid deployment opportunities for smoke characterization, using a combination of existing ground-based and remotely sensed datasets, on-site measurements, and modeling approaches. Appendix D also reviews the roles of FASMEE and FIREX/FIREChem at the FASMEE prescribed burn sites in the Southwestern Campaign in 2019 and 2021 (Fishlake/Kaibab) and Southeastern Campaign in 2021-2022 (Fort Stewart/Savannah River).

B.2 CROSS CONNECTIONS WITH FIRE BEHAVIOR FIELD CAMPAIGNS

The U.S. Department of Defense Strategic Environmental Research and Development Program and Environmental Security Technology Certification Programs (SERDP-ESTCP) have funded a number of projects on wildland fire behavior and smoke, guided by their Fire Science Strategy (Cohen et al. 2014). In 2009, SERDP invested in several projects to advance the science of emissions factors for inclusion in EPA AP-42 (https://www.serdp-estcp.org/Featured-Initiatives/Conservation/Fire/(list)/1/). One of those recently completed projects, Advanced Chemical Measurements of Smoke from DoD-Prescribed Burns, supported field-based and laboratory measurements of the chemical composition of smoke from prescribed burning in the southeastern United States and contributed to a database of wildland fire emissions factors (Johnson et al. 2014). The ESTCP technical committee on Resource Conservation and Resilience (formerly known as the Resource Conservation and Climate Change program area) oversee the execution of a project led by Mr. James Furman and Dr. Rod Linn to validate the numerical model FIRETEC against the RxCADRE dataset and demonstrate its value on prediction of fire-atmospheric feedbacks of aerial ignitions.

Recent SERDP investment has funded four projects to support advances in the fundamental science of wildland fire combustion. Collectively, PIs from these projects have been engaged for potential collaborations and applications of DoD funded research to the FASMEE project.

Ongoing laboratory and field-based studies of fine-scale combustion processes associated with vegetation types managed by DoD include:

1) Fundamental Measurements and Modeling of Prescribed Fire Behavior in the Naturally Heterogeneous Fuel Beds of Southern Pine Forests (Weise, RC-2640): The objective of the proposed work is to provide information about a) pyrolysis and pyrolysis products of live and dead fuels, and b) how these products are affected by heat transfer mechanisms from the flame to the shrub layer in fuel types typically burned with prescribed fire in southern forests managed by the DoD. Through measurement and modeling experiments, this project seeks to improve the application of prescribed fire to accomplish desired fire effects and limit potential escapes.

2) Multi-scale Analyses of Wildland Fire Combustion Processes in Open-canopied Forests using Coupled and Iteratively Informed Laboratory-, Field-, and Model-based Approaches (Skowronski RC-2641): This project uses a suite of measurements at the fuel particle, fuel bed, field plot, and stand scales to quantify how variability in fuel characteristics and key meteorological factors interact to drive fire behavior during low to high-intensity prescribed burns. Experiments are designed to inform the development and evaluation of

mechanistic, physics-based models that explicitly account for combustion, turbulent transfer, and energy exchange by coupling and scaling individual component processes. Outcomes from these experiments will improve the understanding of, and ability to accurately predict, fire behavior under a wide range of management scenarios.

3) Examination of Wildland Fire Spread at Small Scales Using Direct Numerical Simulations and Frequency Comb Laser Diagnostics (Hamlington, RC-2642): The primary objective of this project is to understand and characterize wildland fire spread at small scales (roughly 1 meter to 1 millimeter), using direct numerical simulations (DNS) with reduced chemical kinetics mechanisms that have been calibrated using data from frequency comb laser diagnostics. The simulations are the first of their kind in wildland fire research and will directly resolve fine-scale fluid dynamic and chemical processes relevant to wildland fire spread. The high fidelity of the simulations will be enabled by the calibration and validation of DNS sub-models using data from frequency comb laser diagnostics.

4) Improving Parameterization of Combustion Processes in Coupled Fire-Atmosphere Models through Infrared Remote Sensing (Goodrick, RC-2643): The overall goal of this project is to improve the representation of combustion processes in coupled fire-atmosphere models operating at the landscape level. Models intended to be used for landscape-scale fires (hundreds of meters to tens of kilometers) typically divide the simulation domain into a mesh of grid cells, which typically range in size from 1 to 30 meters on a side. Because the processes governing combustion occur on considerably smaller scales, models require a means of describing these processes capable of dealing with heterogeneity within a cell and must be scalable if the cell size is changed. A detailed examination of these combustion processes will improve our understanding of fine-fuel heat exchange, ignition, and fire spread and how fuel conditions may affect fire behavior.

5) Ignition, Propagation, and emissions of Smoldering Combustion: Experimental Analysis and Physics Based Modeling (Blunck, RC2651). Managing the impacts of smoldering combustion and the resulting smoldering emissions during wildland fire is critical to managing military lands and supporting the Department of Defense (DoD) mission. A coupled approach with laboratory, field, and computational studies will be used to determine the dominant processes that control ignition, propagation, and emissions of smoldering combustion. This project will enable the development of modeling tools that can be used for military fire management for a variety of fuel types and conditions.

B.3 RELATIONSHIP WITH PAST EXPERIMENTS – LESSONS LEARNED

As wildland fire, smoke dispersion, atmospheric chemistry, and global climate models have become more sophisticated, the need has been growing need complex datasets that are coordinated and comprehensive, from ground-based observations of fuels and fire behavior, to near-source plume dynamics and emissions, to smoke trajectories, dispersion and atmospheric chemistry. Since the 1990s, a range of field-based experiments have been conducted across major biomes and regions of the globe to study wildland fire behavior, fire-atmosphere interactions, including plume dynamics, and smoke dispersion. The FASMEE Phase 1 team is synthesizing these studies and will publish a background paper on past studies and legacy datasets that ongoing FASMEE work will augment.

One of the earliest integrated fire-atmosphere observational campaigns was the International Crown Fire Modeling Experiment (ICFME), initiated to evaluate fire propagation and spread in boreal landscapes and the role of boreal wildfires in ecosystem function and global climate change (Alexander et al. 1998; Stocks et al. 2004). The ICFME field campaign began in 1993 with the Bor Forest Island Fire Experiment, a 49-ha fire in an island of mature Scots pine in north-central Siberia (FIRESCAN Science Team 1996). This experiment studied fire behavior in a high-intensity, stand-replacement fire in addition to fire meteorology, trace gas and aerosol emissions, and long-term fire effects and recovery. From 1997 to 2000, 18 burns were conducted at an ICFME site in the Fort Providence area of the Northwest Territories of Canada (Stocks et al. 2004). Observations were collected by over 100 collaborators and included measurements of radiant emissive power, wind and temperature fields, crown fire behavior, black carbon, fuel consumption, trace gas and aerosol formation, and firefighting and structure protection strategies in boreal wildfires. Results of the ICFME were published in a special issue of the *Canadian Journal of Forest Research* with an overview by Stocks et al. (2004). In July 1999, the project FROSTFIRE conducted an 809-ha experimental burn in mixed spruce and hardwood boreal forests near Fairbanks, Alaska (Hinzman et al. 2002). Over 50 research teams conducted integrated sampling and measured fire behavior, fire effects, energy fluxes and trace gas emissions. Datasets from the ICFME are still used today and highlight the importance of these integrated experiments and the legacies of the studies for model development and validation.

In a project on sub-canopy transport and dispersion of smoke, five experimental units were burned as low-intensity surface fires in mature longleaf pine stands in the southeastern United States (Calloway Forest/Sandhills Preserve, North Carolina). This study evaluated sub-canopy emissions and smoke dispersion from low-intensity prescribed burns which are common in the southeastern US, and the results collectively contribute to regional air quality issues (Strand et al. 2013). Observations included pre-fire fuels, consumption and emissions, plume rise and dispersion and were used to evaluate predicted smoke dispersion in the BlueSky Framework (Larkin 2010).

The Prescribed Fire Combustion and Atmospheric Dynamics Research Experiment (RxCADRE) field campaign was recently completed in the southeastern US (Ottmar et al. 2016). The project was inspired by a series of meetings held by the Core Fire Science

Caucus. This was a group of 30 fire scientists who identified critical fire research needs and agreed to support integrated, multi-scale observations of fire and smoke. From 2008 to 2012, RxCADRE conducted several experimental prescribed burns to collect coordinated, multi-scaled observations of fuels, meteorology, fire behavior, radiative power and energy, emissions and fire effects. Burn sites in grassland, grass-shrub, and managed forests of the southeastern US were selected because of the frequent use of prescribed burning in the region, which not only made the project areas highly relevant but also ensured that prescribed burns would be frequent enough to support the experiments. Interdisciplinary scientists collected observations before, during, and after each burn, with the goal of obtaining co-located measurements that could support multiple fire-related disciplines. Measurements and preliminary results were published in a special issue of the *International Journal of Wildland Fire*, and data were made available on a globally accessible archive maintained by the US Department of Agriculture, Forest Service (http://www.fs.usda.gov/rds/archive). Building on the success and lessons learned from RxCADRE, the FASMEE campaign was launched to provide integrated measurements of higher-intensity fire behavior and smoke.

In conclusion, the past two decades have brought enormous advances in not only our understanding of fire and smoke dynamics but also our ability to observe and model fuel consumption, fire behavior, plume development, smoke production and dispersion. Operationally, adoption of fire and smoke models has been rapid. Advanced model output is now routinely available to managers; examples include the incorporation of fire models and the adoption of BlueSky-based smoke impact model runs within the Wildland Fire Decision Support System (WFDSS) and the Interagency Fuel Treatment Decision Support System (IFTDSS, currently under development). Although these systems provide value-added information, they are also relatively simplistic in their treatment of complex fire dynamics and therefore have issues in how well they can perform. More complex models, such as coupled fire-atmosphere-chemistry models (e.g., WRF-SFIRE-CHEM, WFDS and FIRETEC), are in testing. The advances to date offer the promise of capturing the underlying dynamics of fire-atmosphere interactions, but they also require greater input data. Unfortunately, a lack of observational data means substantial uncertainty about exactly what the underlying dynamics are, and how well such systems can represent them. FASMEE is designed to facilitate the transition of advanced modeling systems into operational use by supplying critical data necessary to facilitate improvements, testing and adoption.

APPENDIX C: SIMULATION RUNS TO IDENTIFY MODELING NEEDS

A subset of both currently operational and research-level models were selected to be used in Phase 1 to identify research gaps and measurement needs for evaluating and advancing fire and smoke modeling capacity. Appendix A gives an overview of both types of models relevant to FASMEE, whereas this appendix reviews the model simulations used in identifying the needs for improving fire and smoke models for operational and research use. Data collected in Phase 2 is anticipated to have value for evaluating and validating the full suite of models reviewed in Appendix A.

C.1 OVERVIEW

Since the 1990s, a wide array of tools has been developed to model fuels, fuel consumption, fire behavior and smoke that meet the needs of operational smoke management. Many sources of smoke information are now available to managers, both on the web and as downloadable models and datasets (Strand et al. 2013). Operational systems such as the FCCS, CONSUME, FOFEM, Behave, and FlamMap are available to assess fuels, fuel consumption, fire behavior and energy release, important requirements for driving smoke models. These tools have been developed through simple physics and empirical derived equations that have not been fully evaluated because of the lack of a validation data set. Simple smoke tools (e.g., Simple Smoke Screening Tool, Florida Smoke Screening Tool, VSMOKE-GIS) provide information based on assumed or predicted wind directions. Ventilation indices provide a measurement of the atmosphere’s ability to transport smoke away from the source. Web-based systems (e.g., AirNowTech Navigator, BlueSky Playground, HYSPLIT-Ready) provide access to on-demand, customized trajectories and dispersion modeling. Real-time smoke forecasts are also available from sources such as the National Weather Service, BlueSky-daily runs, and regional modeling centers. Daily atmospheric chemistry modeling that includes smoke is also available from various sources (e.g., AIRPACT, GEOS-CHEM).

Within these systems, methodology is not standardized for either modeling the smoke emissions or their atmospheric chemistry, although several systems use similar methodologies or frameworks (e.g., BlueSky). Many models and datasets exist that cover the modeling steps required for a smoke modeling system. An example is in Figure C-1, which shows the current models and datasets included in the BlueSky Framework (other models exist such as fire behavior models that are important but have not been incorporated into this framework to date).

Recent research further supports the physical description inadequacies of transport and dispersion in operational plume-rise models and smoke transport models (Val Martin et al. 2012, Goodrick et al. 2012). A primary issue is that assumptions have to be made about fire size and heat release, along with the use of simple plume-rise algorithms or some other height representation. There is also a lack of understanding of spatial and temporal variability of fire heat release in relation to plume rise and smoke emissions.

Critically important in any system for modeling smoke are the sources of fire information and meteorological data. Although smoke modeling systems now used in management rely on systems that sequentially step through a modeling chain, recent advances have resulted in a number of coupled fire behavior-atmospheric models, where smoke emissions can influence atmospheric development through physics and chemistry coupling. These models are categorized as atmospheric-weighted (emphasizing atmospheric coupling to fire), and fire physics-weighted (emphasizing fire physics coupling). WRF-SFIRE (CHEM) (Mandel et al. 2011) is an atmospheric-weighted model that has been used for research, but it also has a short-term potential of becoming real-time in an operational fire management setting. Two fire-physics weighted models, FIRETEC (Linn et al. 2002) and WFDS (Mell et al. 2007), are much more computationally intensive and are used in a research mode. Because all three of these models have atmosphere-fire coupling, they have high utility for evaluating the models' ability to predict fire growth, fuel consumption, and plume structure. Other smoke and chemistry models are used both operationally and for research. In particular, three other models, Daysmoke, PB-P, and CMAQ, provide valuable smoke management

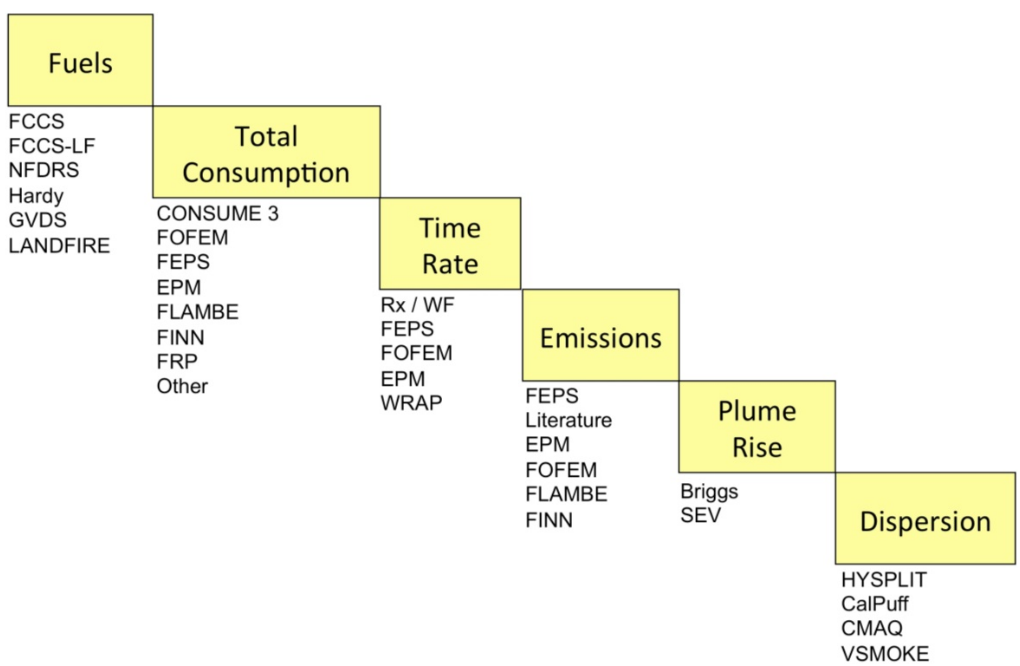

Figure C-1: Models in BlueSky framework v3.5.1. (From Larkin et al. 2013).

outputs assisting managers to make a variety of management decisions on smoke dispersion, transport, and primary and secondary pollutant impacts.

Models used in Phase 1 to identify operational needs through simulation assessments are summarized in Tables C1-C3, followed by details from each of the models described below. These models have identified needs that are relevant for these models as well as the suite of models identified in Appendix A.

Table C-1: Major model properties.

Model	Capacity	Scale
WRF-SFIRE	Level set fireline; Atmospheric physics and chemistry, smoke transport and gaseous products; WRF's nesting	Regional and local; Domain of km or larger; Fire mesh of tens of m.
WFDS and FIRETEC	Emphasis on capturing fire behavior; Relatively near-field smoke plume rise and downwind transport; Simple atmospheric physics included	Local; Domain of about 1 km, larger for WFDS-LS; Grid of m, WFDS-LS, FIRETEC; cm ~m, WFDS-PB
Daysmoke and PB-P	Developed specially for Rx burning smoke; Computationally fast with simple physics; Topography-air interaction for night smoke (PB-P)	Local; Domain of 5 km (Daysmoke) and 1 km (PB-P); Grid cell of 100 m and 20 m.
CMAQ-BlueSky	3D Eulerian photochemical transport; Gas, aerosol, and aqueous phase chemistry; Focus on air quality (especially particulates and ozone)	Regional; Domain up to 1000s of km; Grid cell of 4-12 km (1 km for some fine scale applications)

Table C-2: Modeling issues and gaps.

Issue	Gap
Heat release	Need measurements of heat release along the fire perimeter; Improve vertical distribution of radioactive and convective heat near the fire; Understand the relations between heat structure and multiple plume updrafts.
Fire spread	Parameterization of lateral fire progression may underestimate the lateral fire spread and burnt area.
Plume vertical distribution	Plume rise is provided with large uncertainty; Vertical profiles are mostly specified.
Multiple plume updrafts	No routine measurements are available; Some modeling tools are in early development stage; Parameterization schemes are required.
Smoldering and night smoke	Bulk emission factors not dependent on the burning stage; Nighttime smoke drainage modeling has many assumptions; Not evaluated for burned sites with complex topography.
Pollutants with space and time	Lack in near-event and downwind measurements of O_3, $PM_{2.5}$, their precursors and important chemical intermediate species.
PM and gas speciation	PM, VOC, and nitrogen gas speciation not well understood for different fuel types and combustion conditions.
Fire-atmosphere interactions	Need measurements of all at commensurate spatial and temporal scales to predict and validate effects of vegetation and wind on fire behavior; Effectively represent plume across the scales and fire behavior between fire and atmospheric models.
Smoke-air interactions	Improve entrainment estimates; Better characterize smoke optical properties; Understand effects of pyro cumulus on vertical smoke distribution and fire behavior.

Table C-3: Priority measurement needs.

Field	Property	Parameter	Purpose
Fuels and consumption	Fuel conditions	Type, load, density, 3-D structure, above and under ground	Inputs of fire behavior modeling
Fuels and consumption	Fuel moisture	1, 10, 100, 1000 hr; Live fuel moisture	Inputs of fire and smoke modeling
Fuels and consumption	Consumption	Rate, amount, smoldering/flaming stage,	Estimate fire emissions
Fuels and consumption	Burn block	Latitude/longitude, elevation, slope	Model inputs
Fire behavior and energy	Ignition	Pattern, start time, duration, time and space dependence; Burned area	Inputs of fire behavior and smoke modeling
Fire behavior and energy	Fire spread	Fireline location, shape, depth, time and space evolution; Lateral fire progression	Evaluation of fire behavior modeling; Improving fire-vegetation-air interaction
Fire behavior and energy	Radiation and heat	Spatial distribution and temporal variation; Time dependent location of plume envelope to the downwind distance of neutral buoyancy	Fire model evaluation; smoke model inputs; Improve / develop parameterizations of the fire-induced heat flux and multiple core number
Meteorology and smoke	Fluxes and turbulence	Fire exit vertical velocity and temperature; Sensible, latent and radiative heat fluxes; Atmospheric turbulence; PBL height	Evaluate fire models; Inputs and evaluation of smoke modeling; Assess and improve fire-air interaction modeling
Meteorology and smoke	Weather	3D temperature, winds, moisture, and pressure	Inputs of fire and smoke modeling
Meteorology and smoke	Plume structure	Vertical profile and rise; Multiple updraft plume number, location, time change, merging process	Model validation and improvement of fire gas and aerosol chemical evolution in local and remote areas
Meteorology and smoke	Smoke-air interactions	Entrainment rate; Pyro-cumulus	Inputs of smoke modeling; Improve smoke-air interaction modeling
Emissions and chemistry	Plume O_3 and PM chemical evolution	Speciated and size resolved PM, particle number and diameter and polarity; SO_2, NH_3, CH_4, VOC speciation; Oxidized nitrogen gases, photolysis rates	Smoke modeling evaluation; Understand factors and dynamics of multiple smoke plumes and develop model parameterization
Emissions and chemistry	Lofted smoke emissions	PM, O_3, CO, CO_2, CH_4, VOC speciation (incl. carbonyls); CH_3CN, nitrogen gases	Validate and improve fire emissions estimates; O_3 and $PM_{2.5}$ chemistry
Emissions and chemistry	Smoldering emissions	PM near-fire and downwind; Smoke drainage; super-fog	Inputs and evaluation of smoke modeling; Night smoke modeling
Emissions and chemistry	Plume optical properties	Light scattering/absorption of plume constituents; Cloud and ice condensation nuclei; Solar radiation, jNO_2 photolysis	Better representation of the radiative impacts of smoke

C.2 WRF-SFIRE-CHEM

WRF-SFIRE (Mandel et al. 2011, 2014a) is a coupled fire-atmosphere model based on the Weather Research and Forecasting model (WRF; Skamarock et al.2008) and the Rothermel (1972) fire-spread model implemented using a level set method to evolve the fire front on a Eulerian grid in time (e.g., Mallet et al. 2009). The fuel and topographical data are defined on a high-resolution surface fire mesh (typically ~30m for WRF grids ~300m) used for fire spread computations. Fire-emitted heat and moisture fluxes computed at the fire mesh are integrated into WRF's coarser atmospheric mesh. The fluxes affect the atmospheric state, changing local winds that drive fire propagation (Mandel et al. 2011). WRF-SFIRE is also coupled with a prognostic fuel moisture model, which assesses the moisture of 1h, 10h, 100h, and 1000h fuels, based on local WRF meteorology (air humidity, temperature, and precipitation; Mandel et al. 2012), and it assimilates fuel moisture observations from RAWS (Vejmelka et al. 2014, 2016). WRF-SFIRE is designed to simulate the landscape-scale physics of the coupled fire-atmosphere phenomenon, and focuses on the importance of rapidly changing meteorological conditions at the fireline, taking into account local feedbacks between the fire, fuel, terrain and the evolving atmospheric boundary layer. WRF-SFIRE can be driven by operational numerical weather prediction products like HRRR (High Resolution Rapid Refresh), as well as satellite fire detections (Mandel et al. 2014b). WRF-SFIRE can generate downscaled weather forecasts at a resolution of couple hundred of meters, resolving small scale interactions between, for example, thunderstorm outflow, terrain, and fire. WRF-SFIRE is capable of simulating large-scale, high-intensity fires under various topographical, meteorological, and vegetation conditions (Kochanski et al. 2013b). It has been evaluated in both a research mode (i.e., with 20 m WRF horizontal grids) using FireFlux data (Kochanski et al. 2013a) and a forecasting mode at sub-kilometer horizontal grid resolutions (Kochanski et al. 2013b, Kochanski et al. 2015). Through two-way coupling, WRF-SFIRE resolves basic fire-atmosphere feedbacks, pyro-convection, and plume rise without relying on an external plume parameterization.

WRF-SFIRE was recently coupled (Kochanski et al. 2015) with WRF-CHEM (Grell et al. 2011) so that fire progression is simulated along with fire emissions and chemistry. Smoke emissions are represented as a sum of fluxes of WRF-CHEM-compatible chemical species and ingested into the lowest WRF model layer in each WRF time step. Combustion rates are computed based on the mass of fuel consumed within each fire-grid cell. Emission fluxes are computed as the products of the combustion rates and fuel-specific emission factors. Smoke emissions are transported and undergo chemical transformations in the atmosphere and interact with atmospheric radiation and microphysics, modeled by WRF-CHEM. The coupled system supports existing chemical (MOZART or RADM2) and aerosol (GOCART) mechanisms.

C.2.1 Needed WRF-SFIRE-CHEM Measurements

The following measurements are needed for the WRF-SFIRE-CHEM model evaluation:

1. Fuel

    1.1. Basic fuel properties: Characterization of the fuel parameters, such as fuel bed category, fuel load, fuel depth, and fuel moisture, is crucial for accurate assessment of the fire behavior models. Without an accurate fuel description, fire spread components of coupled fire-atmosphere models are impossible to validate, which ultimately affect plume rise and smoke emissions.

    1.2. Fuel consumption: The actual fuel consumption derived from pre- and post- fire fuel load is needed to evaluate whether the emissions factors used in the model adequately represent fluxes of pollutants and to validate the combustion rate and heat release over time against the total heat release.

    1.3. Spatial fuel heterogeneity: Fire progression and spatial distribution of smoke emissions in coupled fire-atmosphere models are affected by interactions between fuel heterogeneity and the near-fire flow pattern. Therefore, spatial fuel characterization and its heterogeneity is one of the key components needed for model validation.

2. Fire Behavior and Heat Release

    2.1. Estimation of the fire heat release: The amount of heat released from the fire and its geometry are key elements affecting the model's ability to realistically render plume development. High-resolution observations of fireline progression and fire heat fluxes are needed to assess how well coupled fire-atmosphere models resolve fire as a heat source driving pyroconvection.

    2.2. Representation of the heat transport from fire to atmosphere: Surface heat is vertically distributed over the first few atmospheric model layers to approximate the exponential decay of radiative heating and to account for unresolved vertical mixing very close to the surface. Measurements of the heat transport are needed to assess whether this parameterization can realistically render the actual vertical heat transfer and how the vertical decay scale depends on fire intensity.

3. Lateral fire progression

    3.1. Fire progression is a sub-grid scale process, parameterized using the Rothermel formula for head-fire ROS (rate of spread). For winds at an angle to the fire flanks, propagation is computed using the wind speed component normal to the fireline, which may underestimate the lateral fire spread and burned area. Accurate assessment of flank propagation, and the interactions between the local turbulence and flank progression, are important, because flanks contribute to smoke and heat emissions and change the overall flow pattern near the fire. Both a steady fire progression from a simple ignition procedure and frequent measurements of the fire location, rates of spread, and heat fluxes are needed to gain information on the lateral fire rate of spread.

4. Plume development and meteorology

4.1. Representations of local flow and fire-atmosphere feedbacks: Fire spread is computed based on coupled atmosphere-fire winds interacting directly with the fire front. Therefore, the model's ability to resolve the near-fire flow is crucial from the standpoint of fire progression, heat release, and plume development. In situ observations of near-fire wind, temperature, and heat and moisture fluxes at multiple levels, are needed to assess the model's capability to realistically represent the fire-atmosphere coupling.

4.2. Effect of turbulence on pyroconvective updrafts: Plume dynamics and rise are affected by entrainment of colder, drier ambient air into the convective column. Therefore, the model's ability to resolve turbulent mixing near the plume edge as it rises is crucial to realistically represent plume evolution, and it should be assessed based on measurements of turbulent fluxes of heat and momentum, as well as ambient meteorological conditions which define properties of the air being entrained into the smoke column.

4.3. Importance of model resolution relative to fire size: A refined surface grid is used to compute fireline progression, fuel consumption, and fire heat and moisture fluxes, while pyroconvection is simulated on a coarser atmospheric WRF mesh. Doppler LiDAR scans through the plume are needed to assess how the model resolves pyroconvection changes when the burning area becomes small relative to the size of the atmospheric grid cell and the fire surface heat fluxes become poorly resolved.

4.4. Generation of pyrocumulus clouds: Formation of pyrocumulus clouds has important implications for high-altitude smoke injection. Coupling smoke aerosols and microphysics in WRF-SFIRE-CHEM based on the GOCART aerosol scheme could enable simulation of this process. However, observational data are needed to validate this capability.

5. Smoke and chemistry

5.1. WRF-SFIRE-CHEM's smoke dispersion: Vertical distribution of fire emissions is critical for estimating smoke transport and dispersion. Recent plume rise simulations showed good agreement between satellite-observed and model-simulated maximum plume heights. However, because of the lack of in situ measurements, simulated vertical emission profiles have not been validated.

5.2. WRF-SFIRE-CHEM's representation of fire emissions: The model currently uses bulk emission factors that do not depend on the burning stage. A needed assessment is how modeled emissions can be improved by modeling both flaming and smoldering stages and applying different emission factors in each.

5.3. WRF-SFIRE-CHEM's smoke chemistry: WRF-SFIRE-CHEM simulations showed that simulated ozone concentrations downwind of the fire were significantly underestimated compared to observations. A better understanding of the interplay among fire emissions, plume transport, dispersion, and chemistry in the context of simulating air quality impacts of wildland fires is needed. Measurements of the major components of smoke will be helpful in this effort.

5.4. WRF-SFIRE-CHEM's radiative effects of smoke aerosols: Recent observations (Lareau & Clements 2015) suggest that smoke particles may induce significant cooling, leading to formation of density currents associated with smoke transport confined to a shallow (2-km deep) layer near the ground. WRF-SFIRE-CHEM has the required modeling capabilities in principle, but it needs an integrated dataset for evaluation.

C.3 FIRETEC AND WFDS

Both FIRETEC and the physics-based component of WFDS (WFDS-PB) use a finite-volume, large eddy simulation (LES) approach to model turbulence, where large-scale eddies are explicitly resolved in numerical grids and small eddies are simulated with sub-grid scale models. The vegetation-fuel complexes in both of these models are described as a highly porous medium within the 3D numerical grids and are characterized by mean or bulk quantities (e.g., surface area to volume ratio, moisture content, bulk density) of the thermally thin vegetation components of the overall fuel complex. Because FIRETEC and WFDS were primarily developed to predict the evolution of the flaming front, they require the spatial and thermo-physical characteristics of the thermally thin component of the vegetative fuel; non-thermally thin fuels are assumed to not significantly contribute to the flaming front.

Although FIRETEC and WFDS have similar capabilities, they differ in their solution techniques and parameterizations. An overview of the differences between the models is given in Hoffman et al. (2016). Morvan (2011) also discussed FIRETEC and WFDS, as well as other physics-based fire behavior models. For details regarding FIRETEC, see Linn et al. (2002, 2005) and Pimont et al. (2011); for WFDS, see Mell et al. (2007, 2009) and Mueller et al. (2014).

Because both FIRETEC and the WFDS-PB explicitly model the aspects of the combustion processes they need, for a given fire, they utilize much finer computational grids (i.e., smaller grid cells) compared to WRF-SFIRE or Daysmoke. As a result, FIRETEC and WFDS-PB are computationally more expensive than these other models. It is especially challenging to simulate small fires (i.e., fires with a small fire depth) in large domains. This is the case for burns that encompass larger areas (multiple km on a side), and especially those on larger areas but have low-intensity fires with shallow firelines and short flame lengths, which are characteristic of prescribed burns.

The WFDS model can also be implemented using a level set method to propagate the fireline; this implementation is called WFDS-LS (Bova et al., 2016). The method for handling the fireline propagation and heat input into the atmosphere is similar to what is done in WRF-SFIRE, although WFDS-LS lacks many of the models for atmospheric physics (such as water condensation) present in WRF-SFIRE.

The domain-size constraint discussed for FIRETEC and WFDS-PB is weakened, to some degree, if the physical processes governing fire spread (e.g., vegetation degradation and gas-phase combustion) are not explicitly modeled, and if the moving fireline is replaced by prescribed static or dynamic heat sources (or “burners”; see Appendix E6.1) derived from measurements (e.g., overhead IR imagery and estimates of fuel consumption rates). Using this approach, only the hydrodynamic portion of each model would be implemented to capture the buoyancy induced plume rise.

C.3.1 Measurements Needed for FIRETEC and WFDS

The measurement needs of WFDS-LS, which has a simple fire front propagation model, are very similar to WRF-SFIRE and thus are not listed here. Below are additional modeling needs for FIRETEC and WFDS.

1. Ignition Procedure

    1.1. Timing and location of ignition source: Required measurements are 1) the location on the ground of ignition sources (“ping pong balls” or other sources), 2) the time these sources were placed on the ground, and 3) the time needed for an ignition to grow to a fire of the same size and intensity as the measurement resolution (e.g., thermal energy). If these quantities cannot be determined, then some estimate of them will be needed, which will require exploration of the sensitivities to such estimates. This information will help both to implement the burner method and to initialize models that simulate the spread of the fireline.

2. Fuel

    2.1. Basic fuel properties: Implementing the burner method requires fuel properties that support the calculation of the rate of fuel vapor (fuel consumption rate) and the location of flaming combustion from overhead imagery. Char fraction and moisture fraction need to be measured. These may depend on fuel type.

    2.2. Fuel consumption: The rates at which fuel mass is consumed is a critical measurement for implementing the burner method because it is directly related to the heat release rate and moisture vapor creation. The rate of fuel consumption needs to be correlated with overhead imagery of the fireline.

    2.3. Spatial fuel heterogeneity: Ideally, the rate of fuel-mass consumption will be robustly related to the overhead imagery of the fireline. If this is the case, then the influence of spatial heterogeneity in the vegetation will be accounted for implicitly. However, measures of spatial heterogeneity in the vegetation may be required to develop the relationship between overhead imagery and rate of fuel-mass consumption. This measure may be relevant if the spatial heterogeneity of the fuel occurs on the scale of the overhead imagery pixels. Estimates are probably also necessary for the three-dimensional fuel structure and nominal heterogeneity of the pre-fire stand. Some estimate is also needed of the stand structure that remains after the fireline passes, because this estimate determines the drag and thus could affect the indrafts and plume velocities near the ground, especially for lower-intensity fires.

3. Fire Behavior and Heat Release

    3.1. Estimation of the fire heat release: The fundamental quantity needed to implement the burner method is the time-dependent and spatially-explicit heat release rate per unit area throughout the burning domain.

    3.2. Representation of the heat transport from fire to atmosphere: The need for this measure is similar to that for WRF-SFIRE. Measures of heat transport with a vertical component would help to evaluate and improve the model. Estimates are needed of the fraction of the heat release that is transported by radiation and the fraction of the energy that is absorbed by the gas phase and convected upwards.

4. Plume development and meteorology

    4.1. Representations of local flow and fire-atmosphere feedbacks: This measurement is needed for the same reasons listed in the WRF-SFIRE model needs.

    4.2. Impact of turbulence on pyro convective updrafts: Needed for the same reasons listed in the WRF-SFIRE model needs.

4.3. Importance of model resolution relative to fire size: Needed for the same reasons listed in the WRF-SFIRE model needs.

4.4. Atmospheric boundary conditions: These needs are the same as those for WRF-SFIRE. These boundary conditions can also be obtained from WRF simulations.

C.4 DAYSMOKE AND PB-PIEDMONT

Daysmoke (Achtemeier, 1998; Achtemeier et al., 2011; Goodrick et al., 2012) is a local smoke plume dispersion and transport model for simulating three–dimensional distributions and temporal variations of smoke particles with three unique features. 1) Daysmoke was developed specifically for prescribed burning (Rx burning) and has been extensively applied and evaluated in simulating smoke dispersion from prescribed fires in the Southeast (Liu et al., 2009). 2) Daysmoke has relatively simple physics and no chemistry and thus needs much fewer computational resources than complex and interactive dynamical smoke models. 3) Daysmoke includes algorithms to simulate the role of some special smoke properties and processes such as plume cores.

Daysmoke consists of four sub-models: an entraining turret model, a detraining particle model, a large eddy parameterization for the mixed boundary layer, and a relative emissions model that describes the emission history of the prescribed burn. The entraining turret model handles the convective lift phase of plume development and represents the updraft within a buoyant plume. This updraft is not constrained to remain within the mixed layer. A burn in Daysmoke may have multiple, simultaneous updrafts cores. Compared to single-core updrafts, multiple-core updrafts have smaller updraft velocities, are smaller in diameter, are more affected by entrainment, and are therefore less efficient in the vertical transport of smoke. The number of updraft cores is a critical factor for describing plume rise (Liu et al., 2010).

PB-Piedmont (PB-P; Achtemeier, 2005) is a very high-resolution meteorological and smoke model designed for simulating near-ground smoke transport at night over complex terrain. PB-Piedmont runs at resolutions on the order of 30-90 meters to capture terrain features driving the development of local drainage flows. As with Daysmoke, PB-Piedmont is a Lagrangian particle model specifically designed for fire applications with a focus on operating in data-poor environments, using just a handful of weather stations and a single sounding location.

C.4.1 Needed Daysmoke and PB-Piedmont Measurements

All measurement parameters needed for Daysmoke and PB-P models are the same as for WRF-SFIRE, but include these additional measurements:

1. Detailed tracks of ignition if aerial ignition is used. This measure is used to initialize the Rabbit Rules model (RRM) to produce multiple core number.

2. Multiple fire cells and smoke plume cores, including number, location, and size, and their variations with time. This measure is used to run Daysmoke using the burner method and evaluate the RRM simulation results.

3. Nighttime smoke movement, including emissions from smoldering stage, smoke drainage and fog formation, local wind, temperature, humidity, and air pressure. This measure is used to run and evaluate PB-P modeling.

C.5 COMMUNITY MULTISCALE AIR QUALITY (CMAQ) MODEL

CMAQ is an Eulerian model that contains a comprehensive and state-of-the-science treatment of important gas (Sarwar et al., 2011), aqueous (Sarwar et al., 2013), and aerosol phase chemistry. Aerosol treatment includes an inorganic thermodynamic model (Fountoukis and Nenes, 2007), secondary organic aerosol production from precursor yields and subsequent partitioning between gas and aerosol phase and representation of oligimerization processes (Carlton et al., 2010). CMAQ also includes an option to treat organic aerosol with the volatility basis set (Koo et al., 2014), which provides a unique opportunity to estimate fire event $PM_{2.5}$ organic aerosol using two approaches. CMAQ attenuates photolysis rates based on black carbon and dust, but it does not have a robust implementation of attenuation for brown carbon because of uncertainty in optical properties of brown carbon. The Weather Research and Forecasting (WRF) model (http://www.wrf-model.org/) (Skamarock et al., 2008) is applied to generate the necessary meteorology used as input to the Sparse Matrix Operator Kernel Emissions (SMOKE) model (https://www.cmascenter.org/smoke/). The SMOKE model uses wildland fire emissions generated using the Satellite Mapping Automated Reanalysis Tool for Fire Incident Reconciliation (SmartFire2)–BlueSky framework provided by the U.S. Forest Service (http://www.airfire.org/bluesky/).

This modeling system has been applied at local (~1-4-km sized grid cells) to continental (12-km sized grid cells) scale and evaluated extensively against measurements from multiple field campaigns at these scales for O_3, $PM_{2.5}$, key precursors, and meteorological conditions (Baker et al., 2016; Baker et al., 2015; Baker et al., 2013; Kelly et al., 2014). These models are extensively used for retrospective modeling assessments and for operational forecasting by many government agencies (e.g., NOAA; http://airquality.weather.gov), academic institutions, and consulting companies. This modeling system has been used to assess near-field and regional scale reactive pollutant impacts from specific wildland fire events (Baker et al., 2016; Kansas Department of Health and Environment, 2012) and wildland fire impacts in aggregate (Fann et al., 2013).

Wildland fire emissions are currently based on fire location information from the SmartFire2 system (http://www.airfire.org/smartfire/), which relies on default national activity information, such as NOAA's HMS satellite product and, optionally, local activity data. Detailed information about how the EPA develops wildland fire inventories is described in the 2011 NEI Technical Support Document (U.S. Environmental Protection Agency, 2014). The 2011 and 2014 inventories distinguish between prescribed, wild, and agricultural fire types based on satellite detection information. The BlueSky fire emissions modeling framework used here includes Fuels Characterization Classification System (FCCS) version 2 fuel loading model (Ottmar et al. 2007), CONSUME version 5 fuel consumption model (Prichard et al. 2007), and Fire Emission Production Simulator (FEPS) version 2 emission factors (Anderson et al. 2004). The SMOKE emissions model is used to convert daily fire emissions information from fire events to hour of the day, and provide more detailed VOC, NO_X, and primary $PM_{2.5}$ speciation. Smoke plume rise algorithms use heat flux estimates to vertically allocate smoldering and flaming emissions into the 3D grid structure of CMAQ. The key inputs for generating fire emissions are location of the fire (to determine vegetation type), area burned, and wild/prescribed classification.

C.5.1 Needed CMAQ Measurements

The following measurements are needed for the CMAQ model evaluation:

1. Fire location, area burned, fuel type, fuel moisture, and fuel consumption will help evaluate existing approaches for estimating these parameters.

2. Fire emissions of speciated PM2.5, precursors to secondarily formed PM2.5, and precursors to O_3 formation are needed by fuel type and combustion component (flaming to smoldering) to improve estimates of chemically speciated PM2.5 and O_3 impacts from wildland fires.

3. Near-event and downwind measurements of O_3, $PM_{2.5}$, their precursors and important intermediate chemical species, along with distance and time from the fire event, will provide critical understanding of near-fire chemistry and downwind chemical evolution of these pollutants during both day and night hours:

    a. Speciation of VOC and nitrogen gases for different combustion conditions are poorly characterized, yet they have significant impacts on both primary emissions and subsequent downwind secondary chemical pollutant production. Further, better distinction is needed with respect to primary emissions of VOC and nitrogen gases and fast near-source chemical production. These measurements should improve VOC, nitrogen gas, and PM2.5 emissions speciation and better differentiate emissions and chemical production at different scales of plume aging;

   b. Speciated PM2.5 organic aerosol measurements are needed near the fire and at multiple distances downwind to better understand dilution impacts on PM2.5 organic carbon evolution in fire plumes.

4. Fire plume rise and vertical allocation into the atmosphere is not well characterized in photochemical grid models. Warm- and cold-season field study measurements of heat flux, meteorology, and chemistry will allow for better spatial allocation vertically of smoldering and flaming emissions.

5. Optical properties of smoke are critically important to appropriately characterize near-fire and downwind photochemistry so that photolysis can be correctly attenuated in the photochemical model. Currently, smoke optical properties are poorly characterized in these models, meaning that photochemistry is probably overstated near large events, consequently affecting O_3 and secondary PM formation processes.

C.6 DESIRED EXPERIMENTAL CONDITIONS

C.6.1 WRF-SFIRE Desired Burn Conditions

The duration and size of experimental fires are very important factors for modeling. It is desired that the experimental fires be long enough to fully evolve to semi- steady state. An initial WRF-SFIRE simulation for one of the Southeastern burn sites suggests that up to 3 h may be needed to achieve a fully developed plume. The size of the fire plot should be big enough to enable such evolution, and burn plots ~2000 acres meet this criterion. The size of the fire influences the resolution of modeling experiments that can be performed for it, as well as requirements in terms of resolution of observations needed for model evaluation. For example, to resolve an atmospheric phenomenon on a typical WRF numerical mesh, it should be represented with at least 100x100 horizontal grid points. Therefore, assuming a horizontal 20m resolution of WRF atmospheric mesh, the burn plots are suggested to be at least 2 km x 2 km (~1000 acres). This size would also enable investigation of model capabilities at coarser operational resolutions (~500m), where the fire and smoke are only partially resolved on the model atmospheric grid. To isolate the fire impacts on the atmospheric conditions, experimental burns have to be intense enough to ensure a clear fire signature in the measurement data (i.e., have much stronger perturbation in the wind and temperature fields than that due to atmospheric eddies; in other words, high signal-to-noise ratio).

Because WRF-SFIRE is based on simplified fuel descriptions, the ideal site would be covered with uniform fuel close to one of the standard fuel behavior models. For evaluation of model capabilities in terms of plume rise and dispersion, preferred fuel properties would be those that ensure a moderate to high-intensity burn.

The ignition procedure is an important factor affecting the fire behavior and the plume rise. WRF-SFIRE is capable of simulating arbitrary ignition patterns, but cases with complicated ignition are not as useful for WRF-SFIRE validation for several reasons. 1) They increase the complexity of the fire, particularly the fire-atmosphere interaction, and make validation of the effect of individual factors on fire behavior and the associated gain in model skill difficult or impossible. 2) With complex and intense ignitions, the fire evolution and the plume development may become controlled by the ignition procedure itself, rather than by physical interactions between fire fuels and local micrometeorology. 3) In the case of a semi-steady single line fires, adequate measurement sampling is much easier than in complex fires. For these reasons, fires evolving freely from a single ignition line are preferred.

C.6.2 FIRETEC and WFDS Desired Burn Conditions

FASMEE's candidate burn plots are too large to be simulated by current physics-based fire behavior models that explicitly model combustion (e.g., FIRETEC, WFDS). For purely numerical reasons, these models must have sufficiently fine computational grids to adequately resolve the combustion processes that result in the formation and rise of the smoke plume.

For example, if we assume that the fireline depth needs to be covered by three grid cells of 100m X 100m and we have 500 CPUs for processing power, then (based on the memory and speed of operation characteristics of the physics-based WFDS model) resolving a 1-m-deep fireline would restrict the computational domain size to approximately 240 m on a side (i.e., a cubed-shaped domain). This domain size scales linearly with the fireline depth: the maximum computational domain for a 10-m deep fireline is approximately 2600 m on a side if 500 CPUs are available.

If burns within the scope of FASMEE fall within the above model constraints (the burns are over a small enough area or the fireline is sufficiently deep), then the following are desirable:

1. The ignition procedure is as simple as possible and well characterized in spatial location and timing.

2. The ambient winds are steady in direction and magnitude.

3. The vegetation, both raised and on the ground, is characterized by type and spatial variability at spatial scales that are on the order of the expected fire depth.

C.6.3 Daysmoke Desired Burn and Smoke Conditions

Fire and smoke with multiple cores / sub-plumes

The number of sub-plumes is one of the factors for calculating heat fluxes in Daysmoke and therefore is important for plume rise. A major contributor to the formation of sub-plumes is ignition pattern (such as complex tracks from aerial ping-pong ball ignition). Thus, a desired burn includes multiple ignitions or burning in a manner that produces multiple cores.

Burns with well-defined exit properties

Physically based smoke models simulate smoke structure and movements using the mass, momentum, energy, and water conservation laws, together with boundary conditions from the bottom, top, and lateral boundaries. As the bottom boundary conditions, exit temperature and vertical velocity along with particle and water emissions from the ground are needed. Exit temperature and vertical velocity have two properties: (1) their intensity, which would be obtained by the smoke plume dynamics and meteorological measurements during the FASMEE field campaign; (2) some reference height, defined as the base of the plume where flaming gasses and ambient air have been thoroughly mixed. Besides fire intensity, this height is influenced by canopy, whose drag can dramatically reduce not only exit velocity intensity but also the reference height. For smaller-sized prescribed burns, for example, the height may be near 35 m above ground for a typical grassfire but only 10 m for forested lands with canopy. Thus, for the smoke plume measurements to be able to measure the exit properties, at least moderately intensive burning is desired where the canopy will consume to make sure the reference height will be above the canopy.

Nighttime smoke movement in areas with complex topography

Nighttime smoke drainage and possible formation of super-fog could affect local visibility and traffic. The burns should include a smoldering stage to correspond with measurements fire emissions, wind, pressure, possible smoke drainage, and potentially fog.

C.6.4 CMAQ Desired Burn and Smoke Conditions

For CMAQ model development, non-summer season prescribed burns of medium intensity in the southeastern US and non-winter season prescribed burns of medium to high intensity in the western US are desired. The ignition pattern typically used for each of these areas is desirable, because this modeling system is used to estimate PM and O_3 impacts from typical prescribed fires.

APPENDIX D: RECOMMENDED MEASUREMENTS AND JUSTIFICATION

The following measurement specifications are organized into four discipline areas:

1. Fuels and consumption
2. Fire behavior and energy
3. Plume dynamics and meteorology
4. Smoke and emissions

Within each discipline, we address the subtasks, measurement platforms, associated spatiotemporal scales of observations, and recommended methodologies and instrumentation. The prescribed burns have been selected to represent higher intensities, and measurements will occur during both day and night, as indicated in the subtasks. Innovation and the most cost-effective ways to collect the measurements that meet the specifications will be used.

D.1 FUELS AND CONSUMPTION OBSERVATIONAL PLAN

To provide the input data requirements for FASMEE to evaluate and advance currently used fire and smoke modelling systems traditional ground-based destructive sampling fuel and consumption measures for all fuel bed components must be integrated with spatially explicit, non-destructive three-dimensional datasets (Table D-1). Coupling traditional measurements (e.g., loading, height, and day-of-burn fuel moistures) with remotely sensed datasets allows observations to be scaled from fine-scale inputs for physics-based models (WFR_SFIRE-CHEM, WFDS, FIRETEC), to coarse-scale data collection required by traditionally used fire and smoke models (e.g. FlamMap, BehavePlus, CONSUME, FOFEM, Daysmoke). Hierarchical sampling across a range of spatial scales also can provide an important sensitivity analysis of what scale of observations are needed for the models of interest.

Table D-1: Observational specifications for the fuels and consumption discipline.

Instrument / Technique	Spatiotemporal scales	Observation	Additional Specifications and derived parameters
Ground-based			
Ground-based, photoload plot (non-destructive)	1 m^2 micro-plot 30 per burn unit 20 per HIP	• Pre- and post-fire herbaceous, low shrub, downed wood by size class (1-hr in 0-2mm, 2-4mm, 4-6mm, 10-hr and 100-hr) in kg/m^2	• Located at pre- and post-burn clip plot locations, and excluding other plots at the HIPs
Ground-based, photoload plot (non-destructive)	0.02-ha 4 per fuel condition 4 per HIP	• Pre- and post-fire ≥1000-hr downed wood in kg/m^2	• Fuel condition sampled by stratified systematic design.
Ground-based; wire log method for coarse wood consumption	0.02-ha 10m transects	• Coupled pre- and post-measures to estimate ≥1000-hr downed wood consumption by decay class (sound and rotten)	• Large logs and stumps randomly selected within inventory plots at HIPs
Ground-based; non-destructive, forest inventory plot and subplots, transects	0.02-ha 0.01-ha 1 m^2 micro-plots	• Pre- and post-fire forest inventory plot measures, including trees (live and dead), saplings, shrubs, herbaceous, 1000-hr, 100-hr, 10-hr, 1-hr, 0.1-hr, litter and duff	• Canopy, crown, and surface fuel load component bulk densities (kg/m^3) • Compare to and validate with complimentary destructive measurements
Ground-based; pre- and post-burn destructive plots to estimate fuel load	1 m^2 30 per burn unit 20 per HIP	• Pre- and post-burn biomass and bulk density (kg/m^3) by fuel type and size class • Physical fuel properties by fuel type, category and status (live/dead) • Surface area/volume ratio • Bulk density in kg/m^3, packing ratio	• Fuel types include shrubs, grasses, fine wood by size class, coarse wood (sound and rotten), litter, and duff • Validate corresponding non-destructive measurements • Burn unit plots located with stratified systematic sampling, excluding other plots at the HIPs
Ground-based; fuel moisture	Day-of-burn grab samples of fuel components	• Gravimetric water content (%) of fuel components	• Fuel types include shrubs, grasses, fine wood by size class, coarse wood (sound and rotten), litter, and duff

Table D-1 (cont.): Observational specifications for the fuels and consumption discipline.

Instrument / Technique	Spatiotemporal scales	Observation	Additional Specifications and derived parameters
Airborne			
ALS (airborne laser scanner)	Across burn unit, 3-5m resolution ≥8 /m² point density, pre- and post-fire	• LiDAR point cloud characterization of fuel load, pre- and post-fire	• Synoptic 3D canopy and crown fuel mapping including CBD as calibrated by ground measures
Multi-spectral (MS) imagery	Across burn unit, 1-5m resolution, pre- and post-fire	• High resolution, MS characterization of fuel type pre- and post-fire	• Synoptic, overhead imagery of canopy, crown, and surface fuel types as calibrated by ground measures
Thermal IR or microwave imagery	Across burn unit, pre-fire and in concert with background meteorological measurements	• Synoptic measures of fuel moisture dynamics in relation to weather data over a representative period immediately preceding the fire	• Coarser scale synoptic satellite observations also relevant; vegetation fuel moisture dynamics as calibrated by ground measures
UAS			
Structure-from-motion photogrammetry	Across HIP 0-5 to 2m resolution	• Photogrammetric point clouds, pre- and post-fire	• Intermediate scale 3D canopy and surface fuel mapping • Fuel type and status (L,D)
Tower or Tethered Balloon			
Photogrammetry	Across HIP 0-5 to 2m resolution	• Photogrammetric point clouds, pre- and post-fire	• Intermediate scale 3D canopy and surface fuel mapping • Fuel load, type and status (L,D)
TLS (terrestrial laser scanner)	1-100cm resolution	• LiDAR point clouds, pre- and post-fire	• Fine-scale 3-D canopy crown, ladder and surface fuel mapping • Shrub and herb bulk density
Photogrammetry	1-10cm resolution	• Surface fuel density • Fuel type and status • Pre- and post-fire	• Co-located with ground-based fuel sampling microplots

D.1.1 Fuels and Consumption Subtasks

Four Fuel and Consumption discipline subtasks are recommended for observations, organized by measurement platform in Figure D-1:

- Ground-based
- Tower or tethered balloon
- Unmanned Aircraft Systems (UAS)
- Airborne

Fuel and fuel consumption measurements ideally need to meet the course scale and fine scale resolution requirements the traditional and physics based fire behavior models require. To provide estimates of pre- and post-fire fuel mass, volume, or density in 3D, a multi-scale fuel measurement and modeling framework is needed within which point cloud data should be integrated with traditional measures. The density and extent of the point cloud and ground-based measurements are contingent on fuel type and structure; in general, sites with fine surface fuel beds that vary at sub-meter scales, typical of the Southeastern Campaign sites, could be characterized at higher resolution (≤ 1 m), whereas sites with fuel elements that vary at the scale of individual trees, more typical in the Southwestern Campaign sites, could be characterized at coarser resolution (≥ 1 m). Across all sites, overstory tree crown structure should be mapped using airborne LiDAR immediately pre- and post-fire. Existing, recent airborne LiDAR datasets are available for all sites and are needed for planning purposes and field site selection, following a stratified random sampling design, within the constraints imposed by safety concerns and accessibility.

A nested sampling design would provide the greatest flexibility for mapping 3D fuels at multiple resolutions, depending on the actual scale of fuel structure variation in the field. Airborne LiDAR provides the best synoptic coverage for mapping wall-to-wall overstory vegetation, and, with less sensitivity, the lower-level and surface vegetation layers. At

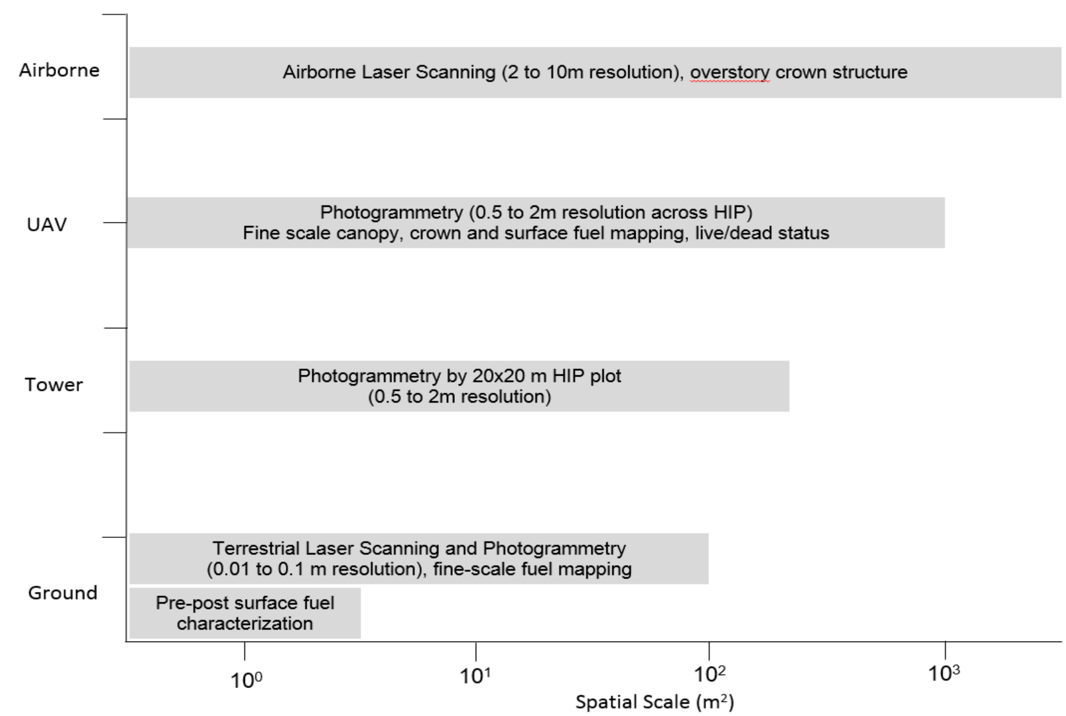

Figure D-1: Hierarchical sampling scales of fuels, from ground to airborne measurements.

smaller scales, multi- or hyperspectral imagery from UAS and/or towers/tethered balloons provide higher resolution data for fuels mapping. Surface fuel components and fuel properties should be intensively sampled within Highly Instrumented Plots (HIPs) in each operational prescribed burn (Figure D-2) or at systematic intervals along transects. Experience suggests that HIPs may be more appropriate for finer-scale surface fuel beds characteristic of the southeastern burns, while transects may have greater utility in the southwestern fuel types. Surface fuel measurements from accurately geo-located HIPs or transects can then be up-scaled to make unit-level inferences. Only by applying a strategic sampling scheme can some important fuel components (e.g., litter, duff, and woody debris) be reliably estimated at the unit level. Point-cloud methods from airborne LiDAR or photogrammetry are, at best, only weakly sensitive to these fuel components. Smaller-scale sampling using terrestrial LiDAR or handheld scanners are a point of future research and may allow for non-destructive sampling of these fuel components pre- and post- fire, providing an estimate of consumption. Until that time, estimation of surface fuel

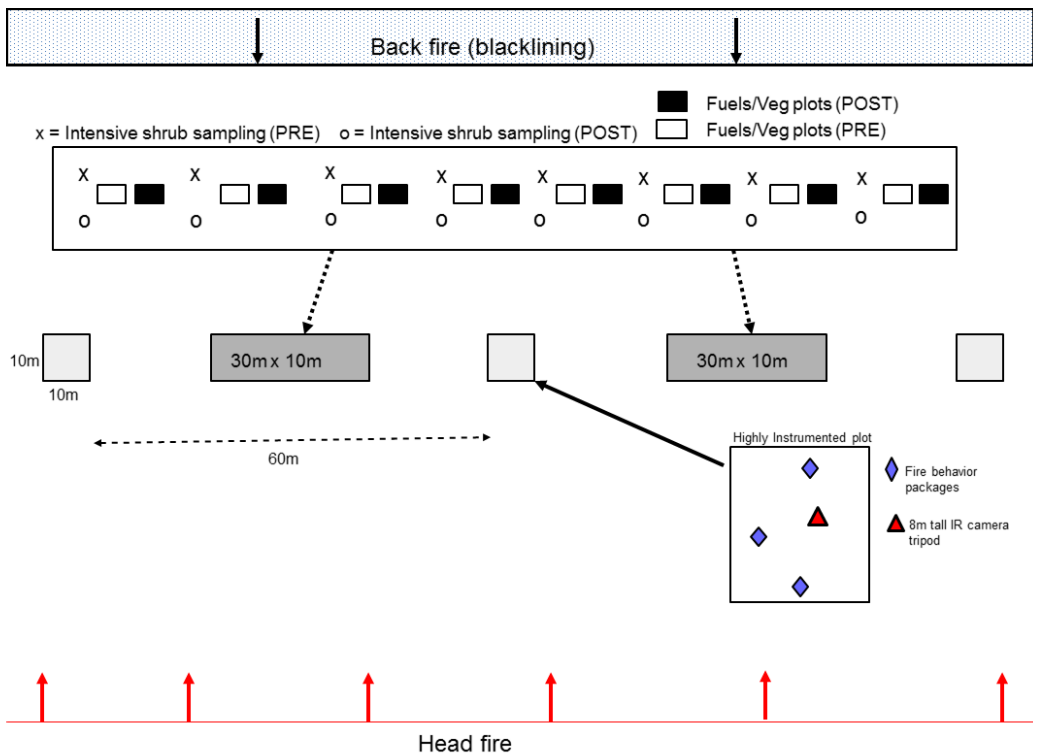

Figure D-2: Schematic of 10 m x 10 m highly instrumented plots (HIPs) interspersed by destructive sampling areas to characterize fuel and consumption by understory fires in southeastern surface fuel beds. Pre- and post-fire clip plots are paired and within destructive sampling areas to preclude trampling in or around the HIPs during pre-fire fuel sampling. Other spatial configurations and designs may be more appropriate, particularly for southwestern fuel conditions.

components will necessarily rely on traditional methods. A strategic sampling scheme is also needed to account for the fuel components that would contribute more to smoldering versus flaming combustion.

FASMEE also requires high-resolution maps of fuel consumption. The rate of fuel consumption per area relates more directly to combustion than fuel load, and consumption by combustion phase varies greatly by fuel component; thus, maps of fuel consumption by component would provide more direct relationships to energy flux and emissions than maps of fuel loads and type. A less desirable but still useful alternative are resolved maps of fuel loading and type linked to models [e.g., CONSUME (Prichard et al. 2005) or FOFEM (Lutes et al. 2012)], such that consumption of the fuel components could be predicted. By characterizing the type of fuels would address the sources of flaming and smoldering consumption. For example, coarse wood and duff on site would be expected to contribute most to short- and long-term smoldering. Coupled IR measurements with mapped fuels would confirm sources of smoldering fuels.

D.1.2 Fuels and Consumption Identified Observations

Table D-1 provides required measurements for fuels and consumption. Three-dimensional fuel modeling systems include Fuel3D and STANDFIRE, which, for example, launch FIRETEC and WFDS using gridded fuels inputs (Parsons et al. 2011). These 3D systems provide a framework for linking traditional fuel measures to point cloud data at tree-stand scales. No chemical analysis of the fuels is identified directly as part of the fuels measurements, but these data could be collected as part of other field campaigns (e.g., FIREX, FireChem).

D.1.3 Fuel and Consumption Measurements Justification

Fuels are the primary independent variable upon which measurements in all other FASMEE disciplines depend to varying degrees. Specifically, the fuel consumption rate, rather than fuel load, determines heat release and other aspects of fire behavior, plume dynamics, and the gaseous and particulate composition of smoke emissions. Fuel consumption is most explicitly linked to fire behavior at fine scales of variability, but it also drives plume dynamics at coarser scales and spatiotemporal variation in smoke near the source (Parsons et al. 2011). Fire and smoke models need to consider the spatial configuration of burning fuels and how it changes over time with the fire progression.

Observations of flux in fire radiative energy (FRE) and power (FRP) relate linearly to fuel consumption and consumption rate, respectively. Wooster et al. (2005) demonstrated this in small-scale experimental fires, where the mass loss rate and FRP flux rate could be monitored. At the landscape-scale of FASMEE or other prescribed burns, fuel consumption must be inferred by comparing pre- and post-burn fuel loads, as proposed for every fuel component in Table D-1. To estimate fuel consumption in a spatially explicit manner requires that pre- and post-burn fuels measurements be collected non-destructively. This approach has been demonstrated as feasible in the New Jersey pine barrens burned with prescribed crown fires (Mueller et al. 2016), where the overstory forest canopy was characterized with pre- and post-fire airborne laser scanning (ALS), and at a finer scale with terrestrial laser scanning (TLS) of forest understory vegetation burned with prescribed surface fires in a longleaf pine ecosystem (Rowell et al. 2016). Fuel measurements at both crown and surface fires are therefore included among the suite of fuels measurements detailed in Table D-1. These point cloud datasets collected via active remote sensing should be augmented with (1) complementary point cloud measurements, (2) stereo photogrammetric points collected with digital cameras mounted on UAS, to bridge the scaling gap between ALS and TLS scales, and (3) close-range stereo photogrammetry (Bright et al. 2016), to characterize destructive sample plots of ground cover and debris prior to harvesting.

The spatial structure of fuel beds and distribution of fuel components are so inherently complex (Keane et al. 2012; Keane and Gray 2013; Hiers et al. 2009; Loudermilk et al. 2009) that spatially explicit measurements must be relied upon to characterize them (Table D-1). However, complementary destructive sampling is needed to predict mass of fuel loads or consumption from metrics derived from the various point cloud datasets. Destructive sampling is also needed to estimate those fuel components that are not amenable to point cloud characterization because of limited visibility, but that all contribute differently to emissions (e.g., litter, duff, and fine woody debris fractions).

Fuel consumption estimates ideally need to meet the fine-scale resolution requirements of the physically based fire behavior models. Fuel consumption estimates are also needed for smoke models, but these can be at coarser resolutions. As such, fuel consumption estimates may be aggregated to coarser resolutions to improve the accuracy of the smoke models, along with measures of spatial variability. Newer, less intensive techniques to more quickly estimate fuel load components, such as the photoload method (Keane and Dickinson 2007), may relate poorly to destructive fuel sampling methods (Volkova et al. 2016); these need to be tested in a rigorous sampling framework. However, the photoload method may suffice for informing smoke models because of the coarser-scale input requirements.

The classification and mapping of fuel type cannot be adequately estimated using point-cloud based techniques alone. Therefore, multi- (or hyper-) spectral image data collections, across the same nested, multi-scale framework as the point cloud data collections are desirable. The digital, passive optical imagery from which photogrammetric point clouds are derived, collected hierarchically using airborne, UAS, ground-based or handheld systems (e.g., Faro Freestyle), may suffice for this purpose.

Finally, to estimate fuel moisture dynamics by fuel type across the burn units, repeated and synoptic thermal infrared or microwave measurements sensitive to dynamic fuel moistures are needed, together with contemporaneous fuel moisture samples collected on the ground and integrated into the models. Such data should be collected not just immediately before the prescribed fires, but perhaps also for a week or more preceding the fires, along with meteorological observations to capture fuel moisture dynamics at hourly to monthly time scales.

D.2 FIRE BEHAVIOR AND ENERGY OBSERVATIONAL PLAN

The Fire Behavior and Energy (FBE) discipline, in collaboration with operations and other disciplines, focuses on answering key science questions related to the character and spatial organization of the “handoff” of mass and energy between the fire and plume. FBE also provides targeted heat source and emissions data across burn units required for model input and evaluation. Achieving these goals requires a combination of remote sensing, coordinated ground measurements, and modeling. FBE activities must not only coordinate with the other FASMEE disciplines, but also link with other projects that focus on fine-scale combustion (e.g., SERDP), regional-scale smoke (FIREX/FireCHEM rapid deployment) and other potentially related efforts to make best use of FASMEE data.

The active-fire measurements described below include a mix of ground- and tower-based measurements and remotely sensed measurements (Figures D-3, D-4). Remotely sensed measurements involve both orbiting and geosynchronous satellites and airborne platforms. The orbiting satellite measurements require, as possible, coordination with the timing of operations, particularly with respect to when ignitions occur. Two kinds of airborne platforms and associated sensors are probably needed to obtain both quantitative fire radiation measurements and fire position data at high temporal frequency. Given currently available sensors and platforms, quantitative imaging from a nadir perspective is best collected from a piloted, fixed-wing aircraft flying back and forth over the burn units at approximately 10,000 feet AGL. Based on experience, passes over the fire can be made every 3-5 minutes. Fire position information is needed at high frequency, such as from a dual-axis scanning instrument flown in an aircraft that orbits the burn unit at approximately 5,000 feet AGL. The expectation is for the imager to assemble an oblique scan of an entire burn unit every 30 s and the aircraft to complete its pattern every 10 minutes. Extensive work in the burn units in the days leading up to each prescribed fire is needed to install ground- and tower-based equipment. Access to the burn unit on the day of the fire (subject to safety constraints) is probably needed to launch equipment. Equipment retrieval will be needed after the fires, and at the same time safety risks must be mitigated.

Some imaging may be accomplished from tall towers erected adjacent to burn units. In high-intensity fires, it will not be possible to obtain overhead, ground-leaving, flame-front radiation measurements from towers at each distributed measurement location in Figure D-4 (i.e., ground/tower locations). Unless a viable plan for using UAS to obtain these measurements is proposed, the airborne quantitative fire-radiation measurements will be the primary data source.

D.2.1 Fire Behavior and Energy Subtasks

The three central measurement challenges for FASMEE's Fire Behavior and Energy discipline are to (1) characterize spatially-resolved and multi-scale Fire Radiative Flux Density (FRFD) across burn units (the radiation field), (2) describe the fire's heat and mass budgets across relevant ranges in variability, and (3) use these measurements and

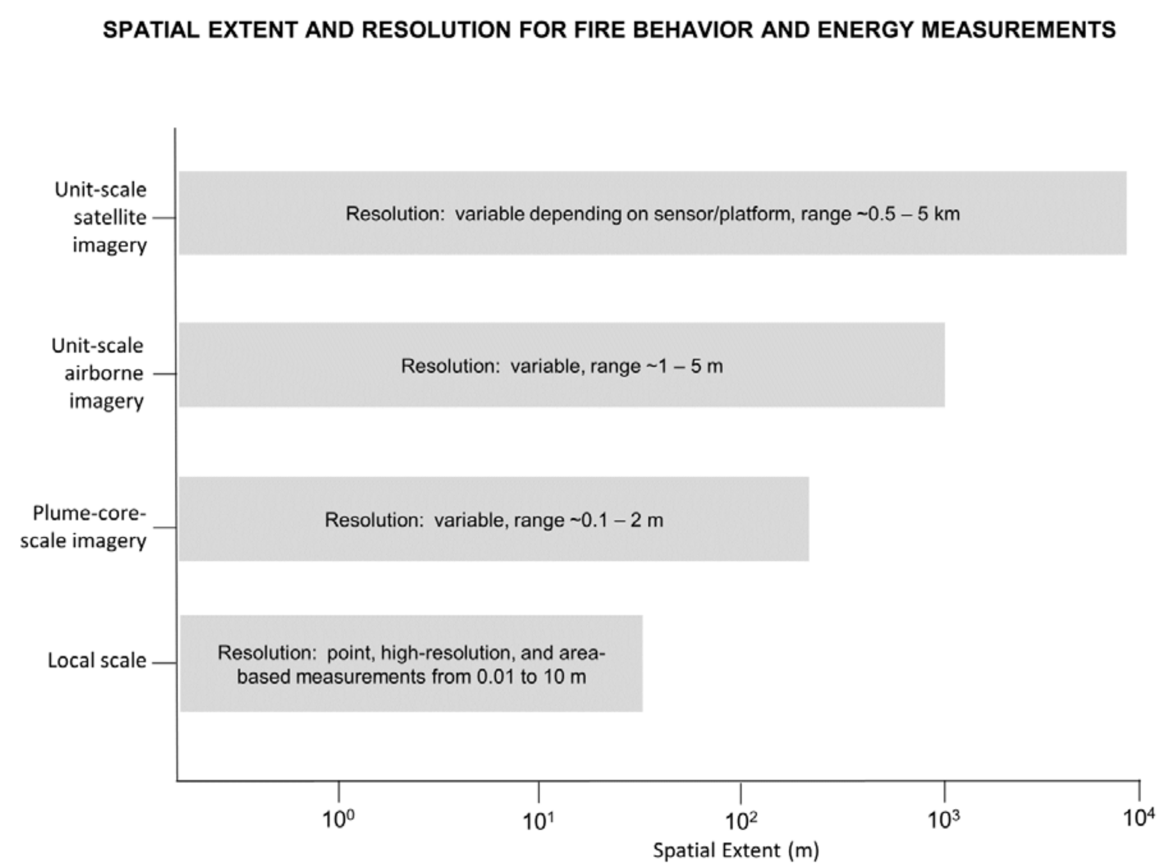

Figure D-3: Hierarchical sampling scales of fire behavior and energy measurements. Satellite and airborne fire radiation measurements will occur at unit and larger extents, respectively. Combustion-core-scale imagery will occur at high temporal frequencies but at moderate extents similar to plume structures. Coordinated fire dynamics and emissions measurements will involve point and flame-front scale measurements from ground and towers.

modeling to derive spatial inputs needed by plume and smoke chemistry models (as possible with future funding). Coordinated measurements (e.g., Hudak et al. 2016a; Butler et al. 2016; Dickinson et al. 2016a; O'Brien et al. 2016a,b) will be conducted hierarchically across their expected range of variability within and among fires. These include fuel consumption rate, emissions partitioning between flaming and post-frontal combustion, and flame front dimensions, dynamics, and energy transfer. Fire imagery will be collected in a nested design (spanning spatiotemporal scales) to characterize plume genesis and evolution from local flame fronts, to interacting flame fronts, to plume cores.

Specific subtasks for this discipline are organized by two primary groups based on the spatial scale of measurement and, by necessity, combine measurement and modeling:

- Unit-scale remotely-sensed fire radiation;
- Plume-scale remotely-sensed fire radiation;

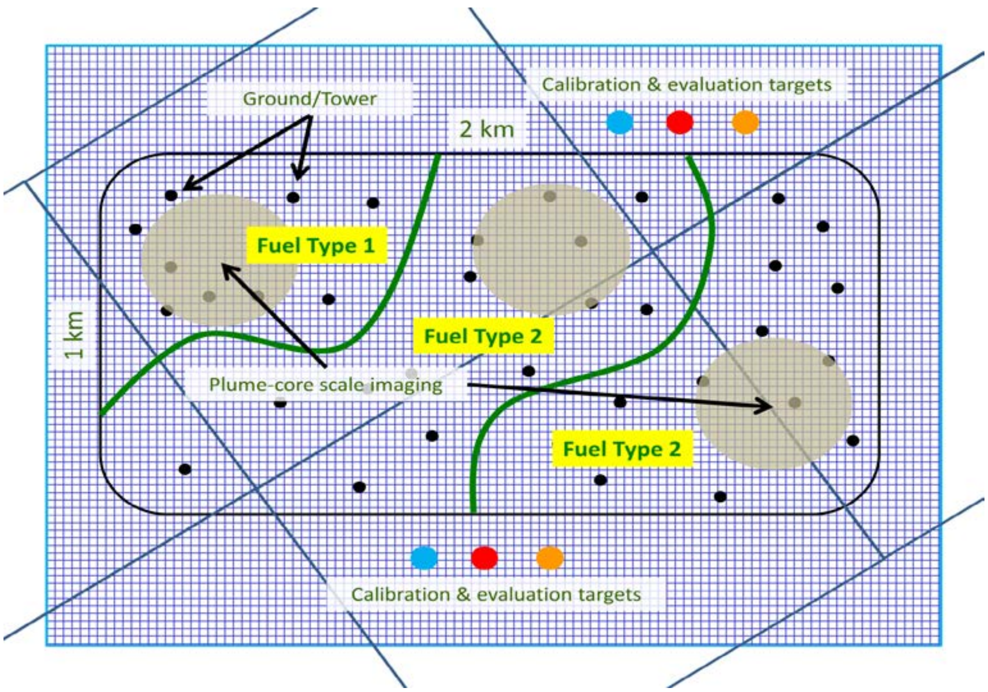

Figure D-4: Example spatial overlay of satellite (large) and airborne measurement grids (small) covering the full extent of burn units. Calibration and evaluation targets will be used to improve airborne infrared radiation measurements. Within burn units, coordinated measurements will be distributed in a stratified manner by fuel type and, as possible, expected fire behavior (e.g., heading vs, flanking and surface vs. crown fire). Imagery collected at high temporal frequency and spatial resolution and moderate spatial extent (coinciding with expected plume core development) will, in combination with flame-front-scale and unit-scale imagery, be used to examine the genesis and evolution of plume cores.

- Coordinated fire dynamics and emissions measurements at local (flame-front) scales.

The unit-scale remotely sensed fire radiation measurements must encompass the spatial extent of burn units (Figure D-3). Modeling is required to correct for canopy interception for surface fires. Plume-core-scale imagery must be of sufficient temporal frequency and spatial resolution and extent to capture the organization of fire heat release. The local, coordinated fire dynamics and emissions measurements should 1) combine ground and tower-borne instruments and 2) be a combination of point measurements, often replicated vertically (e.g., convective and emission fluxes), and area-based measurements (radiometry, fire imaging). Plume-model input datasets must be developed through data integration and modeling.

D.2.2 Fire Behavior and Energy Identified Observations

Table D-2 describes the suite of measurements and modeling tasks proposed for the FBE discipline. Modeling tasks are included that are needed to deliver data to plume and smoke chemistry modelers. Modeling tasks will cover (1) simulation of radiation interception by forest canopies that intervene between fires and airborne and satellite sensors, and (2) specification of stationary burners in a hydrodynamic code that simulates flame front heat generation and provide inputs to plume models. Other modeling exercises may be required to support the measurement process, including, potentially, (1) coupled-fire atmosphere simulations to help identify the relevant spatial and temporal scales for the organization of plumes, and (2) modeling to help characterize flame front characteristics and energy transfer from limited measurements. Because of flame energy and size, certain modifications of the measurement plan for crown fires are needed with sufficient detail to implement. For crown fire flames, unit-scale airborne quantitative radiation imagery may be sufficient for crown fire characterization at distributed measurement locations, although interpolation will generally be needed. Measurements replicated vertically on towers will generally only describe gradients partway through the length of crown fire flames. Extrapolation will be needed to fully characterize flames and lower-plume conditions. This may be facilitated by measurement modification and/or added measurements and modeling, particularly for flame-front dimensions and spread rates, flame energy transport, emissions fluxes and combustion efficiency, and partitioning of flaming and smoldering combustion.

Table D-2: Observational specifications for the fire behavior and energy discipline.

MEASUREMENT	SPATIOTEMPORAL SCALES	OBSERVATION (MINIMUM)	ADDITIONAL SPECIFICATIONS
Unit-scale remotely-sensed fire radiation			
Airborne active fire observation and modeling			
Unit-scale quantitative fire radiation	• Spatial extent – entire burn units • Spatial resolution ≤ 10 m (goal 1-3 m) • Imaging interval ≤ 10 min (goal 3-5 min) over entire burning period (3-7 hours)	• Fire radiative power & energy • Emissivity-area product • Spotting density and distance • Visible imagery	• Compare with ground evaluation data and calibrate as needed • Detail camera specifications and operation including performance at background and high power • Contingency plan relative to Mid-Wave Infrared (MWIR) saturation • Provide refueling/rest plan • Coordinate with other measurement teams and operations
Canopy interception correction for surface fires	• Same as for unit-scale quantitative fire radiation	• Fraction of fire radiative power & energy intercepted by canopy per pixel	• Ray tracing approach preferred • Use canopy data to derive parameters • Assess error from canopy heat interception and (re)radiation
Ground calibration and evaluation targets	• Spatial extent – subpixel to multiple airborne pixel • Spatial resolution – subpixel to multiple airborne pixel • Time scale – entire burning period (3-7 hr)	• Fire radiative power and energy • Combustion total and rate where applicable • Emissivity and area data	• Replicated cold (e.g., water bodies), background, and hot (e.g., fire) targets • Target extent should be multiple airborne pixel as possible • Evaluate against airborne imaging • Coordinate with other measurement teams and operations
Unit-scale fire spread	• Spatial extent – entire burn unit • Spatial resolution ≤ 5 m • Imaging interval ≤ 1 min over entire burning period (3-7 hr)	• High quality infrared imagery, visible as a supplement if possible • Fire spread mapping across unit and through burning period	• Develop algorithm for mapping fire spread rate from high temporal resolution infrared and visible imaging • Provide refueling/rest plan • Coordinate with other measurement teams and operations

Table D-2 (cont.): Observational specifications for the fire behavior and energy discipline.

MEASUREMENT	SPATIOTEMPORAL SCALES	OBSERVATION (MINIMUM)	ADDITIONAL SPECIFICATIONS
Unit-scale remotely-sensed fire radiation			
Satellite active fire observation			
Quantitative fire radiation from earth-orbiting satellites	• Spatial extent – whole burn unit • Time scale – single observation during burning period	• Fire radiative power	• Provide details on schedule, image specifications, and methods • Evaluate against airborne data • Coordinate with other projects (e.g., FIREChem rapid response), measurement teams, and operations
Quantitative fire radiation from geosynchronous satellites	• Spatial extent – entire burn unit • Time scale – multiple observations during burning period	• Fire radiative power & energy	• Provide details on image specifications and methods • Evaluate against airborne data • Coordinate with other projects (e.g., FIREEX/FIREChem rapid response), measurement teams, and operations
Distributed & coordinated fire dynamics and emissions			
Plume-core scale quantitative fire radiation	• Spatial extent ~ 100 m • Spatial resolution – sub-flame front • Time scale >0.5 Hz	• Fire radiative power & energy	• Provide moderate scale imagery to link the local and unit scales relative to fire spatial structure
Overhead, ground-leaving, flame-front radiation	• Spatial extent –locations distributed across burn units • Spatial resolution – flame front • Time scale > 0.5 Hz	• Fire radiative power & energy from flame front • Estimate fire fractional area and flame-front emissivity	• Match units/specifications of airborne quantitative data • Develop correlations with flame-front characteristics and energy transport • Coordinate with other measurement and modeling • These measurements have been made from towers in the past and are probably not possible in high-intensity fires
Flame-front dimensions and spread rates	• Spatial extent – locations distributed across burn unit • Spatial resolution – flame front • Time scale $\geq$ 1 Hz	• Flame front spread rate • Flame residence time • Flame dimensions • Spatial variation	• Methods to include imaging • Consider 3D models from multi-perspective imagery • Coordinate with other measurements and modeling

Table D-2 (cont.): Observational specifications for the fire behavior and energy discipline.

MEASUREMENT	SPATIOTEMPORAL SCALES	OBSERVATION (MINIMUM)	ADDITIONAL SPECIFICATIONS
Distributed & coordinated fire dynamics and emissions			
Flame energy transport	• Spatial extent – locations distributed across burn units • Spatial resolution – flame front • Time scale ≥ 10 Hz	• Flame "exit" convective flux (velocity & gas temperature) • Flame-front radiative flux • Soil heat flux	• Measurement units/specifications for radiative flux comparable to overhead, ground-leaving flame-front radiation • Multi-height measurements expected for convective flux • Coordinate with other measurements and modeling, esp. to constrain fire heat and emissions budget
Emissions fluxes and combustion efficiency	• Spatial extent – sample locations distributed across burn units • Spatial resolution – point measurements at multiple heights • Time scale ≥ 1 Hz	• Convective flux • Latent heat flux • CO & CO_2 fluxes and combustion efficiency • Particulate emissions	• Multi-height measurements to provide vertical gradient through flame and lower plume (i.e., source term after combustion reactions are complete • Monitor the evolution of the combustion process from flaming to smoldering phases • Coordinate with other measurements and modeling, esp. to constrain fire heat and emissions budget
Partitioning flaming & smoldering combustion	• Spatial extent – sample locations distributed across burn units • Spatial resolution – flame front • Time scale ≥ 1 Hz	• Partition flaming and smoldering consumption • Flaming and smoldering contribution to fire energy	• Consider image analysis methods • Relate to emissions fluxes and combustion efficiency • Coordinate with other measurements and modeling, esp. to constrain fire heat and emissions budget
Data integration			
Burner method for integrating fuels, fire behavior and energy, and meteorology to provide input data to plume models (see Appendix C6.1)	• Spatial extent – whole burn unit • Spatial resolution – flame front • Time scale ≤ 1 Hz	• Gas temperature, velocity, and convective flux at flame "exit" • Vertical mixing to lowest level of plume model	• Burners modeled within hydrodynamic code • Canopy attenuation of energy included for surface fires under forest canopy • Coordinate with measurement disciplines

D.2.3 Fire Behavior and Energy Measurement Justification

Fire behavior and energy, together with fuels and meteorology, determine the heat source for plume rise. The spatial organization of that heat release is an important determinant of plume dynamics and the fates of smoke (Achtemeier et al. 2012). Cross-scale measurements of fire radiation (from fuel cells, to interacting flame fronts, to plume structures) will help answer questions about the genesis and evolution of spatial structure in plumes (see 3. Science Questions and Data Needs). Radiation from fires measured from airborne platforms is the only fire behavior and energy measurement that can be accomplished at high spatial and temporal resolution and at landscape extents (Riggan et al. 2004, Schroeder et al. 2013, Dickinson et al. 2016b). Thus, radiation mapping, along with spatial fuel maps, will be foundational to the spatial understanding of fire and plume development and to the success of FASMEE. However, such measurements require broad and numerous assumptions regarding the energy source, the atmosphere, canopy, and other attributes, which lead to considerable measurement uncertainty. The airborne measurements, ground evaluation (i.e., "truthing"), and associated modeling processes described in Table D-3 describe a suite of activities that would provide high-quality fire radiation mapping. Plume models require these measurements in combination with coordinated ground-based measurements. Based on currently available options, one airborne sensor would provide quantitative nadir measurements of fire radiative flux density, and a second oblique sensor would be required to provide high frequency measurement for mapping flame front spread rates. The measurement process should include radiation targets (cold, ambient, and hot) that will permit airborne measurement evaluation and, if needed, provide ground-calibration sources. Measurement requires estimates of fire radiation attenuation when surface fires burn below a forest canopy (Hudak et al. 2016b; Mathews et al. 2016). With canopy characteristics provided by the Fuels and Consumption discipline, established software can be used to model canopy radiation transmission and interception (CESBIO 2016; DIRSIG 2016). FASMEE airborne radiation measurements, particularly with additional rapid deployment opportunities, would also advance the goal of satellite measurement evaluation, which is critical for widespread application of FASMEE science to smoke management (Peterson et al. 2013; Schroeder et al. 2013; Dickinson et al. 2016a).

The coordinated fire and emissions measurements and modeling in Table D-3 form a set of activities allowing FASMEE to use airborne fire radiation data to provide (1) spatial input data to plume modelers, (2) high-quality emissions information to smoke chemistry modelers, and (3) data needed to answer questions about causes of variation in fire heat and emissions budgets (e.g., Kremens et al. 2012). Coordinated measurements will be distributed across burn units to capture variability in fuels and fire behavior (Figure D-4). Two main organizing themes motivate fire behavior and energy measurements and integration with other measurement disciplines. First, in a central data integration step, a subset of measurements is needed to parameterize stationary flame-like vents ("burners") in a hydrodynamic model (see Appendix E.6.1) to provide spatial heat-source inputs to plume models. Development of the input dataset would facilitate the use of FASMEE results to evaluate and compare a suite of plume models for both surface and crown fires. Second, the quantity and quality of emissions from fires is fundamentally determined by the fire's heat and mass budget, which integrates fuel consumption, partitioning of emissions between flame front and post-frontal combustion, combustion efficiency, and energy sinks and dissipation modes. Coordinated in-fire and near-source measurements are needed to constrain the heat and mass budget across a wide range of variability in fuels and fire behavior. Results will provide smoke chemistry modelers with information, allowing them to assess model assumptions relative to source emissions. Measurement constraints are imposed by crown fire conditions. Modification of measurement and analysis methods and, potentially, flame front modeling will be needed to provide flame estimates of key variables such as convective fluxes.

D.3 PLUME DYNAMICS AND METEOROLOGY OBSERVATIONAL PLAN

FASMEE will address several critical topics associated with plume dynamics and fire meteorology, including the vertical profile plume development, entrainment rates, turbulence dynamics, fire-wind interactions, and relationship of sensible heat flux and plume height. To be of practical use for firefighter safety and smoke transport, fire and smoke models must represent the processes behind fire-atmosphere interactions.

D.3.1 Plume Dynamics and Meteorology Subtasks

The measurements needed to address key topics in plume dynamics and fire meteorology overlap substantially, making it practical to address them collectively than individually (Figure D-5). For FASMEE, a suite of instruments will be deployed to gather the necessary data to examine these questions and evaluate models' ability to reproduce the phenomena accurately. This suite includes ground-level temperature, humidity, pressure and wind sensors; tower-mounted sensors for the same quantities; UAS to collect wind and turbulence data beyond heights where instrument towers are practical; and ground-based remote sensed turbulence and winds (Table D-3). The instruments will be deployed in and around the burn unit, capturing ambient and inflow conditions, as well as conditions as modified by the combustion process (Figures D-6, D-7).

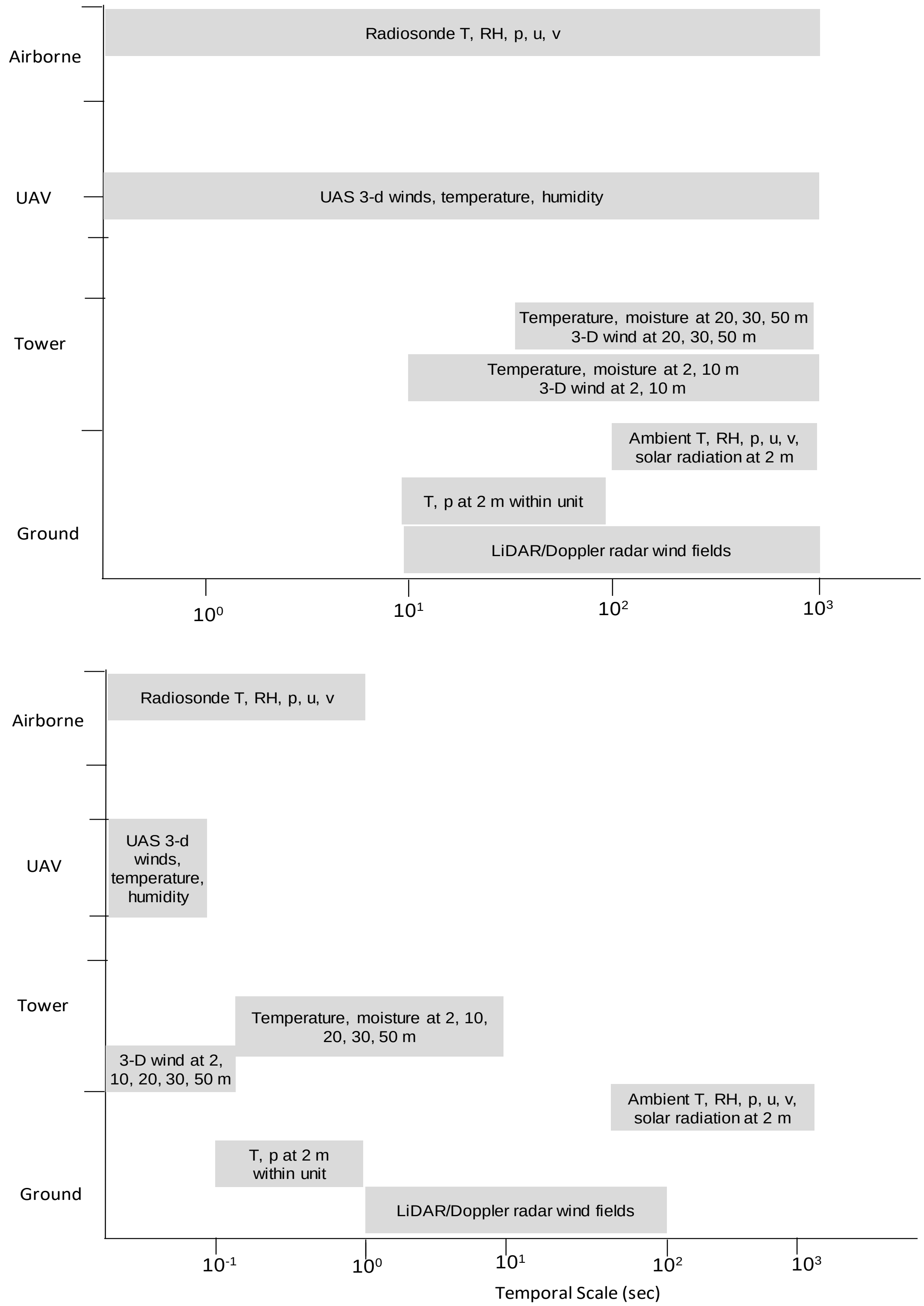

Figure D-5: Hierarchical spatial (top) and temporal (bottom) sampling scales of fire behavior and energy from ground to airborne measurements

Plume dynamics and meteorology measurements will be collected in the following subtasks, organized by measurement platform:

- Airborne in situ observations
- Tower-mounted in situ observations
- Ground-based in situ observations
- Ground-based remote sensing

D.3.2 Plume Dynamics and Meteorology Identified Observations

Table D-3 identifies the measurements needed for the Plume Dynamics and Meteorology discipline, by platform. The main observational goals for the plume and meteorology discipline is to characterize the ambient atmospheric conditions upwind, within, and downwind of the burn unit, as well as the conditions within the plume core, throughout the evolution of the plume. Key meteorology observations will include surface and upper-air meteorological measurements quantifying the ambient atmospheric conditions and environment in which the fire and smoke plume evolve. These measurements comprise basic surface weather conditions surrounding the experimental sites as well as vertical profiles of temperature, humidity, and the three-dimensional winds. The observations are made with upper-air radiosonde soundings and remote sensing profilers (e.g., sodar, LiDAR, microwave radiometer, radar). Surface measurements will be made as close to the burn-plot boundary as possible, while vertical profiling measurements will be located upwind and downwind from the experimental burn unit.

Table D-3: Observational specifications for the plume dynamics and meteorology.

Instrument / Technique	Temporal scales	Horizontal Scales	Vertical Scales	Observation
Airborne *in situ*				
Radiosonde	Hourly	• 1m–1 km	• Variable, 2m	• T, p, qv, u, v,
UAS sonic anemometer with temp and RH	20 Hz	• Up to 1 km from plume	• Up to 500 m above ground	• T, qv, u, v, w, turbulence
Tower-based *in situ*				
3-D sonic anemometer	20 Hz	• 100 m	• 10 m	• U, v, w, turbulence
Temperature and humidity	1-10 Hz	• 100 m	• 10 m	• T, Qv
Ground-based remote sensing				
LiDAR	1-30 s	• 18 m	• 18 m	• Qv, u, v
Ground-based *in situ*				
RAWS-type weather stations	1 min	• 500 m	• n/a	• T, qv, p, u, v, solar radiation
Temperature and pressure	1 Hz	• 100 m	• n/a	• T, p

To characterize the plume structures needed for plume-rise and coupled fire-atmosphere models, measurements are required within the plume from near the surface, or just above the fire front, to the top of the plume. These measurements include the three-dimensional winds and temperature, which can be measured using tall towers and remote sensing instruments. The tall towers allow multiple temperature sensors and anemometers to be placed within and above the canopy. Above this level, remote sensors such as Doppler LiDAR can measure the winds within the plume. Additional airborne platforms such as UAS will sample the middle plume region to collect both kinematic and thermodynamic measurements. Certain measurements in Table D-3 are designated at frequencies of 10 Hz or higher. These are needed to characterize the turbulent character of the ambient and plume-influenced atmosphere.

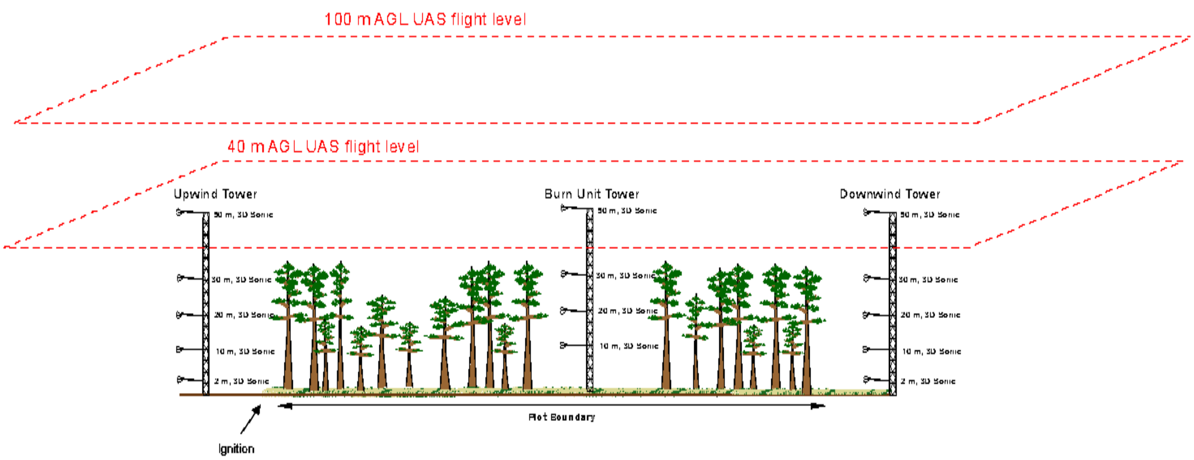

Figure D-6: Sample diagram of a tower, by type of tower, showing vertical placement of instrumentation and/or vertical airspace distribution for manned and UAS operations.

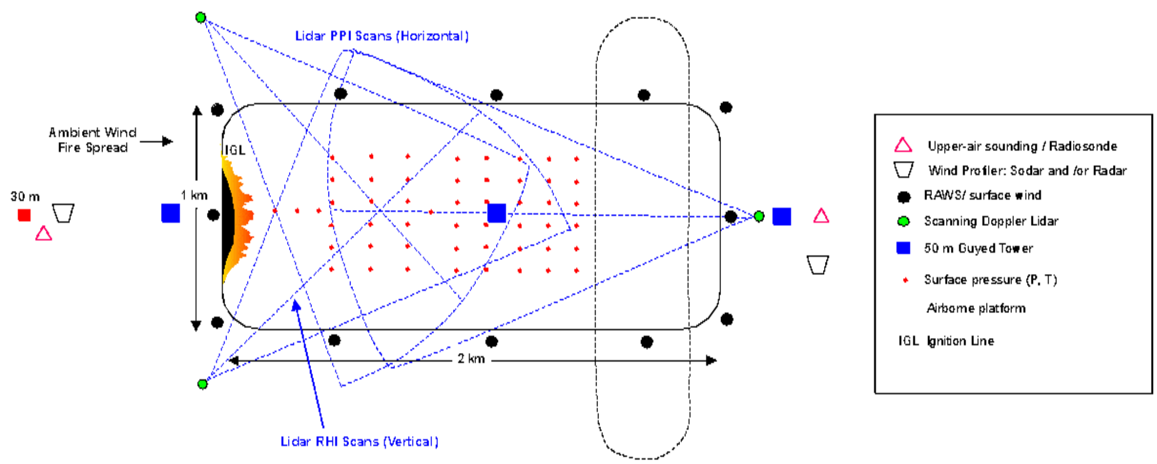

Figure D-7: Schematic of a possible LiDAR sampling and meteorological observations in advance of the flaming fire front.

D.3.3 Meteorology and Plume Measurement Justification

Meteorology and fire behavior are the two most dynamic elements measured in FASMEE. Both fluctuate on time scales of less than a second. Although fire behavior is a shallow-plane phenomenon (vertical scale small compared to horizontal extent), the meteorology relevant to plume dynamics is fully three-dimensional. The plume is subject to the influence of turbulence, mean winds, temperature, and moisture over at least the full span of the fire's horizontal extent as well as the plume's vertical extent and beyond (e.g., capping inversions above the plume top).

It is not feasible to capture the volumetric state of the atmosphere at the temporal and spatial scales of variability for the full extent of a fire. Technology does not exist to make the measurements near the fire, and expense precludes positioning instruments from the ground to the top of the plume throughout the burn area. The proposed measurements seek to maximize the potential to answer questions about plume structure, and to evaluate various models' plume representations, within the constraints of technology and cost. They allow evaluation of characteristics influencing plume behavior, in or near the plume, at temporal and spatial resolutions attainable in the field.

Ambient wind, temperature, and humidity through the troposphere will be obtained from radiosondes. Hourly upwind sondes will capture diurnal changes in these properties without interfering with aircraft operations. The wind shear and stability from these measurements are necessary to determine how they influence mixing and plume rise, respectively.

Mean winds on a vertical line (from the radiosondes) are by themselves insufficient to characterize the environment. They are also inadequate for determining how the fire's convective circulation modifies turbulent flow at, and downwind of, the plume. To accomplish these goals and complement the radiosondes, 50-m towers will be erected upwind and downwind of the burn units, with three more inside the unit perimeter. Sonic anemometers on these will record winds and temperatures at 10 Hz, at various heights. These measurements will allow (1) characterization of turbulence and how it evolves across the burns, (2) computation of mixing of ambient air with the fire plume), and (3) calculation of heat and momentum fluxes.

Shorter towers (3–10 m) distributed throughout the burn units, as conditions permit, will also hold 10-Hz anemometers to record airflow below and within the canopy. This region is particularly important for understanding near-field plume organization and airflow.

Airflow below the canopy is hindered by vegetation. Hot, buoyant plume air accelerates as it rises above the canopy, and the acceleration and mixing of this air must be determined to understand plume rise, and how smoke disperses over height. This region is too high for towers to reach and too turbulent for tethered balloon measurements. The only means available for observations here is 3D sonic anemometers with temperature sensors.

At each tower anemometer location, temperature and moisture must also be measured. These provide the thermodynamic components necessary to determine heat and moisture fluxes. A full surface energy budget station will be placed outside the burn area to measure the net surface radiation, sensible and latent heat fluxes, and soil heat flux. These data are necessary to quantify the mean surface energy budget not affected by the fire and plume.

All of these measurements emphasize point measurements, in vertical stacks, at a limited number of locations across and around the unit. Only remote sensing is capable of measuring airflow over the volume of the plume as it moves through the unit. The primary remote-sensing platform to be deployed for FASMEE is ground-based Doppler LiDAR. Multiple Doppler LiDARs will measure the kinematic structures above the canopy and tower array. The LiDARs provide a means to observe the smoke plume boundaries and plume top by recording the backscatter intensity at high spatial resolution. he LiDARs will also provide velocity measurements along the LiDAR beam, so that wind flow will be captured not only within the plume, but upwind and downwind as well. These measurements are critical to provide the modeling systems inflow and within plume boundary conditions. Furthermore, the three LiDARs are needed to provide measurements at multiple angles within and around the plume, to allow upwind and downwind characterization of flows and plume extent and dispersion. In this configuration, they also provide a virtual meteorological tower where they intersect within the plume so that wind observations can be made in the plume core.

Although the LiDAR will provide wind data, they will do so at a much lower temporal resolution than the sonic anemometers, which will preclude any turbulence analysis from LiDAR data. The only way to remedy this is the possibility of UAS-mounted sonic anemometers, with added temperature and moisture sensors. These will allow turbulence and flux calculations throughout the burn unit, at designated heights where plume entrainment and mixing are still vigorous. The addition of UAS-mounted sonic anemometers is necessary to sample the regions of the plume above the tall towers.

D.3.4 Plume Dynamics and Meteorology Logistical Needs

The measurements and instruments described above will require logistical support for tower installation, LiDAR positioning, UAS management, radiosonde release, and weather station installation.

Towers: 50-m towers will be installed by contractors. They will require access to the tower locations, including guy wire positioning. Towers must be installed in advance to allow subsequent instrument installation.

LiDAR Positioning: LiDAR must be either ground-based, with a clear view across the canopy top of the whole unit, or else scaffold-based to produce that clear view.

UAS management: UAS for meteorology needs to be included in airspace management planning across the burn unit. UAS will need to move with the plume, and be able to get measurements near the plume as well as up-wind and down-wind throughout the burn duration.

Radiosondes: Hourly sonde releases require filing NOTAMs with the FAA, as well as coordination with project aircraft.

Weather station installation: This requires access to a suitable site well before the burn in order to install the station and develop background meteorological context.

Power: Tower instruments and LiDAR will require electrical power. These should be the responsibility of the scientist(s) providing the equipment.

Communication frequencies: UAS and radiosondes will have radio communication requirements. Frequencies are not known at present, but they must be compatible with other RF instruments and devices.

D.4 SMOKE AND EMISSIONS OBSERVATIONAL PLAN

Fresh smoke is a complex mixture of gases and particulate matter (PM, or aerosol). Over 200 gases, including carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), volatile organic compounds (VOCs), and nitrogen oxides ($NOx = NO + NO_2$) are present in fresh fire emissions (Gilman et al. 2015, Hatch et al. 2015, Urbanski, 2014). PM in fresh smoke is mostly 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 have significantly increased our knowledge of the composition (Urbanski 2014, Yokelson et al. 2013) and processing of wildland fire emissions (e.g., Alvarado et al. 2015; Forrister et al. 2015; May et al. 2015). Although the most recent field campaigns (SEAC4RS and BBOP) have yet to publish results and will eventually provide additional datasets for characterizing emissions and smoke chemistry, significant knowledge gaps will remain. With the exception of RxCADRE (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 that is housed in the Fuel and Fire Tools application (https://www.fs.fed.us/pnw/fera/fft/index.shtml) and the First Order Fire Effects (FOFEM) software (https://www.firelab.org/project/ fofem).

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 D-4), 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 were not suitable for a 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 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 in the western US.

Table D-4. 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

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 2013). Chemical production from fires is very complex, highly variable, and often difficult to predict (Jaffe and Wigder 2012). Typically, 3-D photochemical grid models such as 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.

D.4.1 Smoke and Emissions Subtasks

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 package 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 D-5. 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 downwind of the source and locations further downwind (Figure D-8).

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

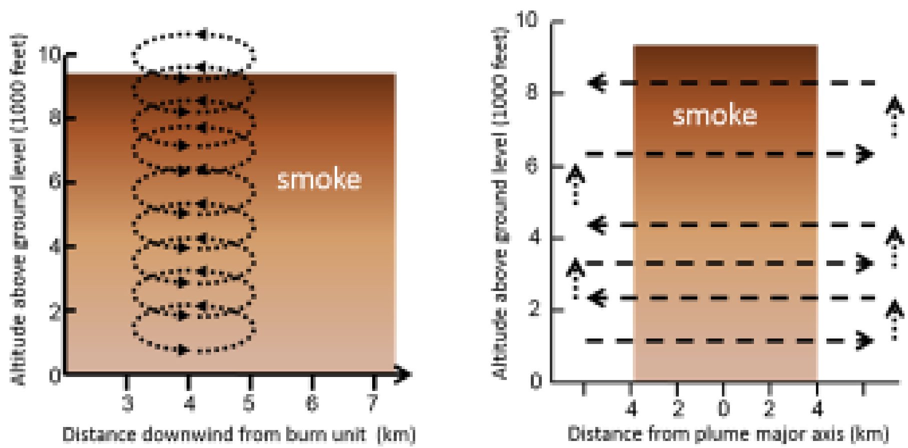

Figure D-8: Vertical sampling of downwind smoke plume. Corkscrew profile (left); parking garage profile (right).

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 VOCs. 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, because its greater mobility would enable sampling of a significantly larger volume of smoke than would an aerostat.

Sub-canopy smoke

Sub-canopy sampling will use ground-based platforms to characterize fresh emissions over the life cycle of the burns. Figure D-9 depicts the subcanopy smoke sampling scheme for a hypothetical burn plot. Subcanopy sampling would use four types of platforms to measure buoyant smoke being entrained into the convective plume, unlofted smoke (drift smoke), and post-fire-front extended smoldering. The subcanopy 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. Unlofted drift smoke will be measured using fixed-site subcanopy instrument packages (SIP) located immediately downwind of the unit, flanking a mobile lab (ML). If available a SIP will be located upwind of the burn unit to monitor background conditions. 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 SIP will also operate for an extended duration and sample smoke from extended smoldering that drifts across the sites.

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 D-10. All UAS and manned aircraft will need to adhere to well-developed flight plans in accordance with regulations and authorities controlling the airspace (see Appendix G.2).

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., NOx and NH_3). The grab method attempts to instantaneously collect an air sample both to provide a snapshot of the chemical composition and to limit the linear

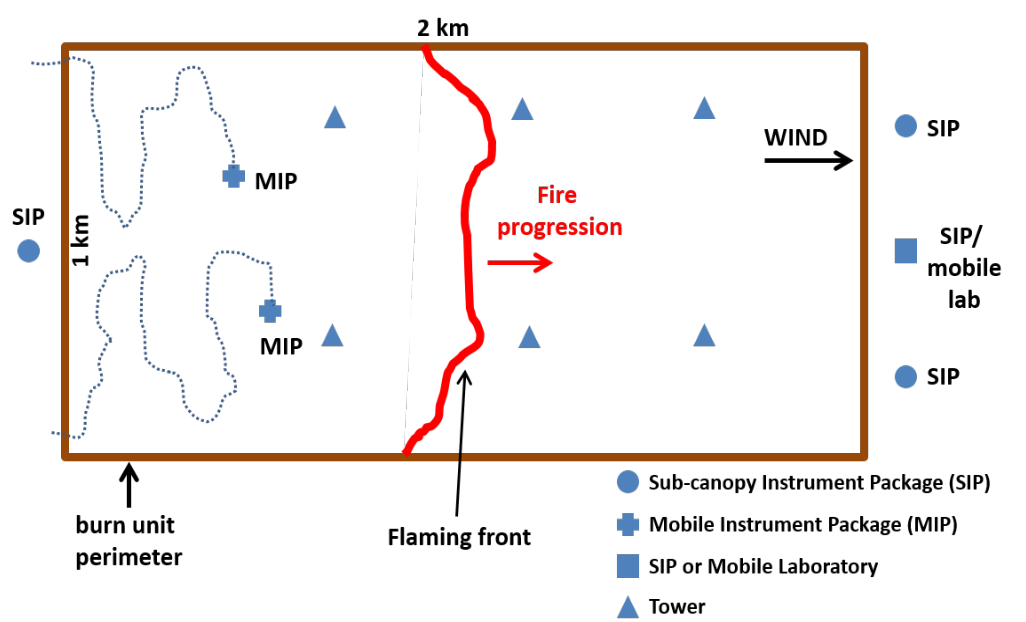

Figure D-9: Ground-based smoke emission diagram for hypothetical burn plot.

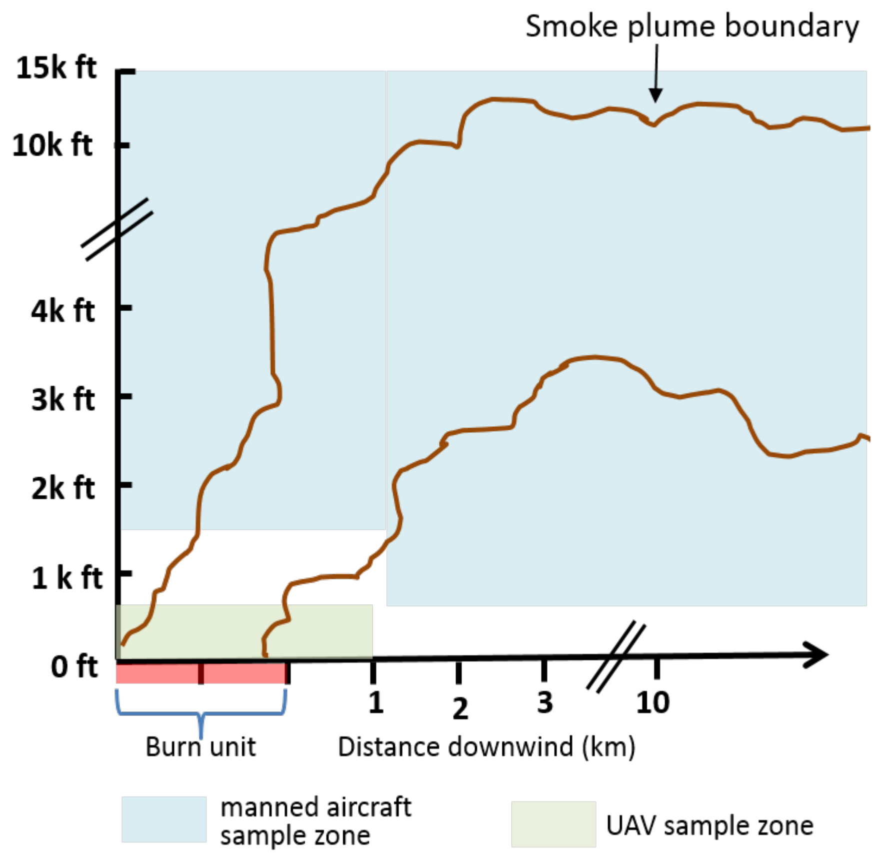

Figure D-10: Sampling scales and measurement platforms of smoke and emissions.

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.

D.4.2 Smoke and Emissions Identified Observations

Table D-5 lists the identified needed measurements for the Smoke and Emissions discipline, divided by subtask. Priority VOCs are listed in Table D-6. 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.

Table D-5: Observational specifications for the smoke and emissions discipline.

Measurement Block	Spatio-temporal scales	Observation	Additional Specifications*
Lofted Plume			
Carbon	Continuous 2 s	• CO • CO_2 • CH_4 • H_2O	• 40 ppb (precision) • 100 ppb (precision) • 10 ppb (precision) • 100 ppm (precision)
Ozone	On-line WAS or Continuous, 10 s	• O_3	• 0.2 ppbv/10% (LOD/accuracy)
Nitrogen containing compounds	On-line WAS or Continuous (Off-line WAS** viable for HCN and CH3CN) 10 s	• NO • NO_2 • NH_3 • HONO • PAN • HNO_3 • HCN • CH_3CN	• 1 ppb/10% (LOD/accuracy) • 0.2 ppb/10% (LOD/accuracy) • 0.5 ppbv (LOD) • 10 ppbv (LOD) • 10 pptv (LOD) • 25 pptv / 20% (LOD/accuracy) • 0.5 ppbv (LOD) • 0.5 ppbv (LOD)
VOCs	WAS and/or continuous 10 s	• Speciated VOC	
Particulate Matter	Continuous 2 s	• Bscat	• 5 1/Mm (precision)
	Continuous 10 s	• PM OM • PM NO_3 • PM NH_4 • PM SO_4 • PM Cl	• 0.40 µg/m3 (LOD) • 0.07 µg/m3 (LOD) • 0.25 µg/m3 (LOD) • 0.05 µg/m3 (LOD) • 0.05 µg/m3 (LOD)
	Continuous 10 s	• Refractory PM (BC)	
	Continuous 2 s	• Particle light scattering (e.g., Bscat by nephelometry)	• 5 1/Mm (precision) Measured at 1 or more wavelengths in visible spectrum
	Continuous 2 s	• Particle light absorption coefficients	Measured at both UV and visible wavelengths
	Continuous 10 s	• Size distribution of fine and coarse PM	
	Continuous 2 s	• Size-resolved particle number (0.1–1.0 µm)	

Table D-5(cont.): Observational specifications for the smoke and emissions discipline.

Measurement Block	Spatio-temporal scales	Observation	Additional Specifications*
Lofted Plume			
Meteorology	Continuous 1 s	• Horizontal wind speed • Horizontal wind direction • Vertical wind speed • Temperature • Dew point temperature • Static pressure	• 1 m/s (accuracy) • 5 deg (accuracy) • 0.5 m/s (accuracy) • 0.5 C (accuracy) • 0.5 C (accuracy) • 3 mb (accuracy)
	Continuous 3 s	• Down-welling actinic flux or photolysis frequencies	
Location	Continuous 1 s	• GPS latitude • GPS longitude • GPS altitude • True air speed • Ground speed	• 20 m (accuracy) • 20 m (accuracy) • 20 m (accuracy) • 1 m/s (accuracy) • 4 m/s (accuracy)
Intermediate Level Smoke			
Carbon	Continuous 30 s	• CO • CO_2	• 1 ppm (precision) • 500 ppb (precision)
Particulate matter	Batch sample ~ 20 min	• PM2.5 • PMEC • PMOC	• 5 µg/m3 (precision)
VOCs	Batch sample ~ 20 min	• Speciated VOC	• Depends on VOC
Meteorology	Continuous 2 s	• Air temperature • Relative humidity	• 0.5 C (accuracy) • 5% (accuracy)
Location	Continuous 2 s	• Latitude • Longitude • Altitude	• 20 m (accuracy) • 20 m (accuracy) • 10 m (accuracy)
Sub-canopy smoke			
Sub-canopy Instrument Packages (SIP) and Towers			
Carbon	Continuous 30 s	• CO • CO_2	• 1 ppm (precision) • 500 ppb (precision)
Nitrogen containing compounds	Continuous 60 s	• NO • NO_2	• 1 ppb / 5% (LOD/accuracy) • 0.2 ppb / 5% (LOD/accuracy)
VOCs	Batch sample ~ 20 min	• Speciated VOC	
Meteorology	Continuous 5 s	• Horizontal wind speed • Horizontal wind direction • Temperature • Relative humidity	• 1 m/s (accuracy) • 5 degree (accuracy) • 0.5 C (accuracy) • 5% (accuracy)

Table D-5 (cont.): Observational specifications for the smoke and emissions discipline.

Measurement Block	Spatio-temporal scales	Observation	Additional Specifications*
Mobile Laboratory (ML) The mobile laboratory observations replicate the SIP observations and add continuous VOC sampling, particle speciation, and particle sizing			
Continuous	10 s	• Speciated VOC	
Particulate Matter	Continuous 10 s	• PM OM • PM NO_3 • PM NH_4 • PM SO_4 • PM Cl	• 0.40 µg/m3 (LOD) • 0.07 µg/m3 (LOD) • 0.25 µg/m3 (LOD) • 0.05 µg/m3 (LOD) • 0.05 µg/m3 (LOD)
	Continuous 10 s	• Refractory PM (BC)	
	Continuous 10 s	• Size distribution of fine and coarse PM	
	Continuous 10 s	• Size resolved particle number (0.1–1.0 µm)	
Mobile Instrument Platform (MIP) – measurement of emissions residual smoldering			
Carbon	Grab sample 60 s	• CO • CO_2	• 1 ppm (precision) • 500 ppb (precision)
VOCs	60 s	• Speciated VOC	

**Desired l*imit 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_3 = nitrate, PM NO_3 = ammonium, PM SO_4 = sulfate, PM Cl = chloride, PM2.5 = total particulate matter < 2.5 µm diameter, EC = elemental carbon, OC = organic carbon.

Table D-6: Priority VOC

Name	Formula	MW1		Name	Formula	MW1
Ethyne	C_2H_2	26		Benzene	C_6H_6	78
Hydrogen cyanide	HCN	27		Cyclopentenone	C_5H_6O	82
Ethene	C_2H_4	28		2-Methylfuran	C_5H_6O	82
Ethane	C_2H_6	30		Toluene	C_7H_8	92
Formaldehyde	HCHO	30		Phenol	C_6H_6O	94
Methanol	CH_3OH	32		2-Furaldehyde	$C_5H_4O_2$	96
Propyne	C_3H_4	40		Styrene	C_8H_8	104
Acetonitrile	C_2H_3N	41		Ethylbenzene	C_8H_{10}	106
Propene	C_3H_6O	42		o-Xylene	C_8H_{10}	106
Isocyanic acid	HNCO	43		Xylenes (m- & p-)	C_8H_{10}	106
Acetaldehyde	C_2H_4O	44		Indene	C_9H_8	116
Propane	C_3H_8	44		Benzofuran	C_8H_6O	118
Formic acid	CH_2O_2	46		Napthalene	$C_{10}H_8$	128
1,3-Butadiene	C_4H_6	54		Camphene	$C_{10}H_{16}$	136
Acrolein	C_3H_4O	56		3-Carene	$C_{10}H_{16}$	136
1-Butene	C_4H_8	56		D-Limonene	$C_{10}H_{16}$	136
Acetone	C_3H_6O	58		i-Limonene	$C_{10}H_{16}$	136
n-Butane	C_4H_{10}	58		Myrcene	$C_{10}H_{16}$	136
Propanal	C_3H_6O	58		Pinene_alpha	$C_{10}H_{16}$	136
Acetic acid	$C_2H_4O_2$	60		Pinene_beta	$C_{10}H_{16}$	136
1,3-Cyclopentadiene	C_5H_6	66		γ-Terpinene	$C_{10}H_{16}$	136
Cyclopentene	C_5H_8	68		Terpinolene	$C_{10}H_{16}$	136
Furan	C_4H_4O	68		n-Decane	$C_{10}H_{22}$	142
Isoprene	C_5H_8	68		n-Undecane	$C_{11}H_{24}$	156
2-Butanone	C_4H_8O	72		Sesquiterpenes	$C_{15}H_{24}$	204
Methyl vinyl ketone	C_4H_8O	72				

[1]MW = molecular weight (g/mole)

D.4.3 Smoke and Emissions Measurement Justification

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 sample emissions from understory burns in light fuels? What are the emission factors for VOCs, NO_X, 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 unlofted 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 subgrid 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 are needed 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 subcanopy 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) 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 evaluate and 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.

Addressing these key science questions requires an observational plan that provides comprehensive measurements of atmospheric chemical composition and atmospheric conditions, as listed in Table D-4. Next, the necessity of these measurements is justified according to measurement blocks: Carbon, VOCs, 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 volatized in fires (Burling et al. 2010, Yokelson et al. 1999). More than 90% of combusted biomass carbon is released as CO_2, CO, and CH_4 (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_2 to the sum of emitted CO_2

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 if relatively close to the fire.

VOCs

Volatile organic compounds (VOCs) and NO_x are important for their potential to form O_3 and secondary organic aerosols (SOA). Photochemical reactions of VOCs and NO_X can lead to O_3 production. The process is highly complex and depends on VOC:NO_X ratios, the availability of free radicals, such as OH, and the formation of peroxynitrates. 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 VOCs in fresh smoke (Hatch et al., 2015). In a field experiment, it is not feasible to measure all of the VOCs believed present in fresh smoke. Therefore, the list of priority VOCs in Table D-5 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_2, NO_X, NH_3, N_2O, HONO, HCN, HNCO, and CH_3CN. NO_x is 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_X (produced by high temperature reactions of atmospheric O_2 and N_2) and the NOx BB emissions are derived from fuel N. HONO and 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. NH_3 is an important species in the formation and growth of aerosol and in atmospheric deposition of nitrogen. Gaseous nitric acid (HNO_3) is formed by the NO_2 + OH reaction, an important chain termination step that removes NO_X and OH from atmospheric oxidation cycles. Like NH_3, HNO_3 is important in the formation and growth of aerosol. Thus, measurements of atmospheric HNO_3 are of tremendous value for understanding both gas phase and aerosol phase chemistry. HCN and CH_3CN (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 [$CH_3COO_2NO_2$]), formed by the oxidation of VOC in the presence of NO_X, is an important reservoir species for NO_2. PAN can reduce O_3 formation in fresh smoke plumes, but it leads to downwind O3 formation when 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 secondary organic aerosol (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. In all probability, there will be a considerable amount of valuable particulate matter data from satellite imagery during 2019.

APPENDIX E: RECOMMENDED FIELD CAMPAIGNS

Three field campaigns are recommended based on FASMEE Phase 1. These are, in likely implementation order:

1. Western Wildfire Rapid Source Characterization Campaign (Not part of the FON)
   Moderately instrumented wildfires done as rapid deployment
2. Southwestern Field Campaign
   Heavily instrumented planned burns under high fuel load / high intensity
3. Southeastern Field Campaign
   Heavily instrumented planned burns under moderate fuel loads / moderate intensity

E.1 WESTERN WILDFIRE CAMPAIGN 2019 (THIS CAMPAIGN IS NOT PART OF THE 2017 FON REQUEST)

A rapid deployment campaign aimed at characterizing western wildfires is planned for July-September 2019 (Figure E-1). This campaign is being funded from outside sources and is not considered part of the 2107 FON request. During this period, the NOAA P-3 (FIREX project), the NASA DC-8 (FIREChem project), and the NSF C-130 large aircraft are all expected to be available and dedicated to smoke and atmospheric chemistry measurements. This coordinated plan offers an unprecedented opportunity to advance the understanding of smoke chemistry, aging, and transport and to provide additional measurements for the FASMEE campaign.

A critical need is a strong source characterization for each wildfire flown by these agencies. Although the aircraft have state-of-the-art instrumentation for smoke chemistry, aging, and transport, the agencies do not have adequate resources, experience, or knowledge to provide a source characterization of the fuels, fire behavior and fire-atmosphere interactions that represent the source of these emissions. FASMEE has been collaborating with these agencies and has identified a subset of measurements that can be completed on a rapid-deployment basis. These measurements will focus primarily on fuels and consumption data collection, but depending on available funding, they also may include aircraft and ground-based remote sensing of fire energy and plume dynamics.

The Western Wildfire Campaign will opportunistically sample plumes from wildfires that occur in western North America during the period of July–September 2019. Because these aircraft are capable of extremely long ranges and will sample more wildfires than are feasible to schedule site visits, the supplementary measurements recommended here will focus on the strongest and longest-lasting wildfire plumes being measured. The specific fires targeted will be identified based on availability of fuel data maps and cooperation of

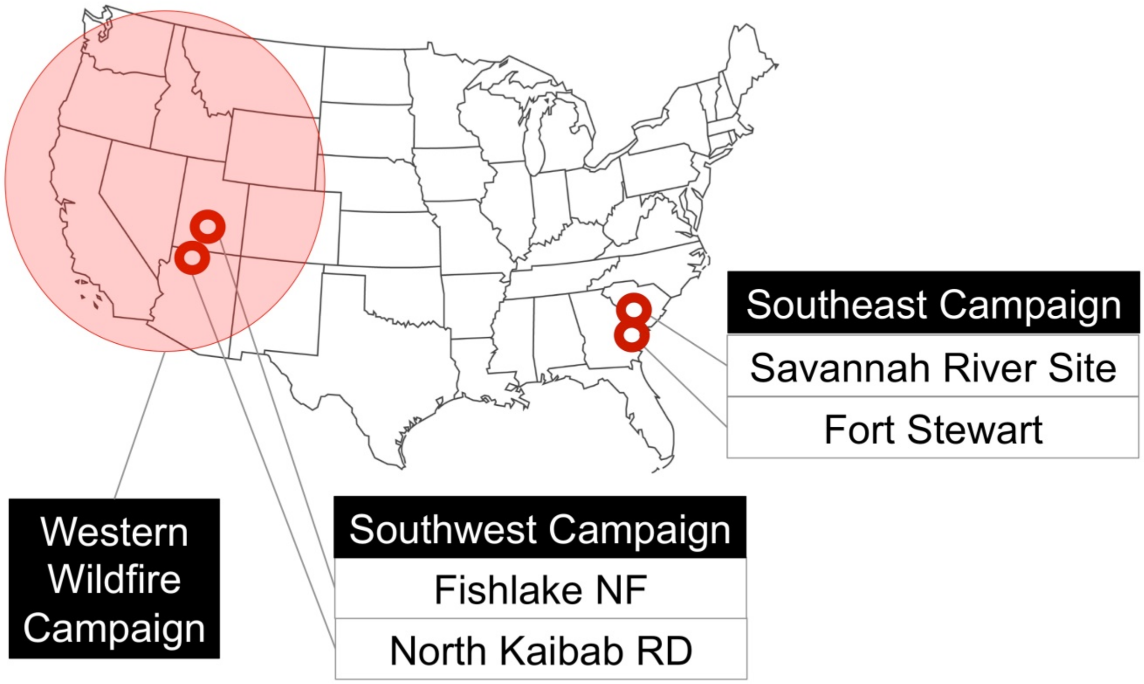

Figure E-1: FASMEE-recommended field campaign sites. The Western Wildfire Campaign will target active wildfires with rapid-deployment source characterization in the western United Sates (shaded red circle) and is not part of the 2017 FON. The Southwestern Campaign will target prescribed burn sites at Fishlake National Forest and/or North Kaibab Ranger District. The Southeastern campaign will target prescribed burn sites at Fort Stewart and/or the Savannah River Site.

Incident Command in conjunction with the joint FIREX, FIREChem, and NSF campaigns. Information on those fires that can be best characterized will be transmitted to the respective agency campaign for incorporation into flight planning.

Benefits to the overall FASMEE goals from the Western Wildfire Campaign are significant, especially if aerial measurements of energy and LiDAR scans can be included. The campaign provides a rare opportunity to link aircraft smoke measurements with the characterization of the fire and plume dynamics. It also offers a better understanding of the dynamics controlling near-source plumes and the resulting chemical composition, aging, and transport of smoke through measurements and observations of fuel, fire behavior, fire energy, and meteorology measurements. Furthermore, there will be a large satellite effort during the 2019 projects that FASMEE will benefit from.

Potential sites will be considered with the following features:

- Wildfires with cooperative Incident Command that will provide basic logistical support, including but not limited to: Burned area reflectance classification maps of initial fire severity produced on large incidents, thermal infrared imagery of the active fire progression, and ancillary data layers from geographic information systems (GIS) teams;
- Large wildfires in shrub and forested landscapes with potential for dynamic plumes with long duration;
- Reasonable access;
- Available pre-fire LiDAR or other fuel map sources.

All wildfires flown by NOAA, NASA, and NSF during the summer of 2019 will have some characterization based on the best available fuel bed maps, gathered fire behavior information and modeling. On at least 10 wildland fires, actual field measurements will be collected to characterize fuels and consumption. Depending on available funding, they may also measure fire behavior and energy flux, and plume development and meteorology. The following sections provide measurement details for the 10 selected wildfires by each of these three disciplines: (1) fuels and consumption, (2) fire behavior and energy, and (3) plume dynamics.

(1) Fuels and Consumption

- Obtain all high-resolution fuel information (e.g., LIDAR maps, recent vegetation and fuels inventory data) over the western US.
- Prioritize, where possible, measurements of smoke plumes generated in source areas of known fuel loadings
- Obtain fuel samples from the types of fuels burned by the measured wildfires and ensure that these fuels are measured for emissions factors and other laboratory studies being completed by FIREX, FIREChem, and other agencies
- Collect surrogate fuel loadings from analogous areas where pre-burn plot information is not available
- Collect post-fire consumption data from existing in situ plot sites that were burned by the measured wildfires
- Develop both enhanced fuel maps and consumption maps for measured wildfires
- Where possible, include post-fire airborne and terrestrial LiDAR fuels mapping

(2) Fire Behavior and Energy (dependent on available funding)

- Obtain measures of fire growth and consumption across days and within single days
- Obtain mapped fire intensity (e.g., hyperspectral, IR) that is rapidly refreshed
- Request high-resolution tasking of satellite systems
- Request high-resolution tasking of National Weather Service forecast models

(3) Plume Dynamics (dependent upon available funding)

- Measure plume evolution and dynamics (Dopplar LiDAR)
- Obtain measures of smoke concentrations vertically in the plume
- Obtain measures of length of time parcels of smoke spend in the buoyant plume
- Request satellite imagery and high-resolution tasking of National Weather Service forecast models

E.2 SITE SELECTION FOR SOUTHWESTERN AND SOUTHEASTERN FIELD CAMPAIGNS

Successfully completing these types of large-scale field campaigns requires strong partnerships with the hosting land management agency. Logistical and management issues for potential host sites exist because of both the size and intensity of the desired FASMEE burns, and the large number of researchers likely to be involved. Participants at these sites must be eager to work through the numerous challenges surrounding such campaigns.

Land management agencies across the United States, including the U.S. Department of Agriculture, Forest Service; U.S. Department of Defense, Army and Air Force; U.S. Department of the Interior, National Park Service, Bureau of Land Management, Fish and Wildlife Service; and U.S. Department of Energy, were contacted as potential hosts for FASMEE. Several criteria were outlined to the potential hosts, including:

- Operational burn (250+ ha) with high fuel loading and a burn window/ignition pattern creating a high-intensity fire resulting in a strong, dynamic smoke plume
- Area accessible to vehicles
- Regional airport nearby
- Environmental impact statement (EIS) and burn plan accepted and approved before FASMEE measurements begin
- Simple ignition to obtain to the best of our ability a free-running fire if possible but not essential

It was also expressed to interested host agencies that FASMEE would be a large and comprehensive study with as many as a hundred scientists on site and that will include many integrated instrumented platforms and sampling protocols. The size of this study requires the host agencies to identify the selected research burn blocks at the highest priority to be completed and have the infrastructure, available resources, and support to host the project. The host agencies will also need to integrate and work closely with the FASMEE leadership team to fulfill the studies goals and objectives and assist in the development of a concept of operations (CONOPS), incident action plan (IAP), and other safety and communication plans to meet the measurement requirements and land management objectives while maintaining a safe environment. The CONOPS is the overarching planning and coordination document of the FASMEE field campaign. The IAP is a subdocument to the CONOPS that outlines the weekly-to-daily details of coordination, location and participation of all individuals or teams during each research burn and accounts for safety and communication. The IAP will change daily.

Based on responses from the host agencies, the desired types of burns identified by the FASMEE Science Team, and site visits, the potential U.S. host sites were narrowed to four: two in the Southwestern Campaign and two in the Southeastern Campaign (Figure E-1). Other land management agencies were interested in supporting the FASMEE project, but they did not have the infrastructure to host a large project. Furthermore, the available research sites were too remote or had too few prescribed burn units available, or the burn window was too narrow. The availability of other host agencies supporting FASMEE can change on a yearly basis. For additional campaigns, land management agencies such as USDA Forest Service regions, BLM, NPS, and Department of Defense Army and Air Force can be re-contacted to determine future opportunities for hosting.

E.3 SOUTHWESTERN FIELD CAMPAIGN 2019-2021

The Southwestern Campaign has targeted forested areas with mixed conifer stands that (1) are heavily infested with insects and diseases and (2) have very heavy fuel loads, often greater than 150 mg/ha (Figure E-2). The potential sites have relatively easy access and are a long distance from critical smoke-sensitive areas, increasing the prescribed burn opportunities with regard to smoke management. The research burns will be ignited using a helicopter that will drop spherical balls, resulting in a mixed-severity to free-running stand-replacement fires. The larger fuel loads targeted for the Southwestern potential research sites and planned ignition patterns will generate the kind of large, dynamic plume desired for the FASMEE project. The burn windows for the Southwestern sites will be September 1–December 1, 2019, and May 15–June 15, 2021.

Fishlake National Forest: One burn site that may be selected is a research unit, Manning Creek, in the Monroe mountain area, at approximately 2,700 meters in elevation and approximately 500 hectares. The Manning Creek unit has an average slope of approximately 30% and is accessed from a well-maintained but narrow dirt road with a variety of access points (Figure E-2A). The forest type is conifer with a mix of spruce, Douglas-fir, white fir, and ponderosa pine with insect and disease damage (Figure E-2B). The understory fuel load is 45-270 mg/ha of grass, shrubs, woody fuels, litter and duff (Figure E-2C). The units will be burned in the fall (September-November) of 2019 or the spring (May 15-June 15) of 2021. The ignition will be by helicopter under a fire prescription and lighting pattern to obtain a free-running, stand-replacement fire that will produce a strong and well-developed smoke column (figure E-2D). The burn ignition will probably commence in the late afternoon and continue into the early evening hours, with long-term smoldering continuing for several days.

Several smaller forested “knobs” (50–100 acres), could be used for “practice” or test fires. These forested knobs would also be ignited by a helicopter to obtain a free-running, stand-replacement fire.

Kaibab National Forest/Grand Canyon National Park: Two research units of over 500 hectares are potential selections for the FASMEE project located on the North Kaibab Ranger District and the North Rim of the Grand Canyon National Park. The units have an average slope of 10 to 30% and are accessed from a well-maintained gravel road with a variety of access points (Figure E-3A, E-4A). On one unit, the forest type is ponderosa pine where fire has not entered the area for over 25 years. The understory fuel load is 40 to 150 Mg/ha of grass, shrubs, woody fuels, litter, and duff (Figure E-3B). On the second unit, the forest type is conifer with a mix of spruce, Douglas-fir, white fir and ponderosa pine, with insect and disease damage. The understory fuel load is 40 to 220 Mg/ha of grass, shrubs, woody fuels, litter and duff (Figures E-4B). The selected units will be ignited over multi-day periods allowing several large plumes to be sampled. Both units will be burned in fall (September–November) 2019, using a mix of hand and helicopter ignition under a fire prescription and lighting pattern to obtain a low to moderate mixed-severity fire that will produce a strong and well-developed smoke column (Figure E-3C).

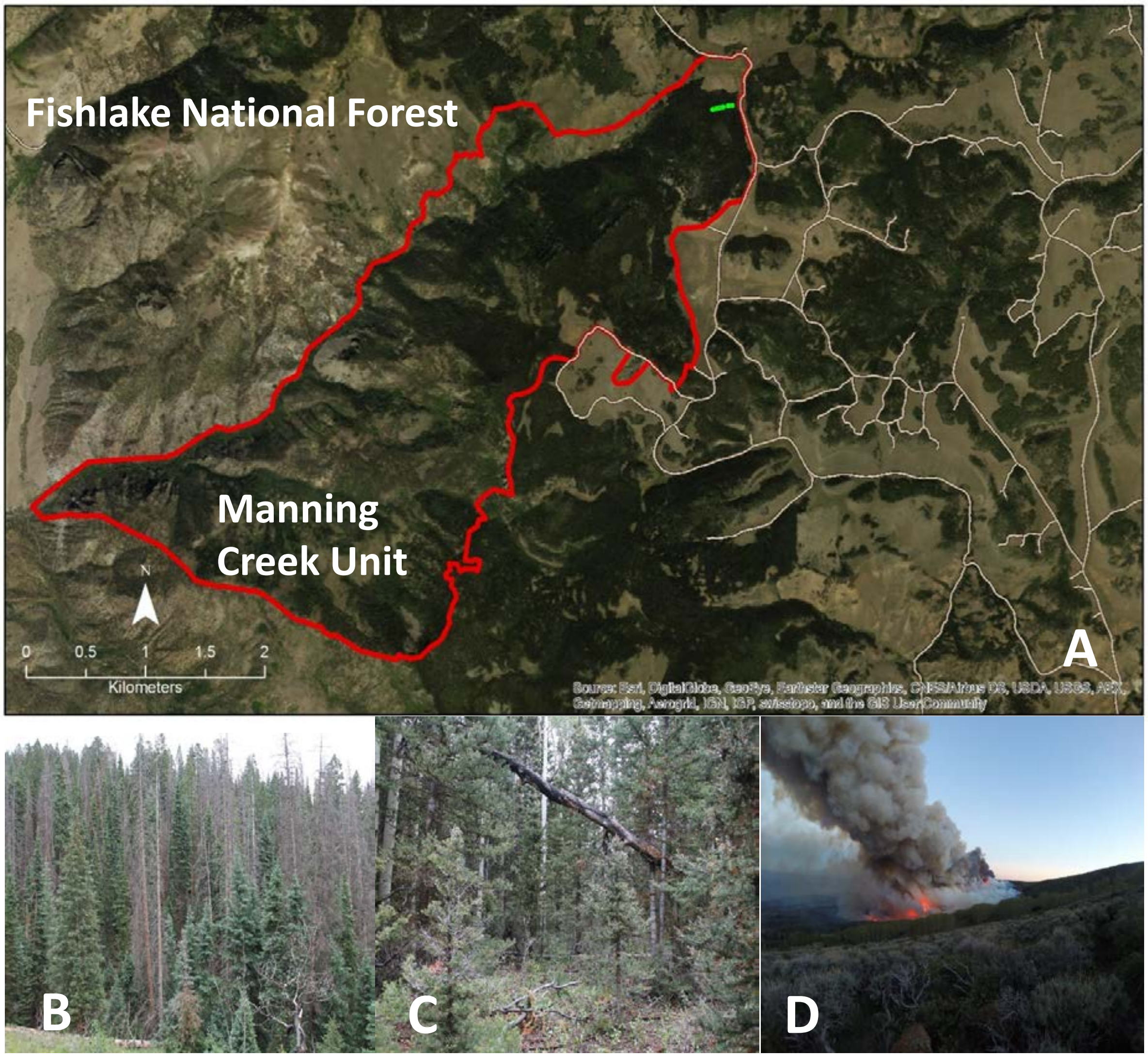

Figure E-2: Fishlake National Forest. Insect-damaged mixed conifer and aspen stand (A) with pre-fire fuel loads between 45 and 270 Mg/ha. (B and C) are proposed for a stand-replacement prescribed burn for the FASMEE project generating a dynamic plume (D). Manning Creek unit is greater than 500 ha.

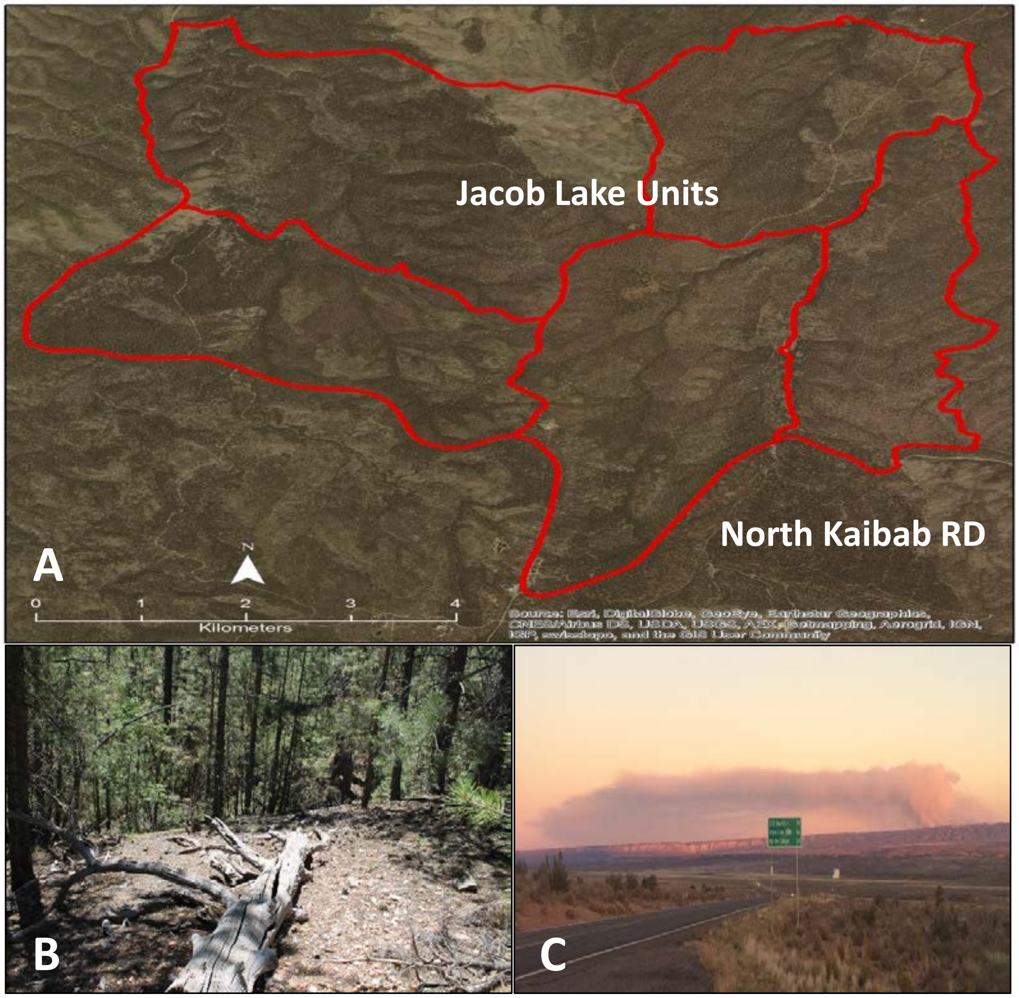

Figure E-3: Ponderosa pine stands (A) with pre-fire surface fuel loadings between 40 and 150 Mg/ha (B) that will be a mixed-severity prescribed burn for the FASMEE project that will generate a dynamic smoke plume (C). Each of the North Kaibab Ranger District Jacob Lake units is approximately 500 ha.

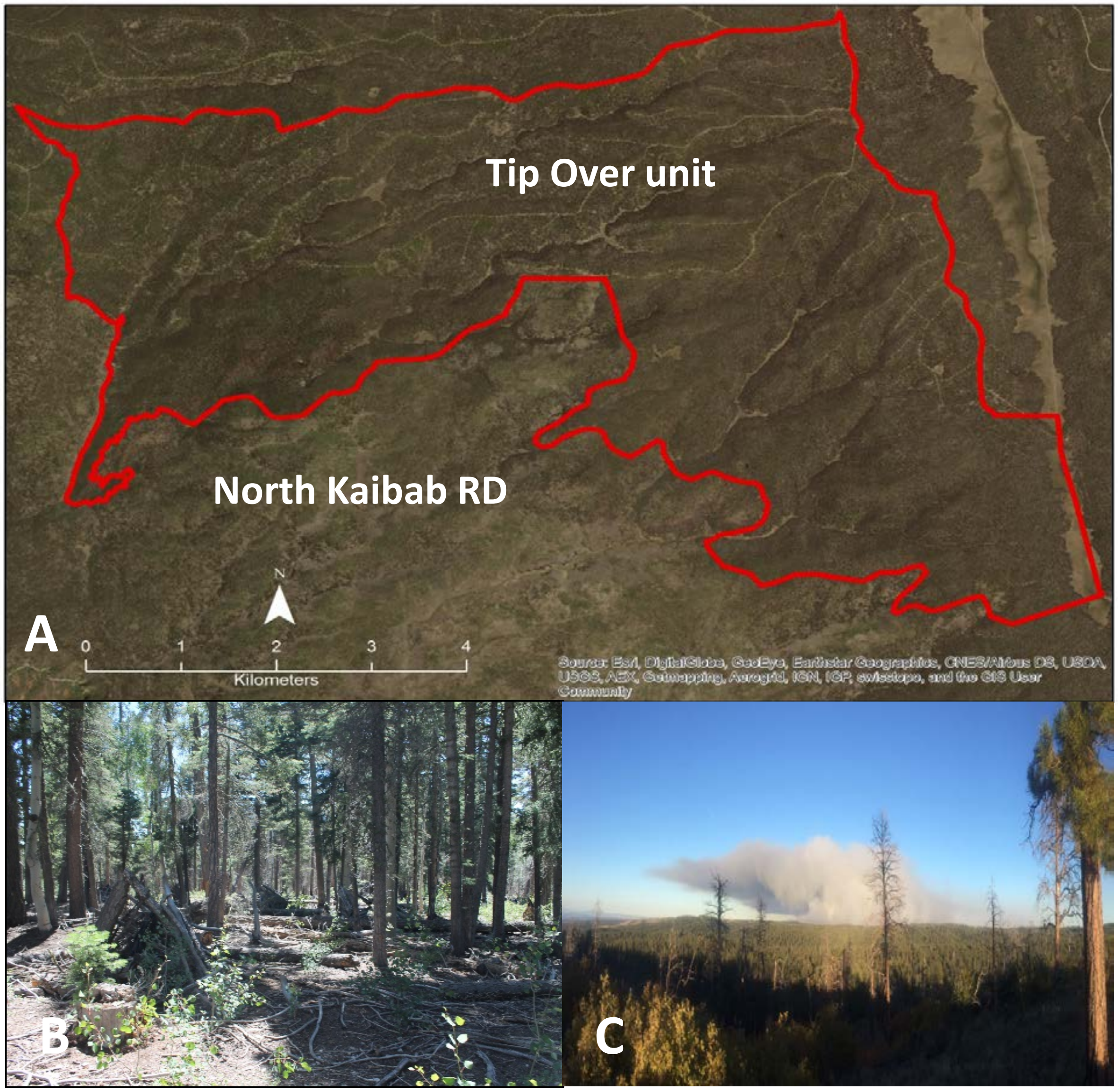

Figure E-4: Mixed conifer and aspen stands (A) with pre-fire surface fuel loadings between 40 and 220 Mg/ha (B) that will be a mixed-severity prescribed burn that will produce a dynamic plume (C) for the FASMEE project. The North Kaibab Ranger District Tip Over unit is over 500 ha.

E.4 SOUTHEASTERN FIELD CAMPAIGN 2021-2022

The Southeastern Campaign has targeted forested areas with longleaf/slash pine plantations that have not been burned for 4 to 6 years and have surface fuel loads of >30 Mg/ha (Figure E-5A). The sites are easily accessed and located a significant distance from critical smoke-sensitive areas, allowing the burns to occur with any wind direction. All fires will be ignited with a helicopter using a plastic sphere dispenser with a low to moderate fire intensity that will reduce fuel loads but maintain the over-story trees. Both the years since fire and the large unit size will provide the best opportunity to generate a dynamic and relatively long-duration plume desired by the FASMEE project.

Fort Stewart, Georgia: Four research units of about 250 Mg/ha are on the short list to be selected for the FASMEE project at Fort Stewart. The sites are in a longleaf pine-dominated forest with significant components of wetland species including black gum, water oak, live oak, and loblolly bay in portions of the drains in the burn area. Total ground fuel loading consisting of shrub and herbaceous live vegetation, woody material, pine litter layer, and a small amount of duff ranges between 40 and 90 Mg/ha (Figure E-5A). The research sites selected are flat, with easy road access to the entire unit (Figure E-5C). The sites will be burned in the winter (dormant season) or early spring (growing season) of 2021–2022 with the areas classified as a 5-year rough (5 years since they were last burned). The 5-year rough unit is expected to provide ample fuel load to produce a dynamic and well-defined plume for the FASMEE project (Figure E-5B.)

Savannah River Site, South Carolina: The alternate research area in the Southeastern Campaign will be the Savannah River Site (SRS) near Aiken, South Carolina. This property is administered by the Department of Energy and will require all participants to obtain badges for entry. Two research units for the FASMEE project have been identified, each approximately 250 ha. The units are flat with easy access to all perimeters. The units are in a longleaf pine-dominated forest that has been thinned, with logging slash on the ground. The ground fuels consist of shrubs, grasses and forbs, pine litter, and a small amount of duff with total fuel loading ranging from 40 to 90 Mg/ha. The research burns will occur during the winter (dormant season) or early spring (growing season) of 2021–2022. By the time of the experiment, it will have been 4 to 5 years since the last prescribed fire at the site. These sites will be helicopter-ignited to produce a well-defined plume.

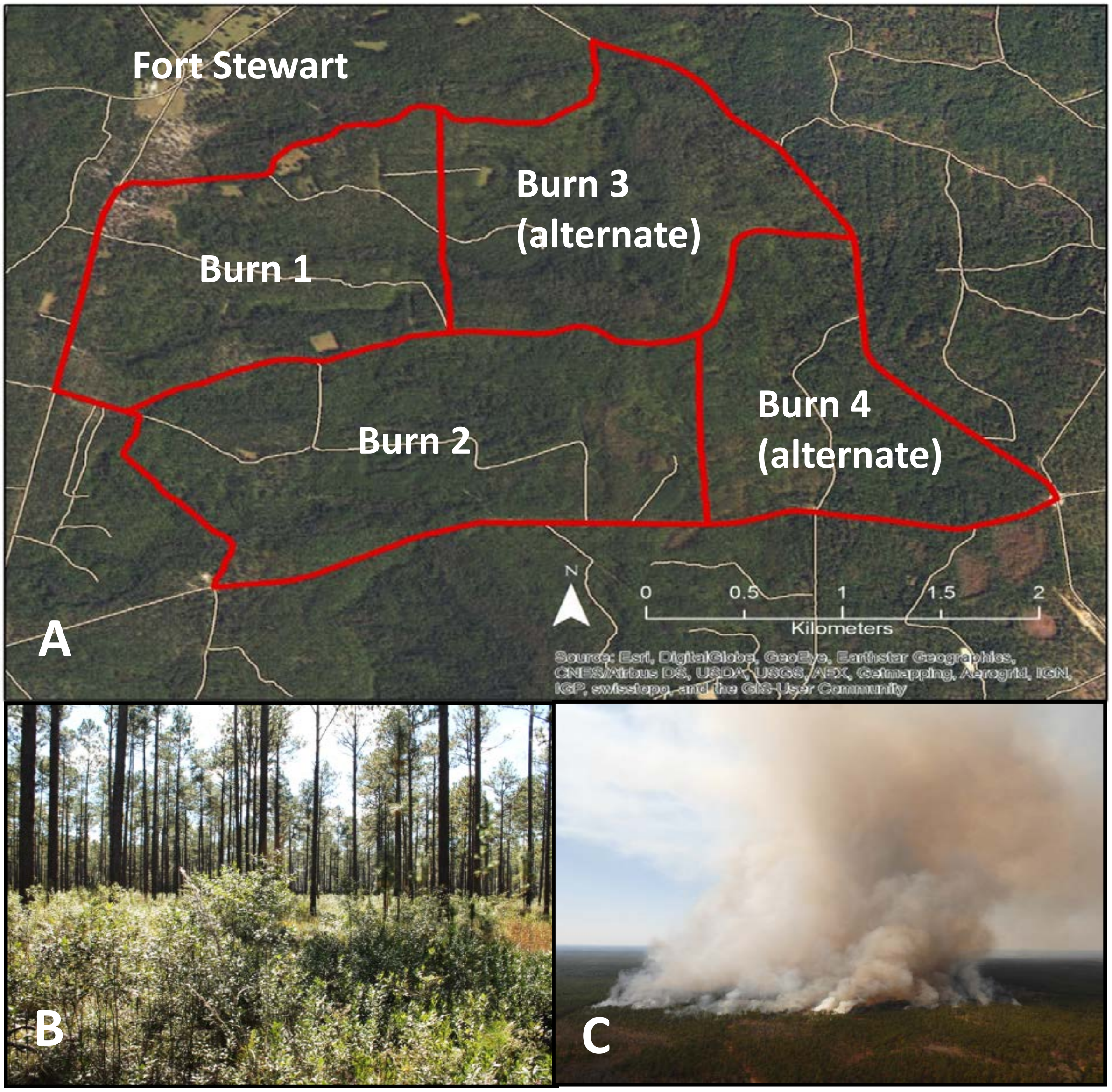

Figure E-5: Longleaf pine stands that have not been burned for 5 to 7 years with pre-fire surface fuel loadings between 20 and 90 mg/ha (A, B) are proposed for underburning for the FASMEE project, producing a dynamic plume (C). Units 1 and 2 are proposed for burning; units 3 and 4 are alternates. Each unit in Fort Stewart, GA is greater than 250 hectares.

E.5 COMMON COMPONENTS

A prescribed fire plan (PFP) will be developed in cooperation with the host agency appropriate administrator officers and burn boss, FASMEE leadership and observational teams, and science and management liaison. The PFP will be a supplement to the IAP for the day-of-burn prescriptions and required resources. The PFP will need to be supplemented on the day of the burn with detailed observations of "what was accomplished" and what deviated from the plans preferred options and conditions. The plan will include a minimum of the following elements:

- Agency administrator ignition authorization
- Prescribed fire go-no go checklist
- Objectives
- Prescription
- Scheduling
- Instrumentation
- Pre-burn sampling and instrumentation placement
- Permanently marking plots
- Pre-burn considerations and weather
- Briefing requirements
- Command and organization structure
- Equipment
- Communications
- Public, personnel, and scientist safety
- Medical plan
- Transportation and site access
- Test fire
- Ignition plan
- Holding plan
- Contingency plan
- Smoke management and air quality
- Project aviation safety plan and airspace deconfliction
- Post-burn data collection and instrument removal
- After-action review

In Phase 2, the FASMEE leadership team will begin working closely with the selected host agencies for the southwestern area to select the final research burn sites, coordinate the timing of the burns and ignition pattern, and finalize the Concept of Operations and Incident Action Plans. Observational leads will collect pre-burn data using permanently located research plots. Instrumentation platforms will be located several weeks prior to the burn window, with other discipline leads arranging aircraft and flight operations well in advance of the research burn ignition. Post-burn fuel measurements and tear-down of instrumentation will occur shortly after it is deemed safe to enter the area following the fire.

See Appendix G for discussion of sub-plans.

APPENDIX F: UTILITY OF DATA – PATHWAYS FOR USE

Once the proposed measurements are collected in Phase 2, how can these measurements be used to improve our current scientific understanding and modeling capabilities?

This Appendix identifies ways in which the data can be useful to various categories of modelling systems with three specific examples of work that might be pursued as future improvements. The modelling systems are divided as follows:

- Systems for describing fuel characteristics
- Systems focused on fire behavior
- Systems that rely on simple modeling of fire plumes

  (Examples: most current operational smoke predictions, CMAQ, BlueSky)
- Systems that model fire plumes explicitly
  (for example, WRF-SFIRE[-CHEM], WFDS, FIRETEC, MesoNH-ForeFire, or Daysmoke-RabbitRules)
- Systems that model smoke chemistry
  (examples: photochemical models such as WRF-Chem, CMAQ)

Applications of the data for each category are listed below.

F.1 FUEL CHARACTERIZATION SYSTEMS

Discrete fuel patches within fuel beds, termed wildland fuel cells (Hiers et al. 2009), have a distinct architecture, density, and composition. Fuels should be characterized at the resolution where they primarily influence fire dynamic behavior. The scale at which fuel cells in a heterogeneous fuel bed significantly influence fire behavior should dictate the resolution at which to characterize fuels by traditional means (destructively or allometrically) or non-destructively (point cloud collections with LiDAR or photogrammetry). The scale of the fuel cells should be commensurate to a 3D cell in a physical fire behavior model. Fuel cell size differs greatly between the clumps of bunchgrass and shrubs to be burned by prescribed surface fire at Fort Stewart, versus individual tree crowns that consist of canopy fuels to be burned in a crown fire at Fishlake NF. A fuel cell approach helps guide the decision of what point density to acquire. In a spatial context, it is important to oversample variation in fuel pattern, relative to the spatial scale of fire behavior and effects. Upon aggregation of fine-scale fuel measures, relative regions of homogeneity (i.e., patches) emerge. If the 3D fuel map input into the fire model captures strong gradients in fuel loads related to patchiness, then we could expect the fire intensity predicted by the model to show a similar spatial structure. If not, we would know the model is not working. In contrast, fuel maps that are truly homogeneous would result in predicted fire behavior that also appears homogeneous upon averaging multiple simulations.

Finer resolution point clouds collected by terrestrial LiDAR or structure from motion (SfM) photogrammetric methods are sufficiently dense to be binned within ~10 cm voxels at <1 ha spatial extents (e.g., HIPs) suited for the fuel data input requirements of WFDS, but they are impractical to collect synoptically across entire burn units. Coarser-resolution point clouds collected by airborne LiDAR have sufficient density to be binned at a resolution that will allow the characterization of individual tree crowns and the gap fraction within forest canopies across entire burn units and at scales commensurate with WRF-sFIRE. Fuel data input requirements of FIRETEC will tend towards an intermediate spatial scale (e.g., ~2 m voxels across burn units of ~500 ha) and will probably require a combination of point cloud datasets collected hierarchically from multiple instruments, as previously described.

Visualizations of the point clouds at full resolution (Figures F-1, F-2) provide assurance of the relevance of these data for non-destructive fuels characterization at the spatial scales at which surface or canopy fuels vary. Summarizing these data in a form useful to fuel modelers requires converting the fuels information using empirical models to a measure of fuel density (e.g., Mg/ha). This approach requires destructive samples or allometric measures of fuel load per unit area to serve as the response variable in predictive models,

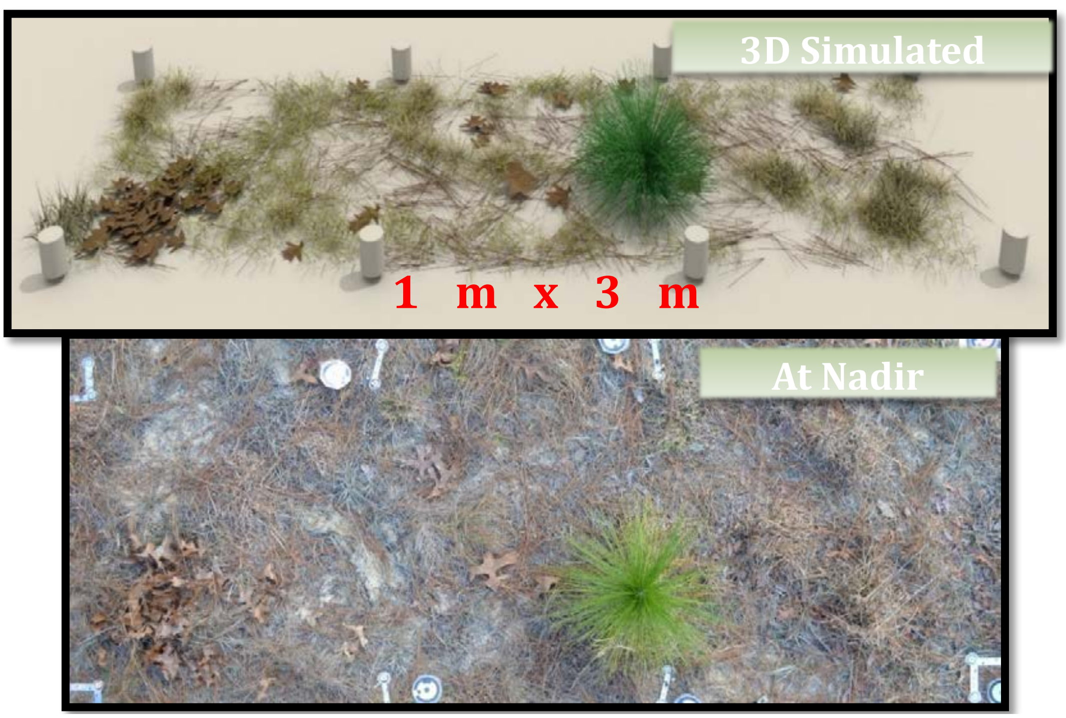

Figure F-1: 3-D rendering of a fine-scale fuel bed (top) based on digital stereo photos of the same (bottom, single photo) in longleaf pine forest, Eglin Air Force Base, Florida.

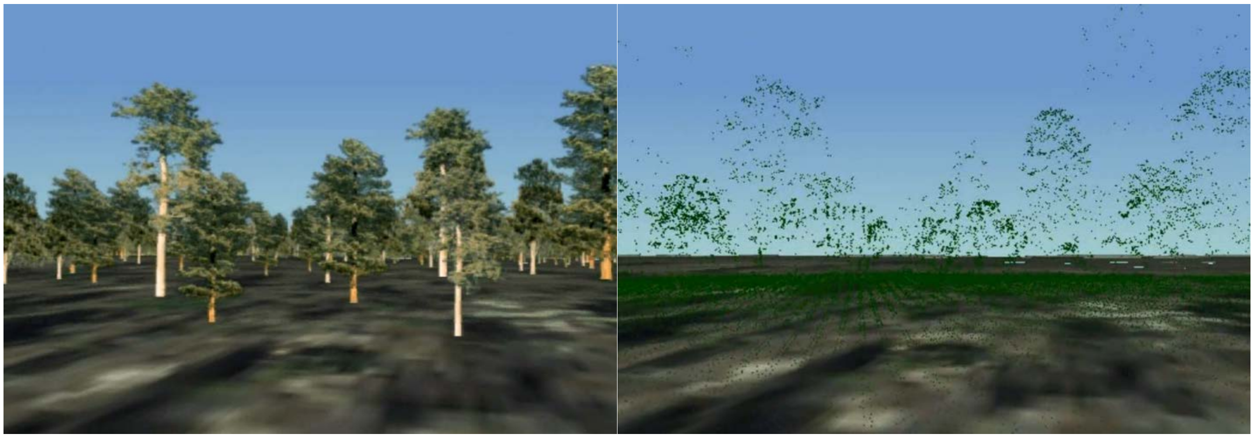

Figure F-2: 3-D rendering of canopy fuel structure (left) based on an airborne LiDAR point cloud of the same area (right) in longleaf pine forest, Eglin Air Force Base, Florida (2012 RxCADRE prescribed burn block L2F).

where metrics reduced from the point cloud data serve as the predictor variables. In a southeastern fuel type at Eglin Air Force Base in Florida, empirical modeling approaches were demonstrated for classifying fuel type at fine scales from close-range photogrammetry (Bright et al. 2016) and for estimating fuel load at coarser scales from airborne LiDAR (Hudak et al. 2016a,b). Airborne LiDAR point clouds can be used to predict canopy bulk density in closed-canopy coniferous forests (Andersen et al. 2005) and individual tree crown attributes in open-canopy coniferous forests (Silva et al. 2016).

Although spatially explicit maps of fuel density are critical for predicting fire behavior or emissions, it is actually fuel consumption that more directly drives these processes. As such, the goal for FASMEE is to map fuels at hierarchical scales both pre- and post-fire, such that differencing these maps will provide spatially explicit estimates of fuel consumption.

F.2 FIRE BEHAVIOR SYSTEMS

Current fire behavior models that explicitly model gas-phase combustion and the thermal degradation of vegetation are too computationally demanding for routine application to large area burns (>10 ha) unless the fire depth is sufficiently large (>10 m). These constraints will lessen as computational capabilities improve and more efficient numerical approaches are developed. In that case, many (if not all) of the data uses listed in E.4 (Explicit Plume Systems) apply here.

F.3 SIMPLE PLUME SYSTEMS

Simple plume systems (SPSs) aim to provide some coarse features of smoke structure, such as plume rise, vertical profile, nighttime smoke drainage instead of concentrations and the geographic distributions of air pollutants such as $PM_{2.5}$ and O_3 produced by fire emissions.

They may consist of conservation equations of mass, momentum, heat energy and water, but the related sources / sinks and dynamics are usually simplified or described using statistical tools. Atmospheric chemistry is usually excluded. Daysmoke and PB-P are examples of SPSs for day and night time smoke modeling, respectively. Land managers could use SPSs as a screening tool to predict local intensity and downwind extent of smoke plume and evaluate the impacts on air quality and road traffic. They also may be used to provide plume rise for complex air quality models.

The FASMEE measurements can be used to improve SPS modeling performance, develop new capacities, and increase scientific understanding of smoke plume dynamics, including:

- Vertical velocity and temperature at the height where fire and ambient gases are well mixed (exit velocity and temperature) are needed to drive plume rise in SPSs. These are often estimated based on heat release and other burning properties with large errors. The FASMEE measurements of fire heat and exit velocity and temperature will provide data for evaluation of existing empirical schemes. These data would improve plume rise simulation and the potential coupling capacity between fireand smoke modeling.
- Multiple updrafts are treated in SPSs by a formula relating their number to heat flux. The FASMEE energy and smoke measurements will provide data to evaluate this approach. These data can also help to develop a parameterization process to estimate the number of updrafts (see example in E.6). This would increase our knowledge of the roles of multiple updrafts in smoke dynamics.
- Entrainment is an important mechanism for smoke plume development. The entrainment rates depend on fire and meteorological conditions and vary with space and time, but are often specified with some empirical values in SPSs. The FASMEE smoke and meteorology measurements can be used to obtain more accurate empirical values and develop relations with smoke intensity and ambient wind and temperature. This would improve the modeling skills of smoke plume rise and particle fallout.
- The development of smoke eddies is affected by ambient air flows, thermal stability, and canopy. These eddies are parameterized as stochastic processes in many SPSs, without consideration of canopy impacts or sufficient evaluation, because of the lack of high-resolution atmospheric turbulence measurements. The FASMEE smoke and meteorology measurements can help fill this gap.
- The FASMEE measurements will provide useful data to simulate and understand formation of smoke drainage and superfog and the effects of topography during nighttime. The SPS simulation skills are limited because of the lack of high-resolution weather information, especially at burned sites with complex

topography. The FASMEE measurements help to specify nighttime smoke emissions, weather, and ground smoke particle measurements for model initialization and evaluation. Furthermore, current models have many assumptions that are often inaccurate. For example, the drainage in PB-P is assumed to be a shallow layer, which could be not appropriate in an area with a deep valley. Some of these assumptions could be removed through analysis of the FASMEE smoke and meteorological measurements.

F.4 EXPLICIT PLUME SYSTEMS

Measurements of the fire progression, heat release, thermal plume structure, and micrometeorological dynamic and thermodynamic measurements near the fire would allow for thorough evaluation of and improvements to capabilities of coupled fire-atmosphere models. These measurements would enable identifying deficiencies in the modeling components, limiting overall capabilities of coupled fire-atmosphere models in simulating fire plumes. In particular, these measurements would help to answer basic evaluation questions, such as:

- Is the fire spread component adequate to resolve fire heat fluxes to a degree needed for realistic plume rise rendering? If not, what is the main reason for this? Is it the limitations of the fire spread model itself, inability to resolve local winds, or limitations of the input datasets (e.g., lack of high-resolution spatial fuel moisture data)?
- Is the fidelity of the fire spread component of the model high enough for accurate plume-rise simulations, and is the fire geometry resolved well enough for the plume rise computations?
- Is the vertical distribution of the heat flux from the fire to the atmosphere resolved accurately?
- Are the plume dynamics realistically resolved by the WRF dynamical core or the hydrodynamic solvers in MesoNH, FIRETEC, and WFDS, as well as other models?
- Are the properties of the smoke plume and the ambient air resolved accurately? Is the impact of the fire on the ambient weather conditions resolved accurately?
- Are the modeled emission fluxes estimated accurately? If not, why not? Are the emission factors responsible for that or rather the fuel consumption estimates? How important is smoldering in this context?
- Are the fire-atmosphere interactions, including the impact of fire smoke on atmospheric radiation and microphysics, represented adequately in the coupled fire atmosphere model? How important are they?

Integrated measurements would also allow addressing the following specific modeling issues:

- Simultaneous sampling of fire plume properties at different heights, including updraft speeds, turbulent fluxes, temperatures, and smoke measurements, to permit assessment of the actual entrainment rates and the model's ability to resolve turbulent mixing between the plume and the ambient air.
- Measurements collected during large-fire experiments that would allow for a comprehensive evaluation of model capabilities to simulate pyrocumulus clouds and their plume injection heights.
- Measurements of the propagation of the entire fire perimeter (including flanks), together with in situ wind observations, to improve the understanding of flow near the fire flanks and assist with future flank spread parameterization for simpler models that do not explicitly simulate combustion processes.
- Measurements of heat fluxes and vertical velocities from fire plumes big enough to be simulated using coarser resolutions, to help determine the model's ability to realistically render pyro-convection at operational forecast resolutions. This information would provide guidelines in terms of spatial resolutions needed for direct plume-rise simulation.
- Observations of the radiative and total heat fluxes at various levels above the fireline, to help delineate the heat extinction depth and develop a method for partitioning between convective and radiative heat fluxes.
- Integrated aerosol measurements to help determine the relationship between radiative heat absorption and simulated smoke concentration.
- Integrated observations of concentrations of primary chemical pollutants in and downwind of the plume, accompanied by ozone measurements, to help locate model deficiencies in simulating elevated ozone levels from wildland fires.
- Integrated measurements of smoke aerosols and radiative fluxes, to provide a better understanding of radiatively-active plumes, and validate model capabilities to render density currents associated with smoke cooling effects.
- Integrated measurements of fuel consumption and smoke emissions, to allow for improving emission estimates through implementation of partitioning between open flame and smoldering emissions.

F.5 PHOTOCHEMICAL SYSTEMS

The FASMEE field campaign provides a unique opportunity to obtain surface, canopy, and upper-air measurements of different specific fire events. This would allow us 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). It is anticipated that measurements from this field study will lead to improved:

- Emission rates for different fuel types;
- PM, VOC and nitrogen speciation by fire type and phase of combustion;
- Distribute plumes spatially and temporally;
- Differentiation of smoldering and flaming portions of the fire event;
- Near-fire and downwind chemical evolution;
- Optical properties of plumes.

This field study is also expected to provide valuable information to improve other less anticipated aspects of fire emissions and air quality modeling as work intensifies in this research area.

As envisioned by FASMEE, a well characterized wildland fire-event, in terms of fuel type, fuel loading, canopy, and surface characteristics used to estimate fire event emissions, can be compared with methods now used for fire event emissions estimates in the National Emission Inventory (NEI)(e.g., SmartFire and BlueSky), with the following anticipated improvements: (1) better emissions estimates by fuel type and combustion conditions (e.g., flaming to smoldering components of the fires); (2) better characterization of understory burning, which would also fill a critical gap in emission inventory development and modeling; (3) improved PM, VOC, and nitrogen gas speciation of fire emissions and a better understanding of appropriate speciation for modeling fires at different scales. Currently, speciation of VOC and nitrogen gases of fire emissions for different fuel types and combustion conditions are poorly understood, yet they have significant impacts on both primary emissions and subsequent downwind secondary chemical pollutant production. Near-event and downwind measurements of O_3, $PM_{2.5}$, their precursors and important chemical intermediate species, along with distance and time from the fire event, would provide critical understanding of near-fire chemistry and downwind chemical evolution of these pollutants during both day and nighttime hours; (4) improved spatial allocation of smoldering and flaming emissions for both prescribed and wild fires.

F.6 EXAMPLE OF IDENTIFIED STUDIES

F.6.1 Smoke Plume Model Development Using Burner Method

As has been discussed, models that explicitly simulate gas-phase combustion and the thermal degradation of vegetation (e.g., FIRETEC and WFDS-PB) are likely to be too computationally demanding for routine simulation of large area burns (>10 ha) characteristic of most of the FASMEE burns. Other model approaches, such as WRF-SFIRE, WFDS-LS, MeshNH-ForeFire, and Daysmoke-RabbitRules, rely on simple fire spread models (with largely unknown errors) for the location and duration of the fire. It would be advantageous to eliminate the need to simulate the fire, explicitly or implicitly, and use measurements to prescribe the heat and mass generated by the fire. An approach has been formulated that does this and is called the burner method. The process would allow all of the above-mentioned models to be consistently applied to smoke plume rise and their outcomes compared.

Advantages

The burner method is a process where the heat and mass generated by the fire is prescribed based on field measurements. The major benefit of the burner method for modeling is that it provides any model that explicitly resolves plume dynamics with sufficient information to model plume rise without having to model wildland fire behavior.

The burner method also simplifies and focuses the measurements. The key FASMEE measurements for this purpose are (1) the minimum set that results in the determination, at all locations along the fire perimeter relevant to smoke plume formation, and (2) the time-course of heat and mass fluxes generated by the fire; that is, areas of active flaming are idealized as "burners".

Implementation

In general, the burner method needs the following measurements and information.

- Characterize the location, fuel consumption rate, and flame residence time of areas aflame that are associated with sufficient heat generation to influence plume formation and rise. At a minimum, this should be measurement of head fire regions along the fire perimeter. More specifically, the minimal set of measurements needed must include:
    - Flame-front position from qualitative airborne infrared or visible imagery at the highest spatial and temporal resolution possible to provide spatiotemporal information for "igniting" burners.
    - Fuel consumption rate from pre- and post-fire fuels or time-integrated quantitative airborne infrared radiation to estimate total heat generated (see Appendix C1).

  - Fire rate of spread (ROS) from qualitative airborne infrared or visible imagery at the highest spatial and temporal resolution possible (see Appendix C2). ROS, in combination with other data, can be used to estimate other flame front characteristics such as residence time. The residence time may be more directly measurable from imagery, thus avoiding the need to determine the ROS.
  - The time-course of flame-front heat generation, which at its most basic is an average rate over the flame-front residence time (see Appendix C2).
- Pre-fire vegetation and terrain measurements are needed to help develop the strategy for locating the ground-based fire measurements to support the determination of flame front residence time and burning rate per unit area.
- Gather information from the FASMEE burn bosses and past experiments (RxCADRE) on expected fire behavior (e.g., fire depth, spread rates, and the influence of vegetation types), ignition procedures, and measurement performance (when available) for each candidate site. This is critical for assessing the scope, location, and the resolution of both the ground and airborne-based measurements.

The burner approach would support a range of smoke plume-rise models, including both current and future models.

To apply the burner method at its simplest level, heat derived from fuel consumption is emitted at an average rate over the flame-front residence time. There are several approaches to estimating either consumption rate or residence time, but must be coordinated strategically across burn units to account for these. Approaches include:

- Combustion rate—Where fires are sub-pixel, the fractional area of the pixel over which above-background radiation is emitted can be estimated from quantitative bi-spectral infrared data and ancillary data on either flame-front emissivity or flame depth. Flame depth and pixel width can be used to estimate fire area within a pixel in a rough way. Knowing fire area would allow an estimate of average flame-front fire radiated flux density (W/m^2), which, in turn, has been directly related to combustion rate in experiments. Coordinated field measurements are needed to determine reasonable values for flame-front emissivity from a nadir perspective.
- Residence time—Flame dimensions (e.g., length, depth) have been related through dimensional analysis to combustion rate in spreading fires. Flame depth is related to residence time through rate of spread. Coordinated measurements in FASMEE would allow the evaluation of relationships for the fuel types in which fires are conducted.

- Residence time—Thermocouple response to flame arrival and departure can be used to estimate residence time. Thermocouple response can also be used as an index of the time-varying heat-release rate over the residence time of flames. Thermocouple measurements should be coordinated with other planned ground measurements.

Figure F-3 illustrates a plume generated by a burner, showing smoke plumes from two line-burners using MesoNH (a model similar to WRF).

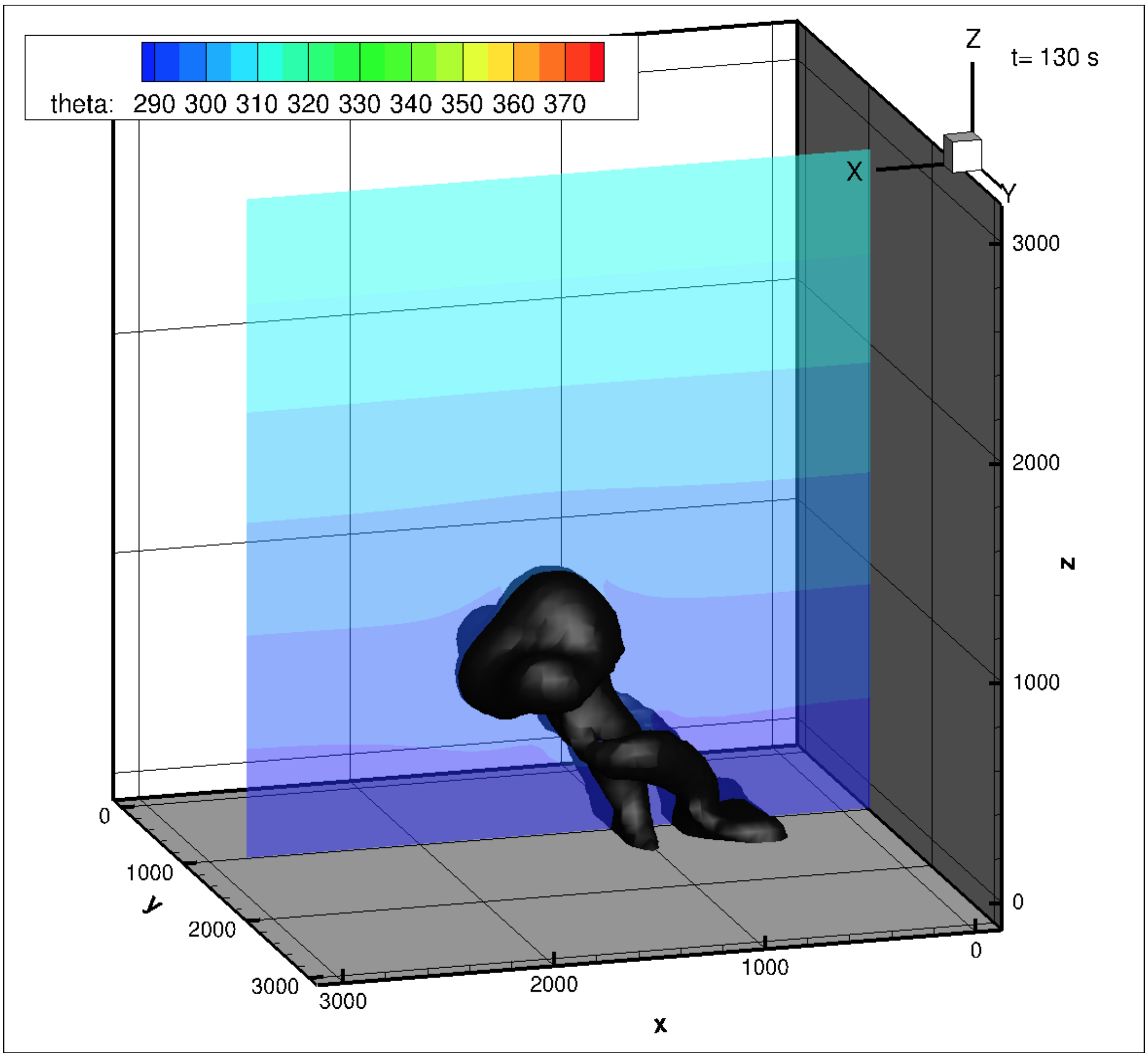

Figure F-3: Output from MesoNH from a simulation with two burners. The heat release rate per unit area was based on measurements in the International Crown Fire Modeling experiments.

F.6.2 Spread Rate from Overhead Imagery

FASMEE will allow the further development of methods to characterize the rate of spread from overhead infrared imagery. Creating a viable method has applications not only for research purposes, but also potentially for fire management and firefighter safety, where increased use of drones and aircraft allows for greater continuous observation of wildfires.

An example is shown in Figure F-4 for experiment 703C at Eglin Air Force Base. This fire was ignited by helicopter via "ping-pong balls" over a domain of approximately 4 km x 3 km. At 10-m resolution, the figure shows output from MesoNH simulating a small (~200 m x 300 m) area in the burn plot. Ignition lines can be seen as locations with relatively few spread vectors. Figure F-5 shows that obtaining a measure of the spread rate is feasible. Work is continuing on this measure to assess the sensitivity of the method to spatial and

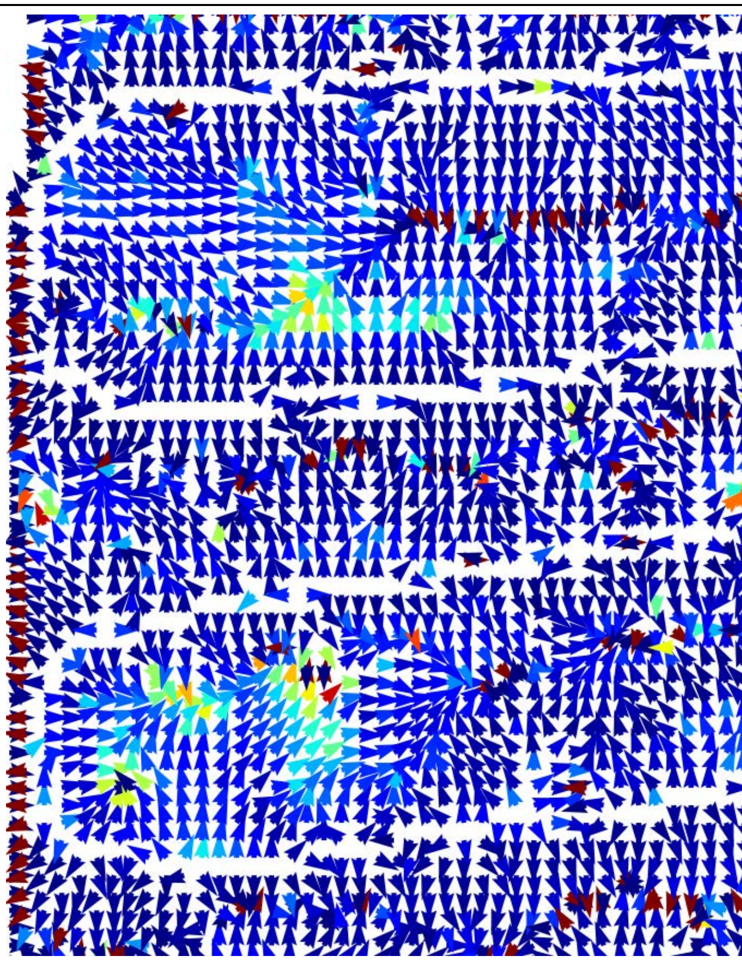

Figure F-4: The rate of spread field over part of burn unit 703C at Eglin Air Force Base (approx. at 200 m x 300 m area is shown) estimated from sequential infrared images. The direction of an arrow indicates spread direction; color represents rate, with rate of spread increasing from cool to hot colors.

temporal resolution. High-resolution imagery obtained by FASMEE will help advance this effort to progress.

F.6.3 Fuel Consumption from Quantitative Airborne and Satellite Infrared Imagery

A growing body of literature, with relatively consistent results, relates fire-radiated energy density (FRED)(J/m^2) to fuel consumption. FRED is derived from time-integrated fire radiated flux density (FRFD)(W/m^2) estimated from quantitative nadir airborne infrared imaging. The experimental work underlying the approach includes stationary fires and one outdoor experiment with spreading fires (Figure F-5). FASMEE measurements will add to that body of work and also explore key uncertainties in the method. In particular, the approach hinges on an estimate of fire-radiated fraction, i.e., the fraction of total energy generated by the fire that is detected as radiation. That fraction has not been estimated for crown-fire flames, large surface fire flames, or a range of wildland fuel types. Estimating the fraction of radiation emitted by flaming versus smoldering is also important for plume rise and would be a valuable addition to the FASMEE measurement suite.

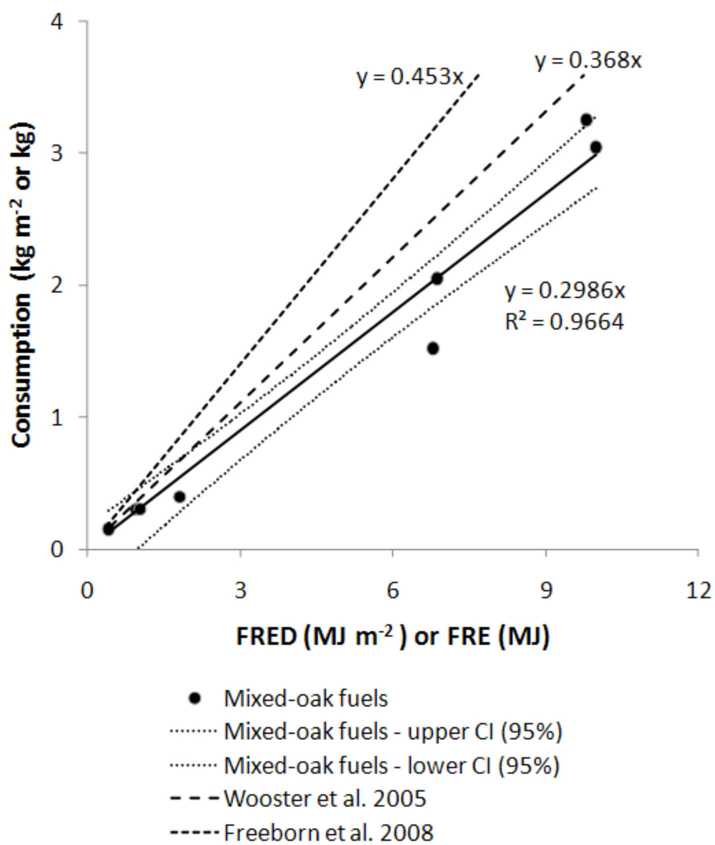

Figure F-5: Relationship between fuel consumption and FRED from spreading fires in mixed-oak fuels (from Kremens et al. 2012).

F.6.4 How to Estimate the Number of Multiple Updrafts

Many sub-plumes (see Figure F-6) form from variables such as the differences in heat released along the fireline, local terrain, wind channeling through vegetation of varying density, and natural atmospheric processes that organize convection. All of these variables are on fine scales and organize to eventually merge into stable columns (cores) of smoke. High-resolution fire energy measurements of structure and dynamic variation can be used to display clearly separate patterns related to ignition patterns and fuel structure. Some spatial tools such as wavelet transform can be used to identify the major separate spatial systems. Minimum size thresholds of the separate systems can be linked to individual smoke plume updrafts. One possible applications of FASMEE measurements is to develop a multiple sub-plume parameterization scheme. This scheme would provide the number of multiple updraft cores based on the measured fire energy and smoke plume number, using techniques such as similarity theory.

The Rabbit Rules Model (RRM) (Achtemeier et al. 2012) is a "rules"-based fire spread model to estimate the number of multiple updraft core number. It is in the very early stage of development and has not been systematically evaluated. The number is determined based on individual air pressure cells created by complex spatial patterns of ignition, fuel, emission, and interactions with the ambient atmosphere. One problem with RRM is that it sometimes may produce too many small air-pressure cells during the burning period, which probably does not represent actual smoke plumes. FASMEE measurements provide high-resolution fire-radiative power and energy, air pressure, and smoke plumes. This will establish a cut-off scale to exclude using some air pressure cells to account for the number of multiple smoke updrafts.

Figure F-6: Photo capturing the development of more than 3 major sub-plumes from a prescribed burn in Fishlake National Forest, UT during June 2016.

APPENDIX G: LOGISTICS PLANS

Given the size and complexity of the recommended field campaigns, FASMEE will require a detailed operational logistics plan called a concept of operations (CONOPS), to be developed in conjunction with each host agency of the Southwestern and Southeastern Campaigns, and with incident command associated with rapid deployments during the Western Wildfire Campaign. Although each CONOPS would discuss similar critical aspects of the designated burns, subplans such as the incident action plan (IAP), Aviation Safety Plan, and Communications Plan would be individualized to account for specifics identified by the host agencies for the prescribed burns or the incident commanders for the western wildfires. Examples of plan elements include:

- Site access will be controlled to ensure both safety and lack of contamination of the broader burn area;
- Site access will be by road to the border of the burn site;
- Site access will require check-in / check-out and radio communications;
- A logistical staging area will be located as near as possible to the burn area without compromising safety;
- Towers, man-lifts, and other specialized equipment that is climbed on by personnel will be required to meet federal safety standards;
- Use of any hazardous material must be identified in advance and a mitigation and contingency plan developed with the host agency; and
- Sites will be rugged with considerable fuels and the standard hazards of field travel and working conditions.

The sections below provide a sample of elements within a CONOPS for the FASMEE project.

G.1 COMMAND STRUCTURE

The FASMEE project will conduct all fire and aviation activities following the standard guidelines of the National Wildfire Coordinating Group (NWCG), U.S. Forest Service (USFS), National Park Service (NPS), Federal Aviation Administration (FAA) and/or Department of Defense (DoD), depending on location the burns are conducted. The CONOPS follows the standard Incident Command System (ICS) organizational chart that is used by agencies when conducting prescribed fire activities (see Figure G-1 for an example). The entire FASMEE project personnel will be under organization control of the Research Branch Director. Air operations will be coordinated by the Air Operations Branch, which works as a bridge between research and operations. The Research Branch Director will coordinate all research activities with the incident management team (IMT), incident commander (IC), or burn boss (BB). Organizational structures may vary slightly among host units, but all will be detailed in an Incident Action Plan prepared for individual planned burns.

Many ground-based research scientists are expected, divided into multiple disciplines for each of the Southwestern and Southeastern Campaigns. These disciplines will have research equipment co-located within the fire perimeter or adjacent to the fire perimeter. Each research discipline will be assigned a fully-qualified single-resource boss (SRB) or squad boss (SQB) who will coordinate the movement of researchers with the research branch director (FASMEE liaison) during the operational periods. Aviation assets, including all UAS, will be coordinated through the aviation branch director, based on a detailed aviation plan attached to every IAP. The UAS airspace authority and operations protocols will follow FTA procedural policy. The research branch director will work directly with the aviation branch director to ensure that research needs are met without compromising the safety of manned flights or operational objectives. The complexity may require that FASMEE bring in additional support with a logistics and safety officer from a Type I, II or III team that is familiar with the host agency operations.

Aviation assets will follow standard FAA separation rules, and all aircraft will be coordinated through the air tactical group supervisor (ATGS) in conjunction with the aviation branch director. For example, protocols governing UAS operations will follow

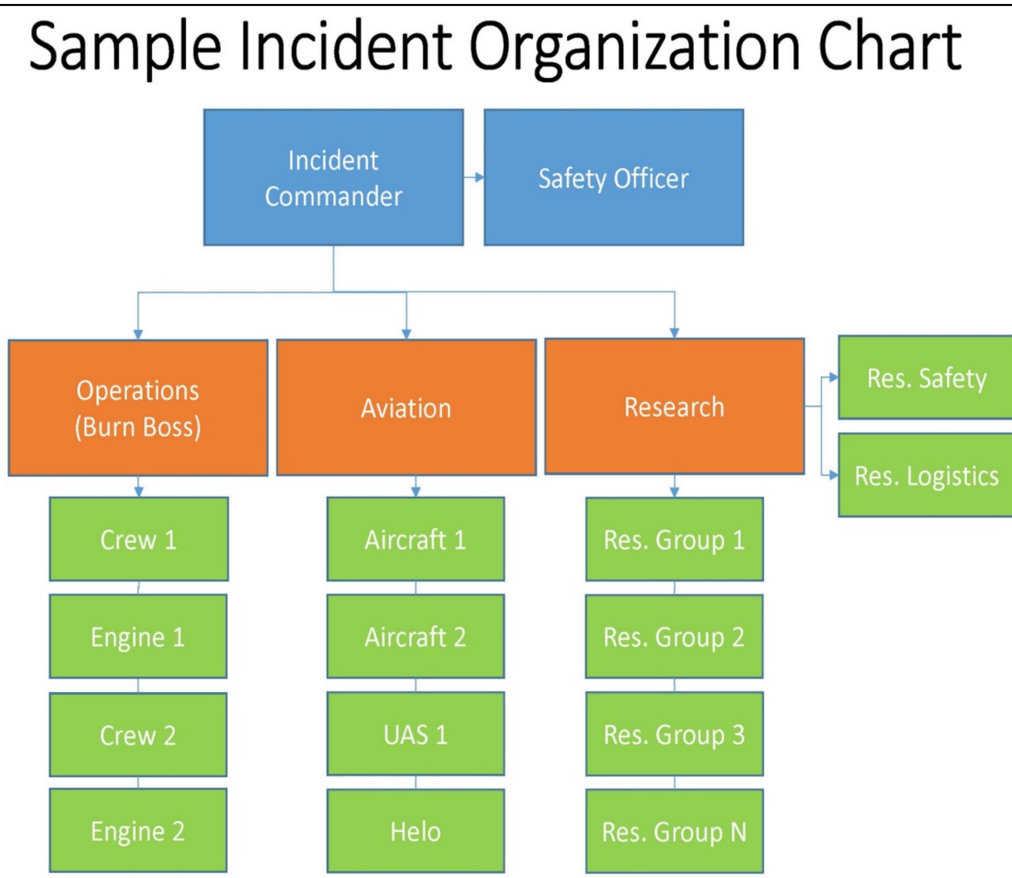

Figure G-1: Sample incident organizational chart for FASMEE research burns.

those of the FAA UAS test site network, which was established in 2013 to promote the development of rigorous, safe procedures for integrating UAS in to the National Airspace System. Before clearance for operations, UAS operators will be required to demonstrate compliance with airspace, communications, and traffic deconfliction protocols. A Temporary Flight Restriction (TFR) will be applied for through coordination with the FAA, but is not guaranteed. The TFR will be for each FASMEE research burn area to alert non-fire aircraft to the hazard and for additional safety assurance. Notices-To-Airmen (NOTAMs) will be posted where relevant. Fixed wing manned aircraft will be operated from local and regional airports. The UAS will be launched and recovered from near the fire activity, depending on the mission, range, and requirements of the UAS (e.g., larger UAS may need improvised runway areas, while small UAS and/or rotary-wing UAS may be hand-launched or launched from unmodified surfaces). The helicopter used to begin the aerial ignition may be co-located at a temporary helibase, to be determined by the Incident Commander. It is anticipated that multiple atmospheric sampling balloons will need to be launched during the operational period, and this will be conducted and coordinated through the aviation branch and research branch. A tethered balloon to sample atmospheric conditions during the operational period could also be used. The raising and lowering of tethered resources will be coordinated through the aviation branch (and communicated to the research branch) to deconflict low-altitude airspace with the UAS.

G.2 AERIAL AND AVIATION

A variety of aviation assets will be part of the FASMEE projects, including manned and unmanned aircraft systems and tethered and non-tethered balloons before, during, and after each research burn. All aviation assets will follow strict protocols as outlined by the aviation plan.

G.2.1 Aviation Separation

All aviation assets will follow a separation protocol as outlined by the aviation plan. The plan will be designed to eliminate the possibility of mid-air collision. Figure G-2 provides an example of such a potential separation plan.

G.2.2 Aerial LiDAR

All burn units will be remotely scanned before and after the prescribed burn experiments with airborne LiDAR. The platform for airborne LiDAR will be a Cessna or similar small aircraft. LiDAR is an optical remote sensing technique that uses returns from laser pulses to measure surface texture of objects on earth. This form of LiDAR is “eye safe” for ground personnel. Air operations prior to the FASMEE check-in will be directly coordinated with the host agency per their policies.

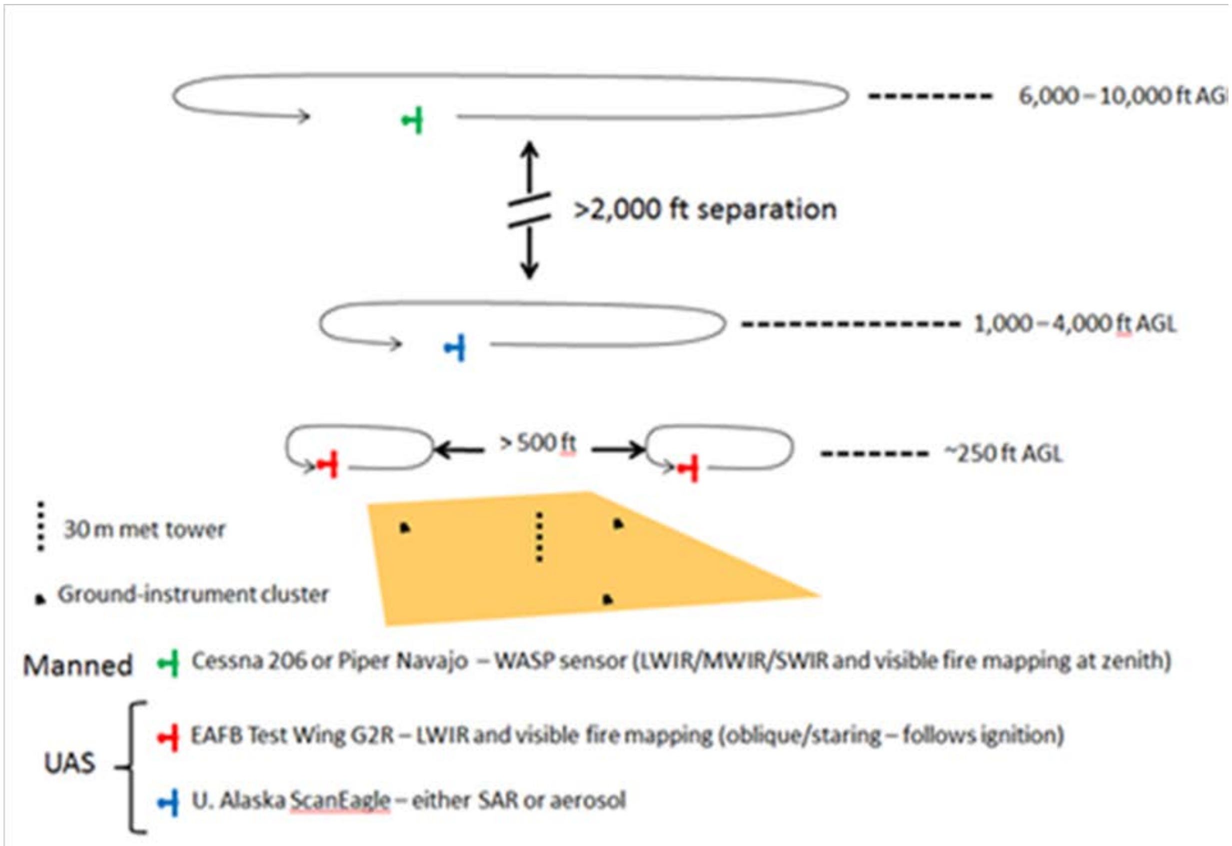

Figure G-2: Example of flight operations separation zones for manned and unmanned aircraft.

G.2.3 Other Manned Aircraft

Other manned aircraft are expected to be involved at altitudes ranging from 500 to 10,000 feet above ground level (AGL), flying patterns above, below, and adjacent to the smoke plume. Some of these aircraft will actually follow the plume, sampling as the plume degrades over time. Current research estimates have the aircraft following the plume in excess of 40 km downwind for durations up to 10 hours. Each flight is expected to meet FAA work rest ratios for pilot and crew, and be rated for altitudes for which missions are planned.

G.2.4 Unmanned Aircraft Systems (UAS)

Multiple types of UAS are expected to be involved during the FASMEE experiments to collect low-altitude data. These systems could include (1) multi-rotor aircraft; which have a relatively short flight duration of about 30 minutes and would be operated at altitudes below 400 feet AGL, and (2) medium-endurance fixed wing aircraft, which can fly at higher altitudes for longer periods (>1 hour).

As each UAS completes its flight mission, it will be autonomously commanded back to its designated landing area(s) and, time permitting, batteries replaced for follow-on flights. Each UAS will have its own assigned rally and loss of link points established in the adjacent areas near its launch point. In the event of a loss of link between pilot and aircraft, the aircraft must be programmed to return to its lost link rally point, at which time the pilot should attempt to re-acquire positive control of the aircraft. If positive control of the aircraft is not possible, the aircraft must land immediately through pre-programmed controls.

The following are go-no go criteria for UAS takeoff:

- Functional UAS (per operator and host agency requirements);
- Scheduled TFR airspace boundaries will be applied for and available and briefed to UAS operators;
- Tethered radiosonde airspace boundaries briefed to UAS operators (if applicable);
- Acceptable weather conditions for UAS flights;
- Real-time, 2-way communications between air tactical group supervisor and research branch director;
- Communications network with incident commander, burn boss, UAS project engineer (FASMEE team lead), and all UAS teams;
- At least a one-nautical mile lateral separation between the manned smoke aircraft and the UAS loiter pattern during fire initiation.

Some UAS operations will be relatively close to the active burning environment, and the thermal effects of the fire on UAS operations may be significant at western sites. Smoke plume temperatures at the canopy height of 10 meters have not exceeded 100°C in previous fire experimental burns, but crown fires at western sites could put temperatures in excess of 100 °C at heights of 90+ meters. In the eastern US, plume temperatures measured within the canopy (~30 meters) are rarely more than 60 °C, and decline rapidly above the canopy because of convective cooling of in-drafts. At the Southeastern Campaign sites, operational environment of UAS flying in the plume between 250–500 feet AGL are not expected to exceed 35–40 °C, which is the equivalent of operations on a summer afternoon. At the Western and Southwestern sites, each discipline team must quantify the operational limits of temperature and updrafts that proposed UAS will encounter.

Moderate to heavy turbulence will characterize the wind environment of the plume at UAS altitudes. On 10-meter towers under the canopy of previous research burns, vertical winds never exceed 10 knots, and above the canopy, 5-knot updrafts have been rare. In-drafts and ambient wind speeds could exceed published wind tolerances for small UAS. Whether winds are at a safe speed for aircraft operations, will be at the discretion of the pilots of these aircraft. Turbulence is more likely to negatively affect the stability of a hand-launched

UAS. Again, whether to fly or not will be the pilot's judgment. If wind speeds are greater than what is safe to fly, the pilots will relay this information to the Research Branch Director, who will consult with the research teams and IC to formulate an alternative plan for collecting the data.

G.2.5 Tethersonde Balloon

Research teams in past fire field experiments have deployed tethered radiosonde balloon systems (Aerostat) equipped with sensors for wind and temperature profile, black carbon and particulate matter (2.5 micron). In general, the balloon is filled with helium and is approximately 15 feet in diameter, but tethersonde designs vary considerably. A high-strength cable attached to an ATV/UTV should support all tethered sampling, or use a fixed anchor on the ground manned by a dedicated operator and a team of research support staff. Raising and lowering of the tethersonde will be allowed only with permission from the incident commander or organizational designee, and 500 feet separation should be maintained from UAS at all times.

G.2.6 Aviation Pre-Brief

Before the first prescribed burn operation, the forest aviation officer (FAO), forest area supervisor (FAS), or their designee, along with the incident commander/burn boss, should host an "All-Hands In-brief" with all the participating units, pilots and UAS operators to discuss the events timeline and burn operation details. The brief should cover the following: communications plan, forecasted weather, safety requirements, accountability, local area brief to the manned and unmanned aircraft operators, burn operations, and contingencies. Once the required in-brief has been completed, support trailers, generators, UAS and other logistical support equipment should be transported to the appropriate research area and set-up.

Absolutely no aircraft will be allowed to fly until the FAO has given the aviation in-brief, and a completed project aviation safety plan (PASP) has been completed and approved according to the Host Unit guidelines.

G.3 INCIDENT ACTION PLAN

The Incident Action Plan (IAP) is a document that explains how the overall incident is managed. The IAP includes the following: incident briefing, incident objectives, organizational chart, division group assignments, incident communications plan, medical plan, safety plan, aviation plan, safety analysis, and other plans/forms required by host agencies that might need to be included (e.g., prescribed fire plan, project aviation safety plan).

The host agency will complete these activities before conducting a project. The FASMEE leadership team will consult with the host agency's representative to add required FASMEE documents to the plan, such as research objectives and research aviation assets and their control frequencies. The FASMEE research branch director will complete an ICS Form 204. This assignment list will be delivered to the host agency representative before completion of the incident action plan. These documents cannot be completed now because of unknown factors, including number of researchers, number and types of research aircraft, unknown frequency requirements, unknown weather conditions, and road conditions at the unit.

G.4 PRESCRIBED FIRE PLAN

The prescribed fire plan will be an added addendum to the IAP in the final documentation and will be written by the host agency with consultation from the FASMEE leadership team.

The FASMEE IAP will follow a similar format to a 2011 IAP from the RxCADRE project. The FASMEE plan will also include a PASP that covers UAS operations and includes go-no go checklists.

G.5 LOGISTICS PLAN

Forest aviation officers need to be contacted to seek their input, guidance and approval for the use of UAS systems on their forests. This should be done as soon as possible, both because policies change with different agencies, and to introduce the FAO to the project. Involving these subject matter experts will provide additional leverage in scheduling TFRs and coordinating with the FAA.

For high-elevation sites, such as Fishlake NF at 9,600 feet (Southwestern Campaign), aircraft instrumentation in the experiment need to be certified in a pressured cabin environment because the aircraft will be flying well above 10,000 feet. High-altitude flights will require additional clearances through the FAA. Aviation charts of the area must be reviewed for jet routes that pass near or over the site. For example, at Fishlake NF, the burn site falls into the jurisdiction of the Salt Lake City air route traffic control center (ARTCC), but Denver Center is only 50 nautical miles (nm) to the east and south and Los Angeles Center jurisdiction is less than 60 nm to the southeast and southwest. A typical TFR has a radius of only 5 nm and extends only up to 2000 feet above the highest land elevation or highest aircraft. However, because of the many jet routes passing near the burn site, and the need to restrict airspace because of UAS operations and the release of weather balloons, close coordination with the FAA will be required. The local forest aviation officer is the first point of contact in this process. They can also explain agency policy concerning

UAS systems and whether other aviation support positions are needed to fill in the organizational structure.

A "P" code assignment to individual FASMEE research burns will be pursued with the Geographic Area Coordination Center (GACC) so that resources can be ordered such as radio frequencies, personnel, catering etc. to assist the host agency.

G.6 COMMUNICATIONS PLAN

The communications plan will follow the traditional incident command system (ICS) used by all Federal agencies. The communication plan for FASMEE cannot be written until all aircraft and personnel associated with the project have been identified. Furthermore, since radio frequencies are assigned to geographic regions, each project location must develop its own plan after radio frequencies have been requested and assigned through GACCs. After the project has identified its own needs, it can then supply the host agency with the research portion of the communications plan so that this can be incorporated into the incident communications plan. The FASMEE liaison will work closely with the host agency staff to provide them with the necessary documents to add to their IAP.

G.7 ACCESS AND ACCOUNTABILITY

Each project location will need an access and accountability plan. Below is an example for Fishlake National Forest.

G.7.1 Example: Fishlake National Forest

The Fishlake NF site is in South Central Utah and is administered through the Fishlake Ranger District in Richfield, Utah. The site location is ~30 miles south/southeast of the town of Richfield. There are two ways to navigate by vehicle. The eastern approach consists of a drive of 40 miles on paved highway, followed by 25 miles of off-road driving that requires a high clearance vehicle with 4X4 capability. The alternative approach is from the west and consists of a 35-mile drive on paved highway and 20 miles of off-road driving. During the site visit in July 2016, the FASMEE team travelled both routes, requiring at least 2.5 hours for a one-way trip without hauling equipment trailers. During the in-brief with the Forest Supervisor, it was made clear that people should not drive at night because of grazing permits on the forest leading to the risk of encountering large herd animals. When forest personnel conduct burn operations in the area, crews are required to camp out until the conclusion on the burn. This may require arranging for camping permits for FASMEE personnel for several days and logistic support that may include meals, water, garbage, and restroom facilities. Parking in this area is limited because all motor vehicles must follow published rules and regulations on motor vehicle operations. Off-highway vehicles are allowed only on designated roads. To limit the number of nonessential vehicles at the burn location, it may be beneficial for the FASMEE project to hire vans to carry people to the site.

Several of the observational science teams will need access to the site to set up towers. Any structure that is set up for the project must be coordinated through the Forest supervisor's office. Such towers may require an environmental assessment, which must be coordinated with the Forest. Such assessment can require several months to complete. Disciplines that may be using towers should contact the Forest Service office and the FASMEE leadership team immediately after funding to start the planning and coordination process.

Any FASMEE site preparation or site visit before the actual project burn must be coordinated with the FASMEE leadership team to assure notifications to the local Forest Supervisor. After the FASMEE project has been approved and the time window for the burn is decided, accountability will be maintained using standard ICS forms and check-in/check-out procedures. When crews are on the site of the burn, all FASMEE crews should plan to be there for the duration of the activity. Daily transportation requests to town can be scheduled through the Incident Command System (ICS form 213 general message). The town of Richfield is a small farming community with a Walmart and several grocery stores. If project crews might need spare parts or specialty items, they bring them.

G.8 DATA MANAGEMENT AND ARCHIVING

G 8.1 Overview

FASMEE will be conducted under an integrated data management plan. The goal of this plan is to integrate all collected measurements into a unified data archive. The data archive will include all data, including quality control flags and information, and all metadata necessary for others to understand and use the data.

It is expected that the data archive will be placed on a publicly available website both for the period of FASMEE and five years after. It will also be permanently archived in a place of the Joint Fire Science Program's choosing, probably the U.S. Forest Service Research Data Archive.

To facilitate integration and archiving of the data, a data manager will be identified who will work with all observational teams as well as leadership.

FASMEE data will be stored in multiple formats:

- Original data file format as taken by the instrumentation;
- Quality assured data files after processing;

- Quality assured data in one of a standard set of openly accessible data formats.

G 8.2 Standard Data Formats

FASMEE leadership will decide specific standard data formats, in consultation with the discipline leads and PIs after observational teams are identified. Primary decisions regarding data formats for Phase 2 will be guided by formats that are open and provide vendor and format-neutral data discovery, access, sharing and integration. FASMEE will use standardized, open and interoperable data formats that follow international best practices and standards for geospatial data, with the goal of increasing the ability to share and integrate Phase 2 data both within FASMEE and among other projects (e.g., NOAA FIREX).

Initial recommended data format specifications for Phase 2 are as follows, with final specifics to be defined in the early stages of Phase 2 and in coordination with NOAA (FIREX) and other on-going related research activities (e.g., NASA FIREChem):

- **Geographic Tagged Image File Format (GeoTIFF)**: An open data format that was developed to establish a TIFF based interchange format for raster imagery, allowing for encoding map projection, coordinate systems, ellipsoids, datums, and other pertinent information for establishing spatial reference information for the file. The GeoTiff format is used in commercial and open-source software. In FASMEE, all raster data products representing continuous areas not containing time series data will use this format. Raster datasets with explicit time information can also use this format with an associated table, in a file format listed, containing the full name of the GeoTIFF and the associated temporal information.

- **Network Common Data Form (netCDF)**: A set of libraries and data formats for managing array-oriented scientific data, such as time series data, imagery, or other multidimensional numerical grids. This format will be used in FASMEE for model simulation outputs, meteorological data, smoke plume or active fire measurements and other raster or point data products representing time series data.

- **ESRI File Geodatabase (GDB)**: A pseudo open standard to be used to store vector and tabular data collected as part of FASMEE. The format is available in most open and commercial Geographic Information Software (GIS) and can store related raster, vector and tabular data in a single, distributable file.

- **LAS Specification Version 1.4 or Greater (LAS)**: All point cloud return data from FASMEE will be stored using the LAS specification version 1.4 or greater.

- **Comma Separated Value (CSV)**: This simple format will be used in FAMSEE to store tabular data. It can also be used to store point data, such as smoke chemistry and emissions, with associated coordinates.
- **International Consortium for Atmospheric Research on Transport and Transformation (ICARTT)**: This simple data format for time series data is used extensively by atmospheric measurement campaigns, including NOAA's FIREX and NASA's FIREChem. All FASMEE time series data will probably be converted to this format for sharing with FIREX and FIREChem.
- **Portable Document Format (PDF)**: This file format will be used to store field notes or other written descriptions as appropriate.
- **Extensible Markup Language (XML)**: This file format will be used to store metadata of datasets collected as part of FASMEE.
- **JPEG, RAW, TIFF, PNG, PSD**: Ground images collected as part of FASMEE will use one of these formats. All ground images will have explicit spatial and temporal information recorded in the file. Other custom image formats for ground-based imagery are acceptable but must conform to initial spatiotemporal data standards and be specifically documented.
- **MPEG-2 or MPEG4 - Video File**: Any motion imagery collected during FASMEE Phase 2 will use one of these formats and, if applicable, will conform to standards presented by the Motion Imagery Standards Board.

APPENDIX H: LIST OF ABBREVIATIONS AND ACRONYMS

AIRPACT	Air Indicator Report for Public Awareness and Community Tracking
AGL	Above Ground Level
ALOFT	Smoke plume trajectory model
ALS	Airborne Laser
ARTCC	Air Route Traffic Control Center
ATV	All-terrain Vehicle
BB	Biomass Burning
BB	Burn Boss
BBOP	Biomass Burning Observation Project
BC	Black Carbon
Bluesky	Smoke dispersion modeling framework
CAMx	Comprehensive Air Quality Model with Extensions
CBD	Crown bulk density
CH_3CN	Acetonitrile
CH_4	Methane
Cl:	Chloride
CMAQ	Community Modeling and Analysis System
CO	Carbon monoxide
CO_2	Carbon dioxide
CONOPS	Concept of Operations
CONSUME	Model for predicting fuel consumption and emissions
CSV	Comma Separated Value
Daysmoke	Empirical-statistical plume rise and dispersion model
DOD	Department of Defense
DOE	Department of Energy
DNS	Direct Numerical Simulation
EPA	Environmental Protection Agency
ESTCP	Environmental Security Technology Certification Program
XML	Extensible Markup Language
FASMEE	Fire and Smoke Model Evaluation Experiment
FAA	Federal Aviation Administration
FBE	Fire Behavior and Energy
FFE-FVS	Fire and Fuels Extension of the Forest Vegetation Simulator
FIREChem	NASA wildland fire tropospheric chemistry project
FIRETEC	Physics based computational fire behavior model
FIREX	Fire Influence on Regional and Global Environments Experiment (NOAA)
FOFEM	First Order Fire Effects Model
FON	Funding Opportunity Notice
FRE	Fire Radiative Energy
FRESC	Forest and Rangeland Ecosystem Science Center
FRFD	Fire Radiative power Flux Density
FRP	Fire Radiative Power

FTIR	Fourier Transform Infrared
Fuel3D	Three-dimensional fuel modeling system
GACC	Geographical Area Coordinating Center
GDB	ESRI File Geodatabase
GEOS-CHEM	3-D Chemical transport model
GeoTIFF	Geographic Tagged Image File Format
GOCART	Goodard Chemistry Aerosol Radiation and Transport model
GPS	Global positioning system
H_20	Water
HCN	Hydrogen cyanide
HIP	Highly instrumented plot
HNO_3	Ammonium
HONO	Nitrous acid
HRRR	High Resolution Rapid Refresh
HYSPLIT	Simple Air Parcel Trajectory model
IC	Incident Commander
ICARTT	International Consortium for Atmospheric research on Transport and Transformation
IFTDSS	Interagency Fuel Treatment Decision Support System
IMT	Incident management team
IR	Infrared
JFSP	Joint Fire Science Program
LAS	LAS Specification Version 1.4 or Greater
LiDAR	Light Imaging, Detection and Ranging
MCE	Modified Combustion Efficiency
MesoNH-ForeFire	Mesoscale Atmospheric Model
MIP	Mobile Instrument Package
ML	Mobile Laboratory
MOZART	Model for Ozone And Related Chemical tracers
MS	Multi-spectral
MWIR	Mid-Wave Infrared
NASA	National Aeronautics and Space Administration
netCDF	Network Common Data Form
NOAA	National Oceanic and Atmospheric Administration
NPS	National Park Service
NWCG	National Wildfire Coordinating Group
N_2O	Nitrous oxide
NOx	Nitrogen oxides (sum of NO and NO_2)
NO_2	Nitrogen dioxide
NH_3	Ammonia
NIST	National Institute of Standards and Technology
NOATM	Computer model for aeronautical information
NOx	Nitrogen Oxide

NSF	National Science Foundation
O_3	Ozone
OC/EC	Ratio of organic to elemental carbon
OH	Hydroxyl radical
PAN	Peroxy acetyl nitrate
PASP	Project Aviation Safety Plan
PDF	Portable Document Format
PM	Particulate matter
$PM_{2.5}$	Particulate matter < 2.5 microns
POA	Primary Organic Aerosal
PPAN	peroxy propionyl nitrate
Qv	Water vapor mixing ratio
RADM2	Regional Acid Deposition Model
RAWS	Remote Automatic Weather Station
RD	Ranger District
RH	Relative Humidity
ROS	Rate of Spread
RxCADRE	Prescribed Fire Combustion Atmospheric Dynamics Research Experiment
SCREAM	South Carolina Regional Emissions and Aging Measurements
SEAC4RS	Studies of Emissions, Atmospheric Composition, Clouds and Climate Coupling Regional Surveys
SEMIP	Smoke and Emissions Model Intercomparison Project
SERDP	Strategic Environmental Research and Development Program
SfM	Structure from Motion
SIP	State Implementation Plan
SOA	Secondary Organic Aerosol
SO_4	sulfate
SODAR	Sonic Detection And Ranging
SPS	Simple Plume System
STANDFIRE	3-D physics based model to evaluate fuel treatment effectiveness
TFR	Temporary Flight Restrictions
TLS	Terrestrial Laser Scanner
UAS	Unmanned Aircraft Systems
UTV	Utility Task Vehicle
UV	Ultraviolet
USFS	United States Forest Service
USGS	United States Geological Service
VOC	Volatile organic Compound
VSMOKE	Gaussian smoke dispersion model
WAS	Whole Air Sampling
WFDS_LS	Wildland-Urban Interface Fire Dynamics Simulator-semi-empirical
WFDS-PB	Wildland-Urban Interface Fire Dynamics Simulator-Physics Based
WFDS	Wildland-Urban Interface Fire Dynamics Simulator
WFDSS	Wildland Fire Decision Support System

WRF	Weather Research Forecasting Model
WRF-Chem	Weather Research Forecasting model coupled with Chemistry
WRF_FIRE	Combination of the Weather Research and Forecasting Model (WRF) with a fire code implementing a surface fire behavior model
WRF_SFIRE	Combination of the Weather Research and Forecasting Model (WRF) with a fire code implementing a surface fire behavior model (open source)

Sensible heat flux can be written as $H_s = \rho c_p \overline{w'T'}$, where the term $\overline{w'T'}$ is the covariance of the perturbation vertical velocity, w', and perturbation temperature, T', averaged for a specified time period denoted by the overbar. This term is multiplied by the density, ρ, and the heat capacity, c_p, of air. Units are W m^{-2}.

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