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Validating the Next Generation of Wildland Fire and Smoke Models for Operational and Research Use – A National Plan

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EXECUTIVE SUMMARY

Air pollution from biomass burning is an increasingly prominent issue for wildland fire management agencies. In addition to primary PM10 and PM2.5, wildfires and prescribed burning also generate other primary emitted pollutants such as CO, SO2, NOx, and contribute toward the formation of secondary pollutants including ozone, secondary aerosols and air toxics. The Clean Air Act and subsequent amendments provide a mandate to monitor and manage effects of air quality impacts. In response to management planning needs, numerous smoke model guidance products have been developed over the last three decades. However, there has not been a detailed quantitative validation of these smoke models due to the lack of comprehensive field measurements from heavy fuels that define much of the observed smoke production.

Currently, there are a number of sources of smoke information available to managers both on the web and as downloadable models and datasets. These include simple screening tools, ventilation indices, web-based systems, real-time smoke forecasts and daily atmospheric chemistry modeling. These models are necessary to help mitigate smoke impacts, which are numerous. Smoke from wildfires has been shown to result in increased physician visits, emergency room visits, hospital admissions, and mortality. Illnesses attributed to smoke exposure can also result in absenteeism from work and school, thereby affecting economic productivity and educational achievement.

Despite considerable smoke model development efforts, there remain some serious shortcomings that limit their accuracy and cost-effective use:

1) Estimating the characteristics of fuels and predicting the consumption of those fuels has improved in the past several years, but uncertainties still remain for specific fuelbed categories (e.g., larger woody, masticated fuels, organic layers (duff and peat), and shrub/forested crowns).
2) The smoke plume rise method most commonly used has large uncertainty and may not accurately represent vertical mixing of smoke for scales ranging from large, intense active flame fronts to smoldering conditions.
3) A greatly improved understanding of the emission rates for the whole range of gaseous and aerosol species (e.g., CO, SO2, NOx, and volatile organic compounds) from fires is needed to more accurately model atmospheric chemistry resulting from smoke.
4) Research is needed to improve understanding of the chemical interactions between wildfire emissions and other sources of air pollution to more accurately model the formation of ozone, secondary PM2.5 and secondary air toxics.
5) Ambient monitoring of gaseous and PM2.5 pollutants has increased over the years (including satellite measurements of gasses and aerosols), but current observations are insufficient in spatial scale, type and frequency detail to effectively evaluate smoke models.
6) Increases in computing power allow for potential advances in smoke models, but without addressing all of the shortcomings, the models will continue to seriously lag behind in scientific capability and public need.

7) Recent research has identified inadequacies in physical descriptions of transport and dispersion in operational plume-rise models and smoke transport models.

Although there are shortcomings in the current ability to model smoke from wildland fire and assess smoke impacts, a more immediate concern is the lack of integrated, quality-assured datasets that cover all important science disciplines that drive smoke models including fuels, weather, fire behavior, energy release, smoke production and dispersion and fire effects. This lack of integrated datasets reduces the ability to evaluate both the smoke models themselves, along with fuel, fire, and weather models that drive the smoke models, and to answer fundamental fuel, fire, and smoke science questions. To help fill this gap, an integrated team of scientists need to be convened to provide the synergy for a program of work that assesses the sensitivity of key smoke models, collects field datasets developed around a thematic stepwise structure that captures and integrates all required input variables driving the smoke models, and develops/implements a data management plan that consistently archives datasets that can be assessed by all potential users. The Prescribed Fire Combustion and Atmospheric Dynamics Research Experiment (often referred to as "RxCADRE") provided such an opportunity for scientists to come together and collect fire data on large and small operational prescribed burns in 2008, 2011, and 2012. RxCADRE was successful in the development of synergies between fuel, atmospheric conditions, fire behavior, radiative power and energy, smoke, and fire effects measurements, all critical inputs to key fire model development and evaluation.

Presented here is a broad plan and technical requirements of a field campaign needed to bring smoke modeling to the next level utilizing a research and data collection organizational structure based on RxCADRE. This plan describes the needed initial work, critical field measurements, and smoke model validation and analysis necessary to significantly improve smoke and air quality models for operational forecasting and research. Subject matter experts from around the U.S. and Canada including universities, the EPA, NASA, NOAA, and USDA developed this plan based on knowledge of smoke model shortcomings, and in part on past field campaign experience. The plan covers 5½ years in three phases at an estimated total cost of $20,231K; a portion of this cost may be eligible for in-kind cost sharing depending upon involvement and roles of government agencies.

Benefits of this work include:

- The ability to improve protection of the public through more accurate smoke predictions and warnings.
- Improved mitigation of smoke impacts.
- Improved understanding of emissions rates and chemical interactions for more accurate modeling.
- Provide a comprehensive dataset for smoke and air quality model validation.
- Collecting the data most critically needed for model improvements by incorporating model sensitivity analyses of the planned burns.
- Observations for assessments of wildfire emissions in relation to climate change studies.

1. BACKGROUND

Smoke is a growing agency and public concern, and a pressing operational issue.

Air pollution from biomass burning is an increasingly prominent issue for wildland fire management agencies. In addition to primary PM10 and PM2.5, wildfires and prescribed burning also generate other primary emitted pollutants such as CO, SO2, NOx, and contribute toward the formation of secondary pollutants including ozone, secondary aerosols and air toxics (e.g., Jaffe and Wigder, 2011; Pfister et al. 2008). In 2005, all U.S. fire combined emitted approximately 411,000 metric tons of PM2.5 compared to approximately 515,000 metric tons emitted by electrical generation (U.S. EPA, 2009). The increased trend in area burned, especially over the last couple of decades, has brought with it increased smoke impacts (e.g., Finco et al. 2012; Dennison et al. 2014). More cases of community evacuations due to wildfire smoke impacts are occurring, and increases in health related smoke impacts have been reported. Smoke exposure can be hazardous to everyone, but particularly for those members of the population who are most vulnerable - the unborn and very young, the elderly, those with pre-existing cardiorespiratory diseases (i.e., asthma, COPD, abnormal heart rhythms and heart failure), outdoor workers, and the socio-economically disadvantaged (i.e., homeless, poor quality housing) (e.g., Dennekamp and Abramson, 2011). Smoke from wildfires has been shown to result in increased physician visits, emergency room visits, hospital admissions, and mortality (Henderson et al. 2011; Rappold et al. 2011; Delfino et al. 2009; Vedal and Dutton, 2006). Illnesses attributed to smoke exposure can also result in absenteeism from work and school, thereby affecting economic productivity and educational achievement. Health related costs have been determined to be several million dollars per year for active fire seasons. Treatment can cost up to $500 per 100-acres burned (Moeltner, 2013). Wildland fire smoke can have a long-range transport component that can generate health impacts significant distances from the fire source (e.g., Figure 1).

Starting in 1970, the Clean Air Act and subsequent amendments provide a mandate to monitor and manage effects of air quality impacts. Wildfires, in as much as they are naturally caused, are generally considered exempt, but nonetheless can have high health impact. Prescribed burning, because it is a human action, is regulated. While the EPA does not directly regulate the use of fire within a State or on Indian lands, EPA has provided guidance that encourages states and tribes to adopt and implement programs to minimize the public health and environmental impacts of smoke from fires (EPA, 1998). State and federal air quality managers require more accurate estimates of wildfire contributions to these regional air pollutants both to quantify fire contributions to exceptional events and to develop effective strategies to attain national ambient air quality standards and visibility goals (e.g., Jaffe et al. 2013). In response to the management planning needs, numerous smoke model guidance products have been developed over the last three decades. However, there has not been a detailed quantitative validation of these smoke models due to the lack of comprehensive field measurements.

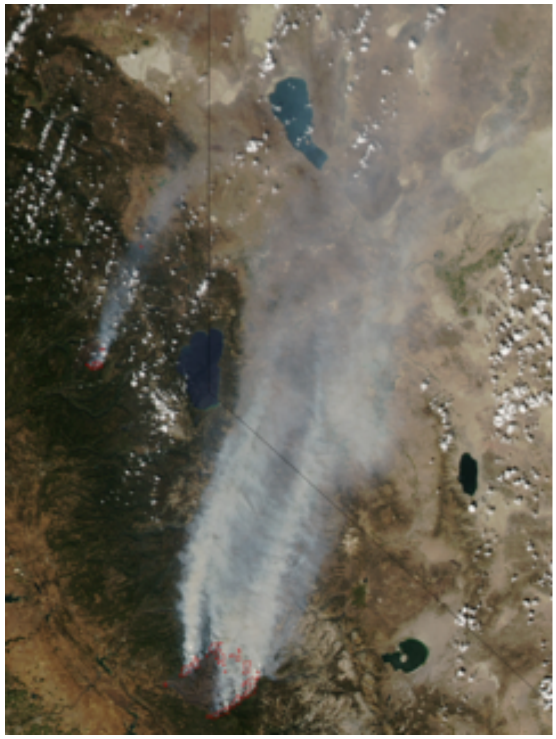

Figure 1. California's Rim Fire as captured by MODIS from NASA's Aqua satellite on August 26, 2013. Smoke from the fire obscures the northern part of Yosemite National Park, and crosses the border into highly populated areas of Nevada. (Image credit: NASA Earth Observatory).

The JFSP Smoke Science Plan (SSP) (Riebau and Fox, 2010) recommended four research themes that should be supported to improve our basic understanding of wildfire smoke science. The Fire and Smoke Model Validation theme, *to develop the scientific scope, techniques and partnerships needed to validate smoke and fire models objectively using field data,* was the basis for the workshop and developing a national smoke model validation plan. The SSP report further justified the need for smoke model validation:

> *"While an accurate emissions inventory is vital for meeting air quality standards, a critical tool for air quality management is air quality modeling. Modeling is required by the Clean Air Act for air quality management. It is used to help identify which sources are responsible for ambient pollution and to evaluate the effectiveness of control strategies. Since wildland fire is among the potential contributors to degraded air quality, accurately assessing fire's contribution though modeling is indispensible. We have seen increasing attention to fire smoke as US states seek to improve visibility and reduce ozone and particulate concentrations. Existing models, however, lack objective field validation and ties to fire behavior, which means their findings are often questioned. The theme of Fire and Smoke Model Validation will help fire management in supporting ecosystem health needs by objectively demonstrating the strengths (and weaknesses) of existing smoke models while providing the data needed to develop better future models. This theme will support*

the three other themes by direct testing of new emissions factors, new generation smoke public health protocols under study by EPA, observation of fine scale meteorology, and observation of long-range smoke transport and plume chemistry. Without objective verification, fire smoke calculations and models will always remain suspect and controversial. Moreover, this theme directly supports work in Core Fire Science on fire behavior and provides for explicit linkages to smoke research; thus providing an opportunity for smoke and core fire science researchers to work cooperatively. One may also note that this theme is a direct recommendation of the 2007 JFSP smoke roundtables, albeit with elaboration from our work. We have had almost universal support for this theme from scientists we have spoken with from NOAA, NASA and EPA."

This document represents an effort of bringing scientists from around the country and across federal and university research programs together to describe a field campaign capable of directly addressing these issues. This is informed from the recent Joint Fire Science Program (JFSP) funded field experiments that were conducted in the Southeast U.S. called Prescribed Fire Combustion and Atmospheric Dynamics Research Experiment (RxCADRE). These experiments were developed to address the need for integrated, quality-assured fuels, fire, and atmospheric data available for development and evaluation of fuels, fire behavior, smoke, and fire effects models. The lack of co-located, multi-scale measurements of pre-fire fuels, active fire processes, and post-fire effects hinders the ability to tackle fundamental fire science questions. RxCADRE enabled scientists to develop processes for collecting complementary research data across fire-related disciplines before, during, and after the active burning periods of prescribed fires with the goal of developing synergies between fuels, fuel consumption, fire behavior, smoke management, and fire effects measurements for fire model development and evaluation. While RxCADRE did have as a focus the collection of data for evaluation of smoke models and addressed a number of fire science questions, the experiments were not sufficient for comprehensive smoke model validation. To successfully validate and improve smoke and air quality models, longer-term intense burns in complex and heavy fuels will be required, and hence the field experiments will need to be in different fuels and of a larger scale than RxCADRE.

To begin developing a smoke model validation national plan, a two-day smoke validation workshop funded by JFSP (13-S-01-01) was held 17-18 September 2013 at the Desert Research Institute (Reno, NV) to formalize the research elements and strategies needed to advance smoke modeling. Participants represented federal, university and international organizations. Several of the participants worked with RxCADRE. Workshop participant expertise included fuels characterization, consumption, combustion, air quality, field experiments, remote sensing, fire behavior, smoke chemistry, dispersion modeling, and atmospheric measurements (see Appendix F for participant list).

2. Current State of Smoke Modeling Systems and Smoke Tools

Current smoke models are limited in their operational and research utility.

Since the 1990s, a wide array of tools of varying complexity has been developed to model smoke and to meet the needs of operational smoke management. Currently, there are a number of sources of smoke information available to managers both on the web and as downloadable models and datasets (Strand et al. 2014). Simple screening tools such as the Simple Smoke Screening Tool, Florida Smoke Screening Tool, and 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 such as AirNowTech Navigator, BlueSky Playground and HYSPLIT-Ready provide access to on-demand, while-you-wait, trajectories and dispersion modeling that is customizable. 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 there has been no standardization of methodology of either modeling the smoke emissions or their atmospheric chemistry though 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 can be seen in Figure 2, which shows the current models and datasets included in the BlueSky Framework, but other models exist that have not been incorporated into this framework.

Recent research further supports inadequacy in physical descriptions 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. While smoke modeling systems currently 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 can be categorized as atmospheric weighted (emphasizes atmospheric coupling to fire) and fire weighted (emphasizes fire physics coupling). Two of these models – WRF-SFIRE (CHEM) (Mandel et al. 2011) and FOREFIRE (Balbi et al. 2009, Filippi et al. 2011), which are atmospheric weighted, have short-term potential to becoming real-time in an operational fire management setting given the rapid advances in computing power.[1]

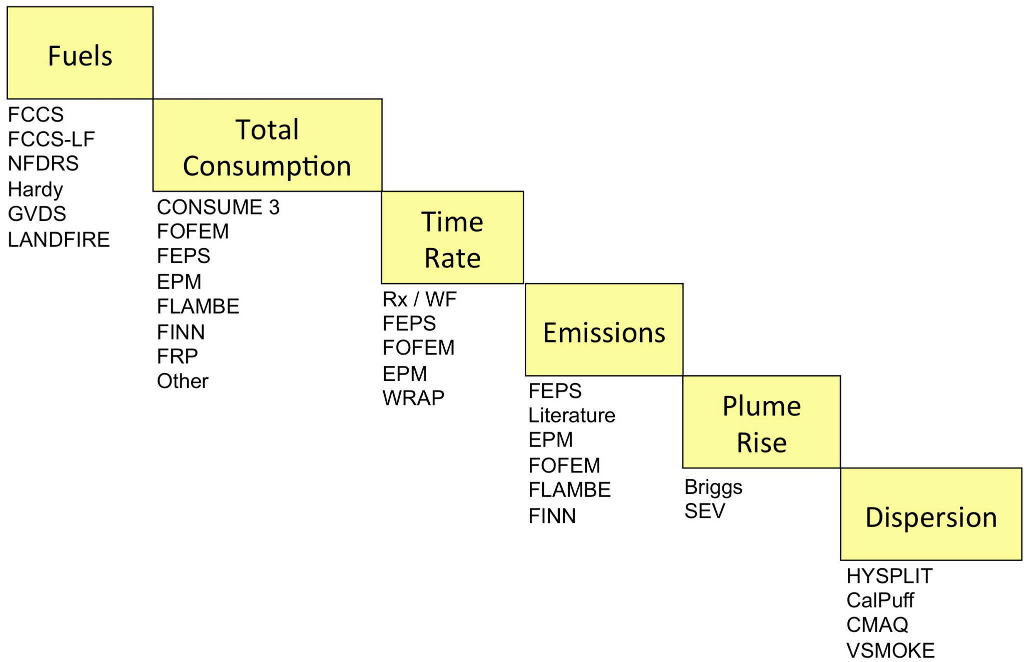

Figure 2. Models in BlueSky framework v3.5.1. (From Larkin et al. 2013).

3. Improving smoke models

Addressing the shortcomings in smoke models requires additional field observations.

Despite considerable smoke model development efforts, there remain some serious shortcomings that limit their accuracy and cost-effective use (e.g., Larkin et al. 2012).

1. Estimating the characteristics of fuels and predicting the consumption of those fuels has improved in the past several years, but uncertainties still remain for specific fuelbed categories (e.g., larger woody, masticated fuels, organic layers (duff and peat), and shrub/forested crowns).
2. The smoke plume rise method most commonly used has large uncertainty and may not accurately represent vertical mixing of smoke for scales ranging from large, intense active flame fronts to smoldering conditions.
3. A greatly improved understanding of the emission rates for the whole range of gaseous and aerosol species (e.g., CO, SO2, NOx, and volatile organic

[1] Two physics weighted models – FIRETEC (Linn et al. 2002) and WFDS (Mell et al. 2007) are much more computationally intensive, but these would be especially valuable to expand a smoke model test bed (beyond field observations) for evaluating the atmosphere-weighted models' ability to predict fire growth, fuel consumption, and plume structure.

compounds) from fires is needed to more accurately model atmospheric chemistry resulting from smoke.

4. Research is needed to improve understanding of the chemical interactions between wildfire emissions and other sources of air pollution to more accurately model the formation of ozone, secondary PM2.5 and secondary air toxics.
5. Ambient monitoring of gaseous and PM2.5 pollutants has increased over the years (including satellite measurements of gasses and aerosols), but current observations are insufficient in spatial scale, type and frequency detail to effectively evaluate smoke models.
6. Increases in computing power allow for potential advances in smoke models, but without addressing all of the shortcomings, the models will continue to seriously lag behind in scientific capability and public need.
7. Recent research has identified inadequacies in physical descriptions of transport and dispersion in operational plume-rise models and smoke transport models.

Results from either sequentially modeled smoke plumes or fire behavior-atmospheric models can drive local to regional scale dispersion or chemical transport models. Dispersion models (HYSPLIT, FLEXPART) include only basic downwind and transport, with limited additional factors (e.g., wet deposition). However, chemical transport models, such as the EPA Community Multi-scale Air Quality (CMAQ) plume transport, chemistry and deposition are explicitly modeled, as is the smoke's interaction with other in-situ pollutants. These models can therefore address secondary pollutant creation and their impacts including such issues as ozone and regional haze. Recent advances have resulted in a wide array of atmospheric chemistry models (e.g., CMAQ, CAMx, WRF-CHEM) each of which contains many options for chemistry.

Sensitivity analyses have been done for the modeling chain from fuel loading through dispersion under the Smoke and Emissions Model Intercomparison Project (SEMIP) Phase 1 (Larkin et al. 2012) for a number of test cases. Figure 3 shows the SEMIP modeling steps and associated models. The results of the SEMIP model intercomparison are shown in Table D. However, it is worth noting that SEMIP did not test either atmospheric chemistry models or coupled fire-atmosphere models, both of which have been identified here as critical components of any future smoke modeling system, and therefore critical in determining the data needed in any smoke field campaign.

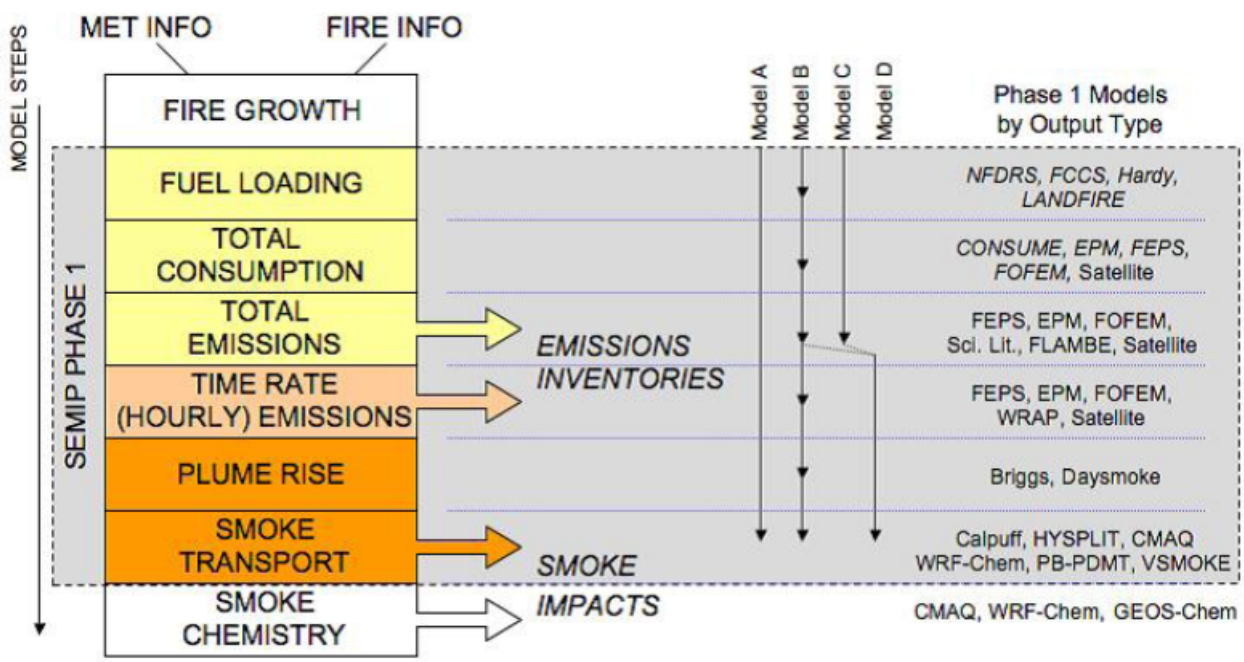

Figure 3. Smoke and Emissions Model Intercomparison Project model steps and model output types. (Adapted from Larkin et al. 2012.)

4. Role of Field Data

Field data are critical to scientific understanding and having an accurate predictive model.

Smoke impacts are becoming increasingly considered in wildland fire management for both prescribed burning and wildfire, including providing public information regarding potential impacts. However, the ability to mitigate smoke effects is limited by the accuracy and reliability of the current generation smoke models. To address the complex public health and natural resource issues associated with wildland fire smoke, air quality regulators, land managers, health experts, and atmospheric scientists need reliable tools that can accurately predict both how much smoke will be generated (smoke emissions), how that smoke interacts with other pollutants in the atmosphere (atmospheric chemistry), and where it will impact (smoke dispersion and transport). A diagram of a generic smoke modeling system is shown in Figure 4. These systems include multiple, sequential modeling steps, each of which may be achieved using a combination of input data and models, and which are combined in sequential or coupled simulation. Simulated smoke impacts are the culmination of multiple, complex modeling steps, and reflect the propagated uncertainties and limitations of the precursor modeling stages (e.g., fuel consumption and plume rise height) and the atmospheric chemistry transport models (e.g., transport, chemistry, and non-fire emissions) in the final step. There is a critical need to quantitatively characterize the uncertainties, biases, and application limits of smoke modeling systems, and to develop improved systems that may be utilized by air regulators, land managers, and air quality forecasters with confidence. Achievement of these tasks requires a detailed evaluation of each modeling step (i.e., sub-model). Such an evaluation necessitates the development of fire event test cases comprised of integrated measurements of the fire environment, fire behavior, fire effects, emissions, and the dispersion and transformation of emissions. The data from these cases provide the necessary information for improving smoke and air quality models, and hence the need for field experiments.

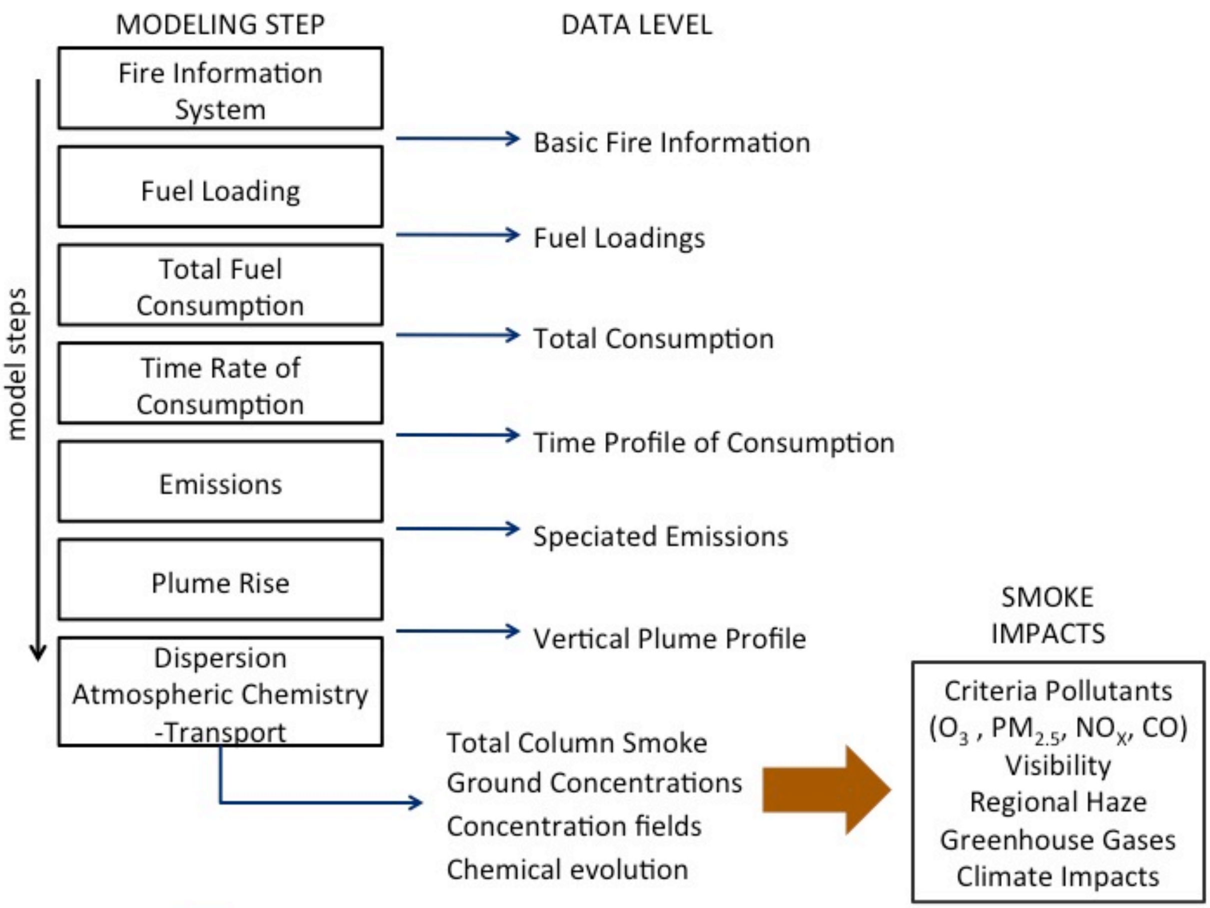

Figure 4. Schematic of a generic smoke modeling system.
(Adapted from Larkin et al. 2014)

5. Needed field experiments

A wide range of wildland fire conditions, terrain, and fuels would need to be observed to gather the necessary quantitative data.

The RxCADRE project (in 2008, 2011, and 2012) was one of the largest fire research campaigns and provided a quality-assured fuel, atmospheric, fire behavior, energy, smoke, and fire effects dataset for evaluation and modification of fire models. Although the major emphasis was on fire behavior, there was also a secondary emphasis on smoke. Smoke emissions measurements were made during grass and forestunderstory prescribed fires with instruments deployed on ground, airplane, and tethered aerostat platforms measuring carbon species, particulates and optical properties.

In a similar effort, the Strategic Environmental Research and Development Program (SERDP) has nearly completed a 5-year program to characterize fuels, smoke chemistry and transport associated with prescribed burning on Department of Defense (DoD) forts and bases in the United States. The study has provided smoke dispersion tracking information and emission factors for more than 100 trace gases and particulate matter in smoke for fuel types found in the southern United States using state-of-the-art instrumentation in laboratory and field experiments. Several smaller campaigns and individual studies related to smoke have been sponsored by the Joint Fire Science Program and range from characterizing fuels and fuel consumption to smoke modeling application and assessment (Ottmar et al. 2011, Larkin et al. 2012). RxCADRE, SERDP and JFSP have provided valuable research data and information; however, measurements from these field campaigns are insufficient to fully characterize emissions from large, heavy fuel fires.

The modeling steps in Figure 4 highlight the measurement needs through the various modeling steps. Estimating the characteristics of fuels and predicting the consumption of those fuels has improved in the past several years, but uncertainties still remain for specific fuelbed categories (e.g., larger woody, organic layers (duff and peat), and shrub/forested crowns). Local-scale meteorology is one of the key drivers of fire behavior and also relates to atmospheric chemistry, dispersion, and transport. The quantity and speciation of emissions are determined by the variation in pyrolysed gases and air participating in the reaction (fire behavior). Consumption of fuels during wildland fire is the basic process that produces heat and smoke driving fire behavior, and accounting for smoke generation and heat release along with other fire effects such as carbon reallocation, tree mortality, and soil heating. Smoke emissions measurements provide a quantitative characterization of the gases and aerosol in fresh smoke in terms of emission factors. Plume dynamics provides the connection between fire behavior and the far-field smoke dispersion as it determines the vertical distribution of the emissions. Detailed precursor and chemical product measurements are needed in the near-field and at different downwind distances (ideally even hundreds of kilometers from the fire source) from a fire extending to transport over a multi-day period in order to define emission rates of key precursors as well as provide a specific signature for any fast chemical processing of fresh emissions.

6. Study design

A three phase approach design for planning, data collection, and data quality control / analysis.

The overall study design closely follows the diagram in Figure 4, which shows the modeling steps and data levels of a generic smoke modeling system. The key impacts that smoke modeling systems may be used to quantify are listed in the final model step in Figure 4. Each modeling step may be achieved using a combination of input data and model(s). Output from each modeling step provides input for subsequent modeling steps. The culmination of the first six modeling steps is a spatially and temporally resolved fire emission source, E(x, y, z, t) with specific primary pollutant emission rates, which provides input to a dispersion model, or ideally, an atmospheric chemistry transport model, in the final stage. It is the final modeling step that simulates the smoke impacts of greatest concern to land managers, air quality regulators, and public health officials. Simulation of most smoke impacts such as PM2.5 and O3 concentrations, regional haze, or the transport of black carbon to the Arctic, can only be realistically simulated using atmospheric chemical transport models (CTMs), such as the Weather Research and Forecasting–Chemistry Model (WRF-Chem) or the Community Multiscale Air Quality modeling system (CMAQ). This point cannot be overemphasized. While a dispersion model provides a first approximation as to where the smoke moves and where it may be thickest, quantitative smoke impacts such as the concentrations of criteria pollutants affecting a population center, result from highly complex, non-linear photochemical processes, and can only be accurately simulated using sophisticated CTMs.

In order to simplify model-observation comparisons, idealized environmental conditions would be needed. Atmospheric conditions should be chosen based on burning and ignition efficiency with wind speed, wind direction, and overall boundary-layer structure chosen for ideal dispersion characteristics. In addition, the burn periods can potentially be conducted when the boundary layer is in a steady-state regime (e.g., convective) eliminating the complexities associated with transition periods such as inversion break-up. In addition, a convective boundary layer environment would provide for more dispersion vertically downwind.

This research plan has selected measurement variables for the evaluation of smoke modeling systems at all modeling steps and data levels (see Appendix Tables B1-6). Many measurement variables may be used to validate the output of, as well as provide ‘ground truth’ input for, different modeling steps. For example, measurements of fuel consumption may be used to validate predictions of the fire effects models in the Fuel Consumption step, and also provide the total fuel consumption input needed in the subsequent Emissions step.

Importantly, initial model runs will need to be done to test and refine the data collection plan once the specific site and fire configuration is identified. Model runs will include sensitivity analyses to see what specific information is most critical to the allowing the model the function, and to see where observational data can most effectively help distinguish between different competing models. This type of initial modeling work is commonly done in other fields such as oceanographic and atmospheric circulation measurements, and has proven to be both valuable in ensuring the most appropriate data are collected. While such modeling goes beyond mere sensitivity analyses, instead becoming data collection design validation, for simplicity here we term all of this initial modeling work as sensitivity analyses.

The budget tables in Appendix D represents a realistic plan for performing such a project at two experiment locations, and assumes that the experiments could be conducted in Canada as well as in the U.S. Two or three sufficiently large burns during each experiment period should provide the necessary measurements. These would be done as prescribed fires, as there are substantial safety and logistics issues in conducting field experiments with wildfires, especially of the size and complexity recommended in this plan. Two experiments at two separate locations are desired to test different environments, but with both consisting of heavy fuels. Ideally at least one of the burns would take place in complex terrain. The specific site locations for the fires need to be determined, but some of the fires need to be done in as close to wildfire conditions as possible. This will require finding special sites, such as unburnt islands left by past wildfires, beetle kill areas, or other sites where large fires may be set. Partnerships with military bases may be useful in obtaining permission to burn, such as was done with the RxCADRE burns at Elgin Air Force base.

Figure 5 provides a timeline chart of the field campaign phases.

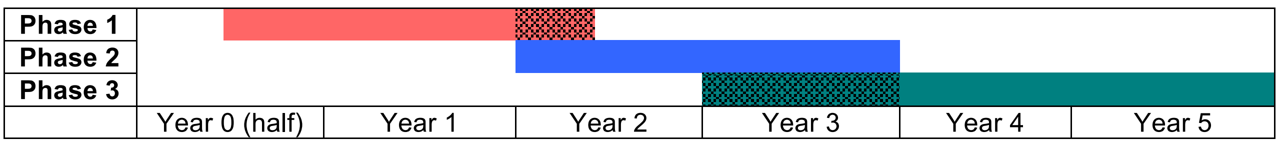

Figure 5. Recommended timeline for the field experiment planning, implementation and post-analysis. The overall project timeline is 5 ½ years, with an expected starting time of approximately April in the first Year (here labeled Year 0 as it is only a partial year).

Phase 1 represents experiment logistics, detailed planning, modeling exercises, such as sensitivity analyses, etc. This phase will last for 1 ½ years prior to data collection in order to accommodate both the significant logistical challenges of choosing a site, lining up timetables and personnel, and performing significant up front work (in conjunction with the developers of models that are targeted) to examine model sensitivities for this particular site/fire setup. Planning for the second round of fires would continue into Year 2.

Phase 2 represents the field campaign. The experiments would likely take approximately one month to set up on the ground and coordinate all of the measurements (e.g., grown, aircraft, satellite). This period also provides for some likely time needed for the proper burning conditions to become available.

Phase 3 represents post-analysis, publications, and initial data analysis. The data analysis component covers only initial data quality control, preliminary analysis, and delivery to data archive. This phase could begin shortly after a field experiment, and thus crosses over into Phase 2. This latter component is critical to the experiment's success in that this is the phase that the models will be improved based on the field campaign measurements. It is recommended that this component be done in conjunction with the relevant model developers and implementers. While not highlighted here, it is anticipated that other significant additional analyses will be enabled based on the experiment data archive.

7. Personnel and equipment

Experts and specialized equipment across a wide range of disciplines are needed to measure the fire and smoke plume.

To do such a field campaign and the subsequent model validation and analysis, a large number of scientists, research staff, and field crew personnel will be required. Specific disciplines needed include (in alphabetic order):

- Atmospheric chemists
- Combustion physicists
- Landscape ecologists
- Meteorologists
- Remote sensing specialists

Additionally, a large quantity of specialized observational equipment will be required (see Appendix B for details). Examples include:

- Aircraft with specialized sensors for atmospheric chemistry
- Canister sampling equipment
- Doppler-SODARs
- Fuel characterization equipment
- GC-MS for atmospheric characterization
- LIDARs
- Particulate monitors
- Radiosonde-Tethersondes
- Meteorology towers

Overall, this effort will require the resources of multiple agencies and universities to provide the needed personnel and equipment.

8. Budget and programmatic needs

A collaborative, multi-agency, multi-university, multi-disciplinary approach is necessary, requiring a realistic budget.

Table 1 shows the estimated 5-year total costs by measurement category. Details on how each section is estimated are listed in Appendix D. Actual costs will vary as sites and specific researchers are identified, but the estimated costs reflect known costs for equipment and personnel that have been associated with large field experiments such as RxCADRE. It is assumed that indirect cost will be required and is shown separately. This cost will vary depending on the agencies, institutions and funding mechanisms involved, but for the current purpose a JFSP rate of 20% is used as a baseline. Also, there may be in-kind opportunities depending upon the agencies involved.

Table 1: Estimated total (5 ½ -year) field experiment costs by component.

Category	Phase 1	Phase 2	Phase 3	Total 5½ years
Sensitivity Analysis	$600K			$600K
Fuels	$520K	$2,606K	$448K	$3,574K
Fire behavior	$60K	$1,230	$353K	$1,643K
Meteorology	$126K	$1,424	$436K	$1,986K
Airborne meteorology	$240K	$2,250	$129K	$2,619K
Airborne chemistry	$34K	$2,676	$403K	$3,113K
Ground-based chemistry	$72K	$1,532	$470K	$2,074K
Satellite analysis	$80K	$360	$335K	$775K
Data management	$95K	$190K	$190K	$475K
Direct total	**$1,827K**	**$12,268K**	**$2,764K**	**$16,859K**
Indirect cost recovery (20%)*				**$3,372K**
EXPERIMENT TOTAL				**$20,231K**
*Estimtated direct costs (75%)***				*$15,173K*
*Estimated in-kind cost-share (25%)***				*$5,058K*

*Each agency/institution that works on the experiment will likely have an indirect cost recovery rate. This will vary considerably. For example, federal agencies might only have around 10% while academic institutions would be closer to 50% or even higher. In order to identify some level of overhead cost, the JFSP capped rate of 20% is used as a baseline indicator.

**The Experiment Total is split into an estimated in-kind cost share based on, for example, government research salaries, with the remainder as an estimated direct cost. The historical average cost share on JFSP proposals is approximately 35%; here we use a conservative estimate of 25% due to the fact that field campaigns require extensive temporary personnel costs, equipment costs, and travel costs, which must be requested as direct costs.

Table 2 lists agencies that the workshop team recommends as highly critical for experiment success and that may be able to provide direct support. Other agencies, such as from tribal, state, non-governmental can play important supporting roles, along with local air quality districts. If a field experiment was conducted in Canada, the Canadian Interagency Forest Fire Centre (CIFFC) and the Natural Sciences and Engineering Research Council of Canada (NSERC) agencies should be included. This plan focuses on U.S. and Canada partners; however, other international agencies such as CSIRO in Australia and forest fire agencies in Europe could well be interested given the potential benefits of experiment results for their smoke and air quality modeling systems.

A recommended step to this plan would be a stakeholder meeting to align each potential funding agency's needs and interests, and to identify and plan for multi-agency support.

Table 2. Recommended partner agencies for field campaign actual support.

Federal	Joint Fire Science Program (JFSP) National Aeronautics and Space Administration (NASA) Department of Defense (DOD) Environmental Protection Agency (EPA) Department of Energy (DOE) Strategic Environmental Research and Development Program (SERDP, run by DOD, DOE, EPA) National Oceanic and Atmospheric Administration (NOAA) U.S. Forest Service (USFS) Department of the Interior (DOI) National Science Foundation (NSF)
State	California Air Resources Board (CARB)
Other	The Nature Conservancy (TNC)

9. Challenges

Careful management of safety, logistic, and cost challenges is critical to success.

Conducting large research campaigns on actively burning fires can be challenging because of safety concerns, logistics, and costs (Lentile et al. 2007a, b). Each one of these should be eliminated or minimized to the extent possible to increase the chance of a successful research campaign.

Safety must be considered throughout the planning process and cannot be compromised to meet accomplishment. For example, the RxCADRE project required all research participants to 1) be fire qualified, 2) checked in and out each day to make sure all individuals were safe and accounted for, 3) qualified for special equipment operation, and 4) attend each daily safety, communications, air operations, and logistical briefing. Furthermore, all personnel were required to have communication at all times, and no research burn was conducted until all personnel were identified and located prior to ignition.

There are several logistical challenges to overcome in implementation of a large research project including but not limited to 1) harsh fire environment, 2) potentially poor access and extreme rugged terrain, 3), extreme variability of the fuels and burning conditions, 4) acquiring support of the management agency that will be conducting the prescribed burn or managing the wildfire, 5) logistical support for managing a large group of scientists and technicians, and 6) a high potential for false alarms. For example, during the RxCADRE project, special instruments and equipment had to be designed to tolerate the fire temperature and heat duration. All-terrain vehicles were acquired to obtain access to the research sites. Additional data collection sites were located to account for the variability of fuel. Eglin Air Force base was chosen for the project because they had the infrastructure to provide the management support for 90 scientists and technicians, controlled air space for deployment of unmanned aircraft, and data acquisition and processing ability. Finally, due to weather and the burning record of Jackson Guard, there was over 90% probability that the burns would occur.

Costs are often directly related to the logistical difficulties. By minimizing the logistical challenges, cost will be minimized. The RxCADRE project controlled costs by selecting a research area where there was a high probability of success and where local resources could be used to support the project. Furthermore, the project was organized by research disciplines and each discipline contained skills that could often be used across disciplines enabling the research data collection to be more efficient. It is recommended that an experienced field campaign manager be employed to manage safety and logistical risks and most importantly to ensure research goals are specified and met.

10. Conclusions

Smoke impacts are becoming increasingly considered in wildland fire management for both prescribed burning and wildfire, including providing public information regarding potential impacts. But the ability to mitigate smoke effects is limited by the accuracy and reliability of the current generation smoke models. Improving smoke models requires additional observational data only available through a targeted field campaign directly aimed at quantifying the fire and smoke plume at scales necessary to address our current knowledge and modeling gaps.

Such a field campaign is a major undertaking and would require the coordination of multiple agencies and universities to successfully complete. A group of experts from such agencies and universities were gathered under the auspices of the Joint Fire Science Program to develop a science plan for a large smoke model validation experiment.

The recommendation is a large-scale 5 1/2-year campaign with specific phases for planning and sensitivity analyses (Years 0/1), observations (Years 2/3), and data analyses and archiving (Years 4/5). The campaign, while ambitious to meet the needs of scientific requirements, is informed from past field project experiences to mitigate concerns over scope, safety, logistics, and cost.

With appropriate multi-agency coordination and endorsement, this plan is fully feasible at this time, and could begin as soon as budgetary resources allow.

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Appendix A. Currently used smoke models

Table A1. List of smoke, emissions and consumption, and fuel characterization models developed in the U.S. (adapted from http://www.nifc.gov/smoke/smoke_modeling.html).

Screening	Regional Smoke Dispersion Systems (web-based)	Dispersion (desktop)	Emission and Consumption	Fuel Characterization	Ensemble of tools
Simple Smoke Screening Tool	Bluesky	Smoke Impact Spreadsheet (SIS)	Fire Emission Production Simulator (FEPS)	Fuel Characteristic Classification System (FCCS)	Interagency Fuels Treatment Decision Support System (IFT-DSS)
Florida Smoke Screening Tool (SST)	HYSPLIT	Simple Approach Smoke Estimation Model (SASEM)	Emissions Production Model (EPM)	LANDFIRE	
	AIRPACT Forecast System WRF-BlueSky-CMAQ	NFSpuff	CONSUME	National Fire Danger Rating System	
		VSmoke	First Order Fire Effects Model (FOFEM)		
		CALPUFF			
		HYSPLIT			
		PB-Piedmont			
		Bluesky Playground			

Appendix B. Data collection

Data collection should comprise fuels, fire behavior, micro and fire site meteorology, smoke emissions, plume dynamics, and smoke transport. Ground, aircraft and satellite measurements would be needed to sufficiently observe these elements. Figure B1 shows example experimental design for meteorological and smoke sampling for the RxCADRE campaign. The proposed experimental design will mirror significant portions of RxCADRE for near-field smoke and fire measurements, but will add in additional measurements of the smoke plume, chemistry, and downwind transport and plume characterization.

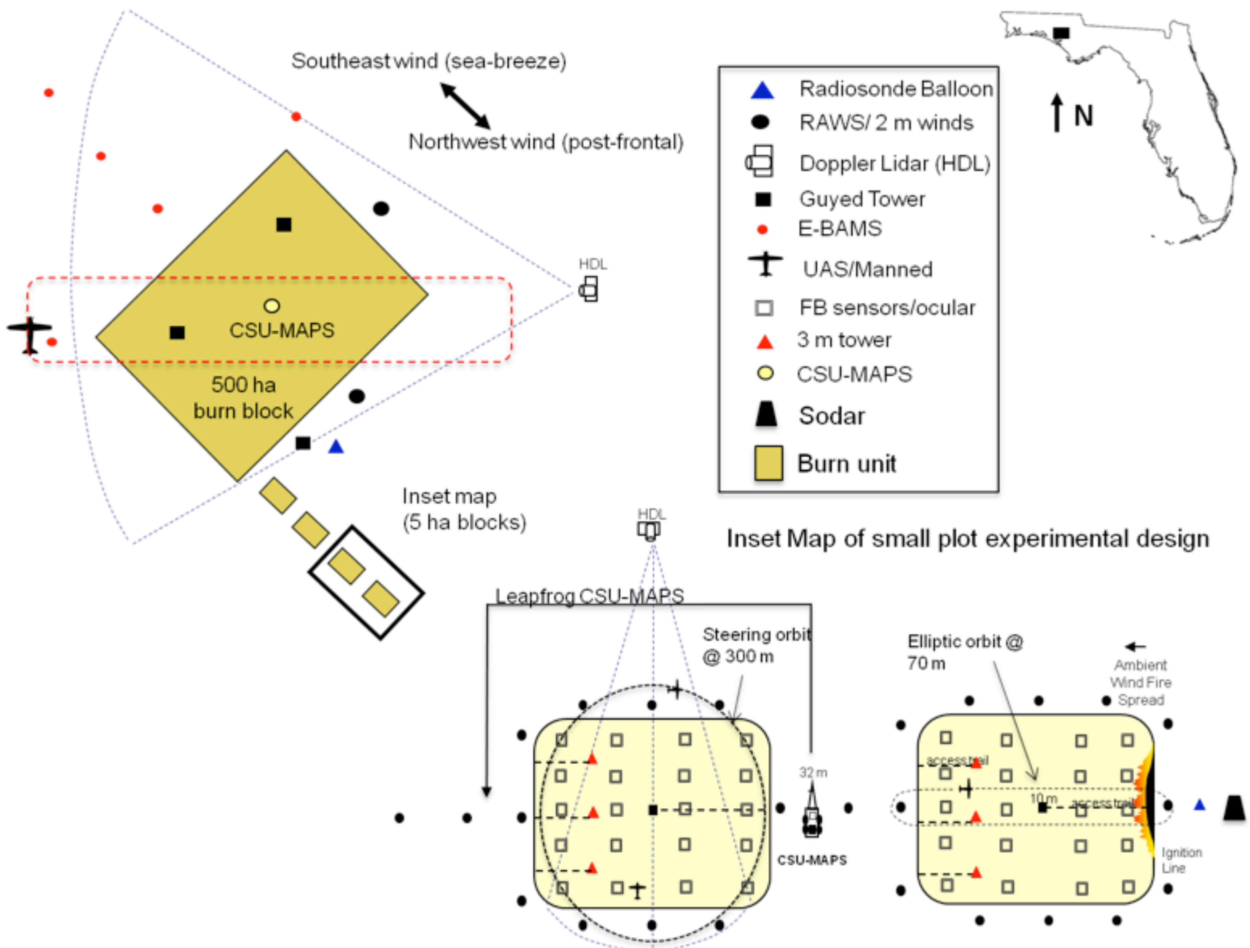

Figure B1. Experimental design for meteorological and smoke sampling for the RxCADRE campaign. This figure does not show the expected downwind measurements that would be required.

a. Fuels

The characterization of fuels and the resulting consumption during wildland fire is the basic process that produces heat and smoke driving fire behavior and accounting for smoke generation and heat release along with other fire effects such as carbon reallocation, tree mortality, and soil heating (Figure 4—Modeling steps). Since smoke models require fuels information to predict heat release rate and emissions, any smoke campaign must collect pre- and post-burn fuels information for all fuelbed categories (trees, shrubs, grasses, woody, litter, and duff) to determine fuel consumption. The methods for collecting this data will include field sampling and LiDAR. Field sampling is the most reliable method for collecting the pre- and post-fire information, but terrestrial and airborne LiDAR will also be used to capture the fuels at the appropriate scale needed for validating various smoke models. A list of required pre- and post-fire fuel characteristics to be measured for calculating fuel consumption, methods for collecting the data and the accuracy required is presented in Appendix Table B1.

b. Fire behavior

Emissions production is a direct result of the chemical kinetics occurring in the reaction process. The quantity and speciation of emissions are determined by the variation in pyrolysed gases and air participating in the reaction. Fire behavior models simulate the reaction, albeit in many cases using crude approximations. Ongoing work by several groups in the US, Australia and Europe are focusing on the development of sophisticated multi-dimensional comprehensive fire behavior models that more accurately simulate fire intensity. Naturally these models could more accurately simulate the reaction process and the resulting emissions. Unfortunately, within wildland fire, emissions prediction models have been developed independently of fire behavior models. This disconnect in many ways has limited both the utility of the fire behavior models and the accuracy and range of applicability of emissions production models. Data needed to verify the accuracy of fire models and provide a basis for emissions production include environmental conditions (local winds, slope, aspect, relative humidity), fuel conditions (loading, distribution, moisture content, species, live/dead, etc.), and climatology. Many of these variables vary in time and space, and the current capability to quantify the spatial and temporal variations is limited. Thus, in many cases point measurements are applied over broad areas. Appendix Table B2 outlines fire behavior measurements and instruments that should be utilized in a large-scale smoke experiment.

c. Micro and fire site meteorology

Local-scale meteorology is one of the key drivers of fire behavior and smoke dispersion. Recent advances in monitoring of *in situ* microscale meteorology at the fire front, while simultaneously measuring plume properties, has provided new insights into the role fire-atmosphere interactions have on smoke dispersion (Seto et al. 2013; Seto et al. 2014). Key meteorological variables needed to characterize fire weather conditions and surface meteorology include ambient air temperature, humidity, near-surface wind speed and wind direction at high spatial and temporal resolutions. The atmospheric environment surrounding the burn unit and region should be characterized with a network of surface stations. Additionally, a network of vertical atmospheric profilers (Radar-Rass, SoDAR, LiDAR) around both the experimental burn unit and outside the experimental region is 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.

In order to better understand the role of surface-layer micrometeorology on fire behavior and smoke dispersion, a suite of tall towers (30-50 m) should be placed within the burn unit (Clements et al. 2007). The desired tower positioning would be in a triangular arrangement approximately 150 m apart. This arrangement would provide a means to measure vorticity within the plume near the fire front. Ideally, the towers would be equipped with 3-d sonic anemometers at multiple levels, fine-wire thermocouples at 1 m vertical spacing, and heat flux radiometers. In addition, turbulent fluxes of CO_2, CH_4, H_2O, and CO should be measured with a fast, GHG flux analyzer collocated with one of the 3-d sonic anemometers and sampled at 10 Hz. These measurements would provide for the first time, direct quantitative measurements of turbulent fluxes of gases emitted at the source, rather than downwind and away from the active fire front.

A major requirement for measurements is mobility of the sensing platforms that allow the sensors and towers to be moved quickly according to surface wind direction. For example, the CSU-MAPS, a Mobile Atmospheric Profiling System, has been tested thoroughly in the fire environment (Clements and Oliphant 2014), and can be deployed with the taller fixed tower array, but easily moved if needed. A system such as the CSU-MAPS ensures that the tower measurements are successful even during a change in wind direction.

Plume rise, entrainment, and fire-atmospheric circulations associated with the plume should be directly measured using a suite of scanning Doppler LiDAR systems. Both dual- and triple-Doppler LiDAR techniques can be implemented to measure high-spatial resolution (<18 m) plume backscatter and radial velocities. The triple-LiDAR technique provides instantaneous 3-d vertical wind profiling of the plume as a virtual tower. This strategy can enhance the tower network by extending the vertical profile above the height of the tower array and through the depth of the plume. Vertical scans from the three LiDARs can provide direct measurements of the smoke column top and plume rise. In addition, the vertical velocity measurement from the triple LiDAR virtual tower would allow more accurate quantification of entrainment into the smoke column. The LiDAR network should be supplemented with a network of SoDAR profilers, a Radar-Rass profiler, and radisonde launches, both upwind and downwind of the experimental site. A list of required variable measurements and instruments is provided in Appendix Table B3.

d. Synoptic meteorology

Upper-air kinematic and thermodynamic observations are needed to characterize the synoptic environment during experimental periods. Observations needed should include a local radiosonde and microwave profiler network, radar wind profilers, and Doppler LiDARs. In addition to an enhanced observational network, standard upper-air observations from available national and regional networks would provide further relevant data.

e. Smoke emissions

Fresh emissions from biomass burning are a complex and rich mixture of gases and aerosol. Smoke emissions measurements provide a quantitative characterization of the gases and aerosol in fresh smoke in terms of emission factors. The emission factors should represent all of the important aspects of a fire's life cycle. A comprehensive chemical characterization of smoke emissions requires the use of multiple instruments and techniques employed from both ground-based and airborne measurement platforms.

e.1 Ground-based measurements

Ground-based measurements typically involve deploying instruments at a fixed location or set of locations a short distance downwind of a prescribed fire burn unit prior to ignition. There are three significant drawbacks to a ground-based measurement approach. First, the fuels, winds, terrain, and fire behavior often produce a smoke plume that is temporally and spatially very heterogeneous; therefore, the representativeness of measurements collected at a fixed location a short distance downwind from the source is highly uncertain. Similarly, a second drawback of ground-based measurements is that they may not be representative of the bulk of the smoke that is lofted in the buoyant plume. Finally, unanticipated smoke behavior, for example due to a shift in wind direction, can result in the smoke plume largely missing the measurement location. This last deficiency may be alleviated by the use of an instrument package on a mobile platform, such as an ATV, that allows for redeployment of the measurement site. However, even with a mobile platform, terrain and/or fire conditions may prevent a successful redeployment. Towers erected within a burn unit or downwind can be useful platforms for characterizing the vertical distribution of emissions.

The uncertainty regarding the representativeness of fixed-point sampling has been addressed using open-path FTIR (OP-FTIR) systems. The OP-FTIR approach monitors the concentrations of gases in ground-level smoke across distances of tens to hundreds of meters. While the OP-FTIR method improves upon the uncertainty in representativeness of the fixed point approach, it does not provide aerosol measurements and it typically measures a smaller number of gases than is possible from laboratory analysis of canister batch mode samples collected from fixed point instrument sites.

A mobile, closed path FTIR system has also been used to measure emissions from independently smoldering fuel components behind the fire front of prescribed burns. This approach, designed to characterize residual smoldering combustion, does suffer from uncertainties regarding representativeness as the selection of targets for sampling depends on site access and is somewhat subjective.

Ground-based emission measurements should be prioritized as follows and ideally would include all three approaches (Appendix Table B4):

1. OP-FTIR measurements of gas emission downwind of the burn unit / fire
2. Post-fire-front sampling of gas emissions from independently smoldering fuel components
3. Downwind point sampling of aerosol and gas emissions

The ground-based sampling approaches described above are useful for measuring emission factors. However an array of surface measurement sites downwind of a fire can provide observations for evaluating smoke model simulations of ground-level pollutant concentrations. The need to have multiple sites generally limits this approach to pollutants for which routine air quality monitoring instruments are available such as EBAMS for monitoring PM2.5.

e.2 Airborne Measurements

Airborne chemical measurements are required to properly validate several smoke model steps in addition to smoke emissions (see Figure 4). Chemical species to be measured from the airborne platform are listed in Table B5 along with sample criteria (collection mode, collection rate, and precision or limit of detection) and possible instruments/analytical techniques. An airborne platform allows researchers to obtain a more representative smoke sample than is possible using ground-based measurements for a key couple reasons: 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 significant advantage of an airborne platform is the ability to bring the instruments to the smoke. Downwind, ground-based measurement sites must be established prior to the sampling period in a location selected based on anticipated smoke behavior. As a result, unanticipated smoke behavior, for example due to a shift in wind direction, can result in the smoke plume largely missing the ground-based measurement location. The primary deficiency of an airborne measurements platform is the inability to sample residual smoldering combustion – post-frontal smoldering emissions that are not lofted a sufficient height above the canopy or terrain to be accessed by an aircraft.

f. Plume dynamics

Plume dynamics describes the behavior of the plume from its source until is reaches neutral buoyancy. As such plume dynamics provides the connection between fire behavior and the far-field smoke dispersion as it determines the vertical distribution of the emissions. Studies have shown the important role played by the spatial distribution of heat and emissions in determining air quality impacts at the regional scale (Achtemeier et al. 2012, Garcia-Menendez et al. 2014). A number of measurements proposed in the micrometeorology section of this proposal are well suited to furthering our understanding of plume dynamics. These measurements include vertical profiles of temperature, humidity and winds from radiosondes and profilers, as well as wind field data provided by multiple Doppler LiDARs. In-situ meteorology at the fire front along with other measures of fire behavior is also essential for improving our understanding of the linkage between fire behavior and plume structure. For a large, multi-day experiment detailed local measurements will need to be augmented with remote sensing data from both airborne and satellite based platforms. Videography from multiple vantage points will allow for qualitative assessment and limited quantitative analysis of plume behavior with the level of quantitative analysis dependent upon the number of vantage points available and their distance to the plume (e.g., Figure B2).

Figure B2. Image of plume from one of the RxCADRE burns at Eglin Air Force Base showing multiple updraft cores (Photo courtesy of Ailie Csaszar).

For a multiple day fire some consideration must be given to observing smoke at night. Work on studying nocturnal smoke in the southeast has employed observer patrols and aerial photography (Achtemeier 1998). Observer patrols are largely limited by the available road network surrounding the burn unit and can be impractical in some cases. Aerial observations using suitable cameras are a possibility, especially collecting IR imagery of the fire at night to document fire location and intensity. Adding a single camera properly equipped for low light conditions would provide a means of tracking unlofted smoke moving across the landscape at night (this could be done using an improvised tower, tethered UAS, or aerostat).

Figure B3 shows a schematic of an idealized plume, and aircraft and UAS flight patterns. Ideally, measurements would occur concurrently with satellite overpasses.

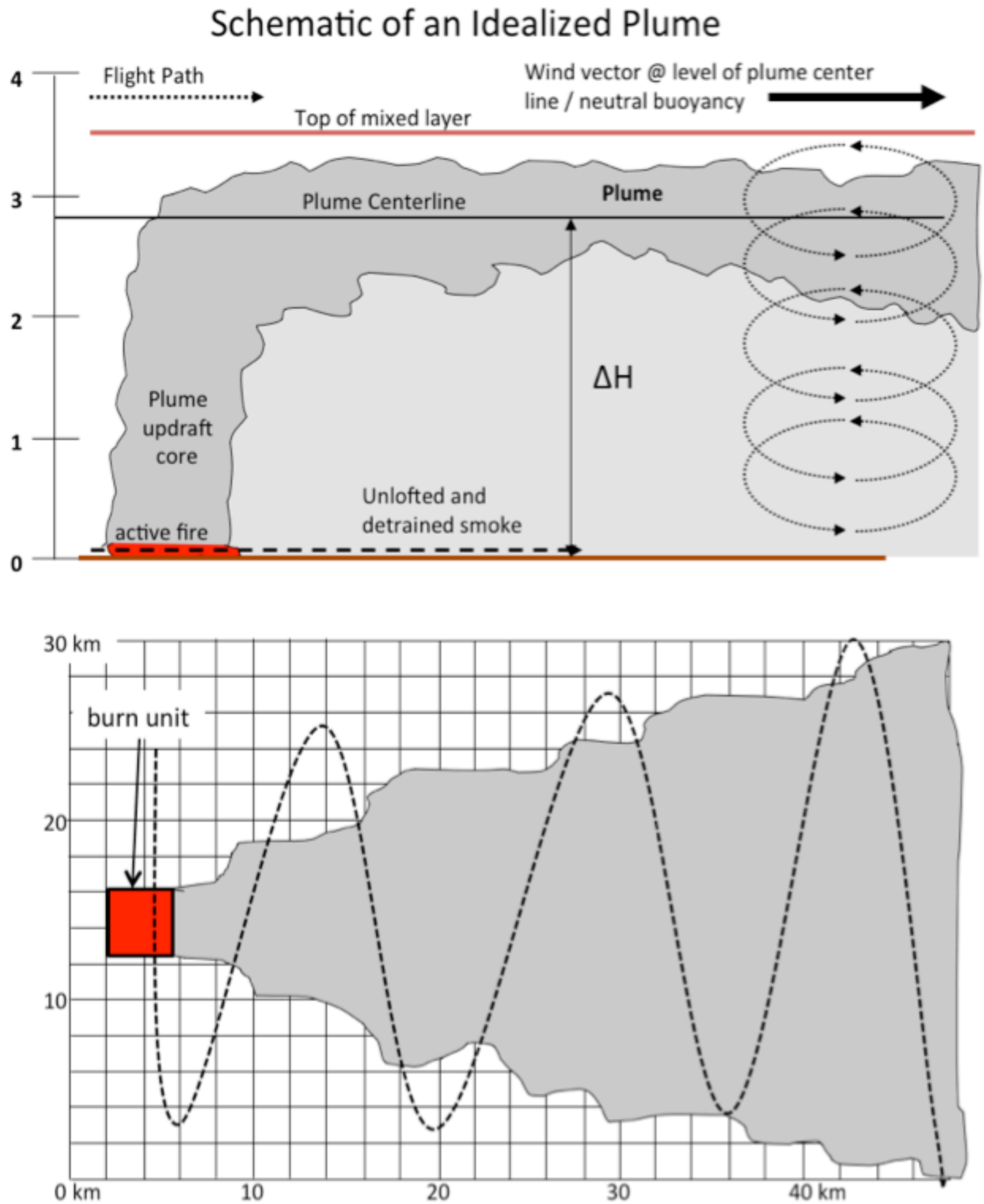

Figure B3. Schematic of an idealized plume (source: RxCADRE).

g. Plume chemistry

For complete evaluation of CTMs used for fire and other pollutant modeling, detailed precursor and chemical product measurements are needed in the near-field and at different downwind distances from a fire extending to transport over a multi-day period. The near-field measurements can be used to help define emission rates of key precursors as well as provide a specific signature for any fast chemical processing of fresh emissions. In this regard, it should be recognized that gridded CTMs treat emissions as well-mixed within the grid cell where the emissions occur. As such, any fast chemical processing that occurs within the primary grid cell will produce species, which will be treated as essentially primary emissions. The far-field measurements at different distances and over multiple days will provide documentation of the chemical production of ozone, secondary aerosols, and air toxics as a function of plume age. Appendix Table B5 includes the chemical species and other parameters of interest.

Several case studies are required to produce a database of chemical processing useful for evaluation of the CTMs under different conditions. Ideally, these case studies would include forest and rangeland fires with different emission signatures. These case studies should also include plume trajectories, which produce interactions of fire emissions with biogenic VOC emissions and also interactions with urban plumes. The first case should be easily realized since wildfires occur in forested or rangeland areas and thus the surroundings are likely to be strong BVOC source areas. The second case will probably occur less frequently and thus, requires flexible aircraft flight planning to identify and sample plumes interacting with urban emissions. This type of planning will require a chemical transport forecast system to guide daily field study operations.

h. Ground smoke and deposition

Smoke measurements taken near the ground are critical to assessing smoke models because ground smoke concentrations are the smoke that impacts health and ecosystems. Ground smoke measurements are routinely done using both nepholometers (e.g., ESAMPLERS) and beta attenuation (e.g., EBAMS) instrumentation. Additionally, smoke can be collected for a period of time by blowing air through a collection filter or tape, or using a canister for a period of time. Both techniques have value here, as the ESAMPLERS and EBAMS can provide better time resolution, and be calibrated against more accurate filter measurements. Additionally, aetholometers can measure the component of smoke that is optically black resulting in EC / BC measurements.

Based on past experiments, multiple arrays of ground smoke measurements are required. A near-field array can help characterize smoke emissions (see subsection *e* above). This array needs to be arranged relatively close the fire to capture near-ground level smoke drifting from the fire and at locations to capture differences in smoke across the fire front, and throughout the burning period. A far-field array provides valuable data on smoke impacts downwind, that can also be used to calibrate aloft vs. near-ground smoke differences. The far field array has been done on an ad-hoc basis on wildfires previously. Separation in the far field array locations needs to be calibrated to the ability of the smoke models, in order to characterize smoke at a wide spread of model grid cells (to capture the overall smoke pattern and its evolution), the within grid cell variation of smoke, and also the across observational systems (e.g., EBAMS vs. canister) differences.

There are a number of EBAMS that have been used effectively in the past, including at RXCADRE (17 were used there). There is also a national fire cache for operational use of 20+ ESAMPLERS that may be able to be utilized. Canister measurements can be purchased for use. More limited and expensive are aetholometers, which will need to be judiciously placed for optimal comparison with airborne measurements.

i. Videography

In situ video imagery of fire as it burns through a specific fuel array is invaluable in characterizing and understanding the mechanisms driving fire intensity and emission production. A well established sensor system and protocol has been developed for potential use in a smoke experiment (Butler and Jimenez 2009). Improved higher resolution cameras could run at 30hz or faster and would provide HD resolution imagery. Components for this system are presented in Appendix Table B2.

j. Satellite information

Satellite observations have become increasingly indispensable in the study of fire and smoke distribution and certain important properties, particularly at regional scales. Indeed, these observations contribute toward improving the representation of biomass burning quantitatively in climate and air-quality modeling and assessment. A comprehensive review of satellite contributions to the quantitative characterization of biomass burning for climate modeling, especially during the last couple of decades, is provided in Ichoku et al. (2012). Essentially, the satellite observations that are related to biomass burning (see Appendix Table B6) may be classified into five broad categories: (i) active fire location and energy release, (ii) burned areas and burn severity, (iii) smoke plume physical dispositions, (iv) smoke-aerosol distribution and particle properties, and (v) concentrations of pyrogenic trace gases. Each of these categories involves multiple parameters used in characterizing specific aspects of the biomass-burning phenomenon. Some of the parameters are merely qualitative, whereas others are quantitative, although all are useful for improving the scientific understanding of the spatial and temporal distribution of biomass burning and their overall impacts. Some of the qualitative satellite datasets, such as fire locations, aerosol index, and gas estimates are fairly long-term records that have been available since the late 1970s, whereas the quantitative parameters such as fire radiative power, aerosol optical thickness and particle properties over land, smoke plume injection height and profile, and essential trace gas concentrations at improved resolutions became available only since the early 2000s following the sequence Earth-observation satellite launches by NASA and its partners, as well as a few international space agencies.

Some of the prominent satellite launches to highlight include: Terra (1999, NASA) Aqua (2002, NASA), Envisat (2002, ESA), Aura (2004, NASA), Parasol (2006, CNES), CALIPSO (2006, NASA), Suomi-NPP (2011, NASA/NOAA) and OCO-2 (2014, NASA); most of which are carrying a host of sophisticated instruments providing high quality measurements of parameters related to biomass burning and other phenomena. These improved data products have enabled significant progress in the study of biomass burning from space. However, many of the measurements are associated with appreciable uncertainty that still needs to be addressed through field experiments, complemented by airborne measurements. Furthermore, satellite observations are not necessarily compatible with ground-based measurements or model parameters. Nevertheless, climate and other atmospheric models are making significant adjustments to take advantage of quantitative satellite measurements in studying biomass burning activity, emissions, and impacts (e.g., Zhang et al. 2014). These assets can be used in an integrated manner for evaluation of comprehensive chemical transport models such as described by Herron-Thorpe et al. (2014) who used an array of satellite products and ground-based O3 and PM2.5 observations to evaluate the CMAQ modeling system applied to wildfires during 2007 and 2008. New research directions should include not only improvements in ground-based measurements, satellite retrievals, and modeling accuracies independently, but also increased synergy between them, such that measurements can be directly input into models without requiring elaborate interpretation.

k. Aerial support

The cornerstone of the field study research will require a combination of heavy aircraft sufficient to carry the range of instrumentation needed to follow and quantify fire plume emissions and transport, and small, unmanned aircraft needed to monitor fire behavior and sense the atmosphere in the fire environment. An example of existing aircraft capability is the US Forest Service (USFS) Region 4 Twin Otter. USFS Region 4 Aviation has a demonstrated track record of supporting smoke research with their Twin Otter aircraft. Between 2006 and 2012, the USFS Region 4 Twin Otter has been used for five successful smoke emissions and chemistry characterization experiments, including projects funding by the DoD SERDP, NASA, NSF, and JFSP. The Twin Otter has the space, power, and lift capacity to deploy the extensive suite of instruments required for the chemical measurements.

NOAA's atmospheric science field programs have utilized UAS of all sizes from the largest, a Global Hawk to hand-launched PUMA small UAS (sUAS). A mid-sized UAS was flown around fires in 2006. The payload included a multi-spectral infrared remote fire sensor, a high-resolution carbon monoxide in situ sensor and Chromatograph for Atmospheric Trace Species (UCATS). The UCATS measured H2O, CO, CH4 and H2 on one gas channel, the other channel measured N2O and SF6 and an ultraviolet ozone photometer.

m. Model sensitivity analyses

A critical sensitivity analysis on smoke models targeted for evaluation is needed before the field campaign is initiated. This analysis would provide important information on the relative importance of each input variable for the models in question and enable the research to target the most critical measurements, the number of replicates that will be needed and at the appropriate scale. Furthermore, it is imperative the research team engages with the model developers for additional input on the importance of variables and the design of the field campaign. Investigating the required inputs before the field campaign will make the overall study more efficient and less costly while provided more pertinent data for model evaluation. This process will be very complex and time consuming requiring a separate phase of work prior to the field data collection and data management. We note that significant model sensitivity analysis were already performed by the Smoke and Emissions Model Intercomparison Project (SEMIP) Phase 1 (Larkin et al. 2012). Results from SEMIP are shown in Table B7. The work recommended here is specifically designed to:

- Analyze how the models will perform for the specific observation campaigns planned,
- Model and test both the atmospheric chemistry and fire-atmosphere couple models discussed here that were not included in SEMIP Phase 1,
- Ensure that the data collection effort is useful in analyzing the models in terms of spatial scale, temporal scale, type, quantity, and precision of data collected, and
- Help determine the best locations and most cost effective sampling design.

The model sensitivity analysis will be performed as part of Phase 1, prior to the observational data collection.

o. Data management

Data management will not be a trivial activity with this large effort and will require a data manager to be assigned at the beginning of the research effort. Many lessons learned from the RxCADRE project should be acknowledged. Each scientist or team of scientists will have a fair degree of autonomy in experimental design, instrument selection and the production of data products but will generate widely-varied data products: simple Excel spreadsheets, massive meteorological data files, infrared imagery, still photographs and video, and LiDAR are some examples. It is generally expected that a central project-sponsored facility to collect all project-sponsored data will be required to facilitate the transfer of project-sponsored data to a permanent data archive. It is further envisioned that a data archivist be attached to the campaign to establish appropriate data formats, standard data product for archiving.

The data management component is to support the entire distributed team and ensure delivery and archiving of all relevant data. This approach was successfully used in the RxCADRE field campaign, and should be used for the experiments described here.

Table B1. Required pre- and post-fire fuel characteristics to be measured for calculating fuel consumption, methods for collecting the data and the accuracy.

Data Category	Data Name Variable	Instrument/ Sensor/ Data type	Ground, Tower, Balloon, Aircraft	Units	Spatial Scale	Temporal Scale/Freq	Field Description	Justification
Fuels	Live and dead shrub mass	Shrubs based on clip plots and airborne and terrestrial LiDAR	Ground	Mg/ha	$1m^2$	Pre- and post fire	Unit and plot average shrub load from clip plots/ terrestrial LiDAR. Statistical and integrated techniques to map.	Identify/quantify shrub loads and map spatially to support fire behavior, smoke, and fire effects modeling
Fuels	Live and dead non-woody mass	Non-woody based on clip plots and airborne and terrestrial LiDAR.	Ground	Mg/ha	$1m^2$	Pre- and post fire	Unit and plot average non-woody load from clip plots/ terrestrial LiDAR. Statistical and integrated techniques to map.	Identify/Quantify non-woody loads and map spatially to support fire behavior, smoke, and fire effects modeling

Data Category	Data Name Variable	Instrument/ Sensor/ Data type	Ground, Tower, Balloon, Aircraft	Units	Spatial Scale	Temporal Scale/Freq	Field Description	Justification
Fuels	Fine fuel mass	Fine woody based on clip plots and line inventory.	Ground	Mg/ha	$1m^2$	Pre- and post fire	Unit and plot average fine woody load from clip plots/line inventory. Average distribution to map.	Identify/Quantify fine woody loads and map spatially to support fire behavior, smoke, and fire effects modeling
Fuels	Large woody mass	Large woody based on line inventory and terrestrial LiDAR	Ground	Mg/ha	$100m^2$	Pre- and post fire	Unit and plot average large woody load from line inventory/ terrestrial LiDAR. Average distribution to map.	Identify/Quantify large woody debris and map spatially to support fire behavior, smoke, and fire effects modeling
Fuels	Litter depth and mass	Litter based on clip plots, forest floor plots, line inventory, terrestrial LiDAR	Ground	mm Mg/ha	$1m^2$	Pre- and post fire	Unit and plot average litter load from clip plots, forest floor pin plots, line inventory, terrestrial LiDAR. Average distribution to map.	Identify/Quantify litter loads and depth and map spatially to support fire behavior, smoke, and fire effects modeling

Data Category	Data Name Variable	Instrument/ Sensor/ Data type	Ground, Tower, Balloon, Aircraft	Units	Spatial Scale	Temporal Scale/Freq	Field Description	Justification
Fuels	Duff depth and mass	Duff based on clip plots, forest floor plots, line inventory	Ground	mm Mg/ha	$1m^2$	Pre- and post fire	Unit and plot average duff load from clip plots, forest floor pin plots. Average distribution to map.	Identify/Quantify duff loads and depth and map spatially to support fire behavior, smoke, and fire effects modeling
Fuels	Mineral soil exposure	Mineral soil exposure based on forest floor plots, line inventory	Ground	%	$1m^2$	Pre- and post fire	Unit and plot average mineral soil exposure from line inventory and forest floor pin plots. Average distribution to map.	Identify/Quantify mineral soil exposure and map spatially to support fire behavior, smoke, and fire effects modeling
Fuels	Fuelbed depth	Fuelbed depth based on line inventory	Ground	cm	$100m^2$	Pre- and post fire	Unit and plot average fuelbed depth from line inventory. Average distribution to map.	Identify/Quantify fuelbed depth and map spatially to support fire behavior, smoke, and fire effects modeling

Data Category	Data Name Variable	Instrument/ Sensor/ Data type	Ground, Tower, Balloon, Aircraft	Units	Spatial Scale	Temporal Scale/Freq	Field Description	Justification
Fuels	Fuel consumption	Fuel consumption based on clip plots and line inventory	Ground	Mg/ha	1m^2	(Pre-fire) minus (post fire) by fuelbed strata and category	Unit and plot average fuel consumption by fuelbed strata and category	Identify/Quantify fuel consumption by strata and category to support fire behavior, smoke, and fire effects modeling
Fuels	Moisture content	Fuel moisture based on plot samples	Ground	%	40m^2	Pre-fire	Unit average live/dead fuel moisture contents for fuelbed components	Identify/Quantify moisture content by fuelbed category to support fire behavior, smoke, and fire effects modeling
Fuels	Surface cover fractions	Vegetation, litter, char, ash, and soil cover fractions	Ground	%	1m^2	Post-fire	Plot-level optical measures collocated with fuel consumption plots	Quantify fractional cover change, relate to fuel consumption, calibrate/validate remotely sensed imagery

Table B2. Fire behavior characterization sensors

Data Category	Measurement	Sensor	Spatial Distribution	Sampling Rate	Sensor Type	Justification
Fire behavior	Wind speed and direction	3.3m tall anemometers	>every 50 m around burn unit	1 hz	Cup and Vane	Spatially explicit wind flow
Fire behavior	Fire Radiant Emissive Power	Narrow Angle Radiometer	Varied	30 hz		Metric of fire intensity
Fire behavior	Fire radiosity	Medtherm Dual sensor	Varied	30 hz	Medtherm	Metric of fire intensity, can relate to fuel consumption
Fire behavior	Fire power	Custom	Varied	30 hz	Kremens	Metric of fire intensity, can relate to fuel consumption
Fire behavior	Air temperature	Type R 1 mil TC	Varied	30 hz		Critical to characterization of kinetic efficiency
Fire behavior	Air flow	Pitot probes	Varied	30 hz		Useful for characterization of convective energy release rate
Fire behavior	Fire imagery	Multispectral infrared and visible HD video	Varied	30 hz		Invaluable for characterization and interpretation of data

Table B3. Meteorological measurement platforms and sensors.

Data Category	Data Name Variable	Instrument/ Sensor/ Data type	Platform	Units	Height/ spatial scale	Temporal Scale/Freq	Quantity	Justification
Ambient Surface Meteorology	Air Temp	HMP155C	Tower	ºC	2 m	5 min	20	Characterize ambient air temperatures
Ambient Surface Meteorology	Humidity	HMP155C	Tower	g kg^{-1}	2 m	5 min	20	Ambient humidity to characterize fire weather conditions
Ambient Surface Meteorology	Wind Speed	RMY5103	Tower	m s^{-1}	2 m	5 min	20	Ambient surface winds to characterize fire behavior and fire weather properties
Ambient Surface Meteorology	Wind Dir	RMY5103	Tower	deg	2 m	5 min	20	
Micromet	Solar Radiation	NR01	Tower	W m^{-2}	2 m	15 min		Surface energy budget
Micromet	Soil Heat Flux	HFP01	Tower	W m^{-2}	-0.05 m	15 min		
Micromet	3-D wind, turbulence, sonic temperature	ATI Sx-Probe	Tower	m s^{-1}, ºC	10 m	10 Hz	10	Turbulence, Sensible heat Flux measurements of fire front and plume
Micromet	3-D wind, sonic temperature	CSI CSAT3	Tower	m s^{-1}, ºC	10 m	10Hz	10	Turbulence, Heat Flux measurements
Micromet	CO_2/CO/H_2O	CRDS	Tower	ppm/ g kg^{-1}	10 m	10Hz	1	Gas fluxes
Micromet	Air temp	Thermocouple	Tower	ºC	1 m-30 m	5 Hz	50	Turbulence, convective heat measurement
Upper-air	Air Temp., Humidity, Wind Speed and Dir, Press	Radiosonde/ Tethersonde	Balloon	ºC, g kg^{-1}, m s^{-1}, Deg., hPa	1 m up to 15 km	1 s	4 systems local, 2 regional NWS	Atmospheric vertical profiles in and around fire

Data Category	Data Name Variable	Instrument/ Sensor/ Data type	Platform	Units	Height/ spatial scale	Temporal Scale/Freq	Quantity	Justification
Upper-Air, UAS	Air Temp., Humidity, Wind Speed and Dir, Press	Dropsonde Temp, RH, Wind sensors	UAS	ºC, g kg^{-1}, m s^{-1}, deg, hPa	1 m up to 15 km Horizontal – 100 m	1 s	8 sUAS 1 UAS	Atmospheric vertical profiles over and around fire
Upper-air, remote sensing	Air Temp, Humidity	Microwave profiler	Ground	ºC, g kg^{-1}	50 m, up to 10 km	1 min	2 systems	Ambient profiles and plume thermodynamic measurements
Upper-air	WS, WD, Turbulence statistics	Doppler SoDAR	Ground	m/s, deg	5 m, 15-200 m AGL	15 min	2-3 systems	Wind profiles surrounding experiment
Upper-air	WS, WD, Turbulence, plume dispersion, Backscatter intensity	Doppler LiDAR	Ground based	m/s, deg, m	18 m, up to 9.6 km	1 s	3 independe nt systems	Three LiDARs are needed in order to scan plume and boundary-layer dynamics. Triple-LiDAR scanning allows 3-d winds within the plume to be measured.
Upper-air	WS, WD, T	Radar Wind Profiler/RASS	Ground based	m/s, deg, ºC	100 m, 0.1-2 km	30 m	1 or 2 systems, regional network	Provides boundary layer properties
Upper-air, aircraft	3-d Winds, U,V,W, Air Temp, Humidity	AIMMS-20 probe	Aircraft	m s^{-1}, deg, ºC, g kg^{-1},	--	20 Hz	1	In situ, boundary-layer meteorology and plume properties

Table B4. Smoke emission measurements from ground-based platforms.

Chemical Measurement	Measurement Platform		
	Downwind open path FTIR	Post fire front RSC point	Downwind at fixed points
CO_2, CO	X	X	X
NMOC	X	X	
NO_X	X	X	
HCN, CH_3CN	X	X	
$PM_{2.5}$, PM10			X
Aerosol speciation (OC, EC, black carbon)			X

Table B5. Airborne chemical measurements of smoke emissions, plume chemistry and smoke transport.

Data Category	Data Level	Data Name Variable	Instrument/ Sensor/ Data type	Sample Criteria[1]	Justification
Emissions Plume chemistry Atmospheric transport	Emission factors Speciated emissions Vertical plume profile Plume rise height Concentration fields Chemical evolution Total column smoke	CO_2, CO, CH_4, H_2O	CRDS	Continuous Collection rate: 2 s Precision: CO_2 0.5 ppm, CO 50 ppb, CH_4 5 ppb	CO_2 and CO contain most of C emitted by biomass fires and are needed to derive EF and quantify combustion efficiency. CO has a long atmospheric lifetime and serves as a tracer of emissions transport in the atmosphere. Ratios of reactive species to CO are necessary to quantify concentration changes due to chemistry (as opposed to atmospheric dilution). CH_4 is an important greenhouse gas.
Emissions Plume chemistry	Emission factors Speciated emissions Chemical evolution	Non-methane Organic Compounds (NMOC)	Canister samples analyzed by GC-MS, GC-FID, GC-ECD and FTIR or proton-transfer MS (e.g. PTR-MS or PIT-MS)	Whole air samples (canister or in-situ) and continuous	Over 190 species identified in fresh smoke. It is important to measure as many of these as possible. However, priority is given to species that are: 1) known to be emitted in significant quantities and/or 2) are highly reactive and/or 3) are of particular importance in SOA or O_3 formation.
Emissions Plume chemistry	Emission factors Speciated emissions Chemical evolution	NO_x (NO, NO_2) and NO_y	FTIR or chemiluminescence	Continuous or in-situ WAS (not stable for canister based sampling) Collection rate: ≤ 5 s Detection Limit ~ 10 ppb	NO_x are a critical species in atmospheric chemistry. NO_x is also a CAP.

Data Category	Data Level	Data Name Variable	Instrument/ Sensor/ Data type	Sample Criteria[1]	Justification
Plume chemistry	Chemical evolution	O3	FTIR or chemiluminescence	Continuous or in-situ WAS (not suitable for canister based sampling) Collection Rate 2 s Precision ~ 5 ppb	O3 is a CAP.
Emissions Plume chemistry Atmospheric transport	Emission factors Speciated emissions Concentration fields Chemical evolution	HCN, CH3CN	FTIR (HCN), PTR-MS/PIT-MS, Canister samples analyzed by GC-FID/ECD/MS	Continuous or WAS canister Collection Rate 2 s Detection Limit ~ 50 ppt	CO is an excellent tracer, but HCN and/or CH3CN are needed when the smoke plume mixes with emissions from anthropogenic combustion.
Emissions Atmospheric transport	Emission factors Concentration fields Chemical evolution	Integrated light scattering	Nephelometer λ = 550 nm	Continuous Collection Rate: 2 s	Integrated light scattering at λ =550 nm provides a sensitive measurement to identify smoke plume boundaries and measure relative aerosol density.
Plume chemistry	Chemical evolution	Actinic flux	Radiometer	Continuous Collection Rate: 2 s	Actinic flux is needed to model photochemistry

Data Category	Data Level	Data Name Variable	Instrument/ Sensor/ Data type	Sample Criteria[1]	Justification
Emissions Plume chemistry	Emission factors Speciated emissions Chemical evolution Total column smoke	Aerosol concentration by chemical component: Organic aerosol, organic carbon, sulfate, nitrate, ammonium, chloride Particle sizing	Aerosol mass spectrometer	Semi-continuous Collection Rate ≤ 5 s	Measurement of PM2.5 concentration. Chemical composition is a key determinant of aerosol optical properties and climate effects. Chemical evolution of aerosol is crucial to understanding regional haze and SOA formation. Aerosol chemistry may be an important factor in toxicity.
Emissions Plume chemistry	Emission factors Speciated emissions Chemical evolution Total column smoke	"Black carbon" There is no single, standard definition of black carbon. It is defined by the measurement technique.	"refractory black carbon" (rBC) – single particle soot photometer (SP2) aethalometer Elemental carbon (EC) – thermal/optical transmission IR/UV absorption	Continuous or Semi-continuous Collection Rate ≤ 5 s	Measurement of PM2.5 concentration. Chemical composition is a key determinant of aerosol optical properties and climate effects. Chemical evolution of aerosol is crucial to understanding regional haze and SOA formation. Aerosol chemistry may be an important factor in toxicity.
Plume chemistry	Chemical evolution	Peroxy acetyl nitrate (PAN)	FTIR or Chemiluminescence	In-situ WAS (Not stable for canister based sampling) or semi-continuous Collection Rate ≤ 5 s	PAN is an important NOx reservoir species. PAN transport can result in and NOx regeneration and O3 formation 100's-1000's km downwind of original NOx source.

[1]The measurement collection mode may be characterized as continuous, semi-continuous, batch, or whole air sampling (WAS). The batch mode acquires an air sample over some period storing the air in a canister or collecting aerosols as the sample is drawn through filters. The canisters and filters from batch sampling are later analyzed in the laboratory. In WAS a "grab sample" of air is quickly captured and then it is analyzed in-situ in the sample cell of an instrument (e.g., airborne FTIR) or transferred to non-reactive storage canisters for later laboratory analysis. The data collection rate pertains to continuous or batch sampling.

Table B6: List of variables related to biomass burning that can be observed/measu
from satellite and potentially useful for climate and/or air-quality modeling (Ichoku e
2012).

Data Category	Observable Variable	Acronym/symbol	Satellites/Sensors
Active fire	Fire Location	FL	MODIS, VIIRS, ASTER, GOES
	Fire Temperature	FT	GOES, ASTER
	Fire Area	FA	GOES, ASTER
	Fire Radiative Power	FRP	MODIS, VIIRS, GOES
Burned surface	Burned Area	BA	MODIS, SPOT/VEG
	Burn Severity	BS	Landsat/TM/ETM/ETM+
Smoke plume dispositions	Near-source Plume Height	PH	MISR
	Plume Vertical Profile	PVP	CALIPSO
Aerosol distribution and particle properties	Aerosol Index	AI	Aura/OMI, TOMS
	Aerosol Optical Depth or Thickness	AOD or AOT	MODIS, MISR, VIIRS
	Aerosol Absorption Optical Depth	AAOD	OMI
	Aerosol Effective Radius	R_{eff}	MODIS, MISR
	Aerosol Fine Mode Fraction	FMF	MODIS, MISR, POLDER
	Aerosol Type	AType	MISR
	Aerosol Angstrom Exponent	Aexp	MODIS, MISR
	Aerosol Single Scattering Albedo	SSA or ω_0	OMI, MISR
Trace gas concentrations	Carbon Monoxide	CO	MOPITT, AIRS, TES, SCIAMACHY
	Carbon Dioxide	CO_2	OCO2, AIRS, SCIAMAC
	Methane	CH_4	MOPITT, AIRS, TES, SCIAMACHY
	Nitrogen Oxides	NO_x	GOME, SCIAMACHY
	Formaldehyde	HCHO	OMI, GOME, SCIAMACH
	Ozone	O_3	OMI, TOMS, SCIAMACH TES, GOME

Table B7: Recommendations from the SEMIP project by modeling step (from the final report, Larkin et al. 2012).

Modeling Step	Recommendations
Fire Information	Community-accepted methods of reconciling fire information datasets to one complete, cohesive whole needed. (Note: this is the focus of current JFSP projects under the latest RFA.)
Fuels	Newest datasets (LANDFIRE-FCCS 30 m/1 km and LANDFIRE 30 m) are not in close agreement. Need significant fuel research-led effort to determine why and how to determine the best dataset for a given area.
Consumption	Models compare reasonably well overall. However, there are significant issues with certain fuel components (e.g., deep organics, shrubs, canopy, etc.)
Time Rate	A large unknown. Intrinsically related to fire behavior and the lack of reliable fire behavior predictions.
Emissions Factors (EFs)	Need to focus research on smoldering vs. flaming EFs; $PM_{2.5}$ and NO_x along with lesser emitted species (VOCs, BC) including toxics; may need vegetation-specific or fuel layer specific emissions factor work.
Plume Rise	A major unknown. Statistical corrections to current models possible using large-scale comparisons like ones done here, but dynamic plume models with realistic plumes awaiting fire behavior modeling advancement.
Dispersion	Dispersion models appear not to be the current weakest link in the smoke impact chain. Results are critically dependent on the plume rise, time rate, and overall emissions calculated, as well as the accuracy and grid scale of the available meteorological models.
Plume Chemistry	Not currently assessed within SEMIP. This would be a logical expansion for SEMIP.
Fire Behavior	Note: many issues above (time rate, plume rise) point to the need to advance fire behavior modeling. These models were not assessed as part of SEMIP. However, our findings point to the need for advances in fire behavior modeling done *specifically for smoke modeling* purposes to predict: fire growth, consumption, and emissions by hour or sub-hour time step including how these emissions are organized into convective "cores" or plumes.

Appendix C. Fuel types

There are only a small number of quality assured validation datasets for smoke model modification and evaluation. The largest smoke validation databases that will be fully available in 2015 are associated with the RxCADRE and SERDP projects. They contain measurements of ground level and airborne fuel, fuel consumption, fire behavior, heat release, smoke concentrations, and photographic documentation of plume development from prescribed burns carried out in operational grass, grass/shrub, and forest types in longleaf fuelbed types of the southeastern United States. However, this is the initial start of compiling a smoke dataset and was limited in fuelbed types assessed. Additional fuel types and ecosystems where validation data sets are needed are included in the Tables below ranked by importance (Tables C1 and C2). The list is split into prescribed fire and wildfire since the prevalence of fire in these ecosystems is significantly different depending on the type of fire. The ranking criteria include the availability of validation data, prevalence of fire, smoke management concerns, and the ability to successfully complete a research campaign.

Table C1. Fuelbed type and ecosystem priorities for prescribed fire smoke measurements during prescribed fires.

Rank	Fuelbed Type	Ecoregion	Fuel Loading	Type of fire	Season	Size
1	Southern Pine	Subtropical	>20 t/a	Prescribed, moderate intensity, long duration	Spring/ winter	50+ ha
2	Ponderosa pine	Temperate steppe/desert	>20 t/a	Prescribed, moderate intensity, long duration	Spring/fall	50+ ha
3	Deep organic soils (Pocosin/Boreal)	Subtropical/ Subartic	>20 t/a	Prescribed, moderate intensity, long duration	Winter/ summer	50+ ha
4	Mixed Conifer	Temperate steppe/marine	>20 t/a	Prescribed, moderate intensity, long duration	Spring/fall	50+ ha
5	Mixed hardwoods	Subtropical, Warm continental, Hot continental	>20 t/a	Prescribed, moderate intensity, long duration	Winter	50+ ha

Table C2. Fuelbed type and ecosystem priorities for smoke measurements during wildfires.

Rank	Fuelbed Type	Ecosystem	Fuel Loading	Type of fire	Season	Size
1	Ponderosa pine	Temperate steppe/desert	>20 t/a	Wildfire, moderate intensity, long duration	Spring/fall	50+ ha
2	Mixed Conifer	Temperate steppe/marine	>20 t/a	Wildfire, moderate intensity, long duration	Spring/fall	50+ ha
3	Chaparral/sagebr ush	Mediterranean, Temperate steppe/desert	>20 t/a	Wildfire, high intensity, short duration	Any season	100+ ha
4	Deep organic soils (Pocosin/Boreal)	Subtropical, Subartic	>20 t/a	Wildfire, moderate intensity, long duration	Winter	50+ ha
5	Grasslands	Temperate steppe, Tropical/subtropical steppe, Tropical/subtropical desert	>2 t/a	Wildfire, high intensity, short duration	All seasons	200+ ha
6	Mixed hardwoods	Subtropical, warm continental, Hot continental	>20 t/a	Wildfire, moderate intensity, long duration	Winter	50+ ha

Appendix D. Budget estimation

Presented here is a realistic budget plan based on the experience of the workshop team. The plan is abstracted and does not identify or utilize specific budgetary information. Therefore all costs are included. We expect that approximately 25% of the overall budget may be contributed in-kind through, for example, government salaries, once specific personnel are assigned. Additionally, identification of specific personnel and specific sites and planned fires will allow a more exact costing to be developed including a full budget justification, which is not provided for this budget estimate.

The budget tables in this Appendix represent estimates based on costs from previous experiments such as RxCADRE and known costs for the instrumentation and personnel needed for the experiments outlined in this plan. These numbers incorporate salary fringe, but do include indirect cost. The budget summary Table 1 in Section 8 includes an indirect cost estimate.

Table D1. Estimated costs for ground-based field fuels data collection.

Years 0-1 Experiment logistics, detailed planning, modeling exercises, etc.			
Personnel/ Instrument/Other	**Number**	**Cost**	**Justification**
Principle Investigator / Lead Scientist Ground-based fuel sampling	1	$60K	0.4 FTE (total): FTE Site visit, field campaign planning, administrative tasks
Crew boss	1	$40K	0.4 FTE (total): Site visit, field campaign planning
Field crew	2	$32K	0.4 FTE (total): Site visits and selection, field campaign planning
Statistician	1	$54K	0.6 FTE (total): model sensitivity analysis
Travel		$40K	Travel and airfare for 3 personnel for site visits and planning meetings
Years 0-1 Total		**$226K**	

Table D1. Continued.

Years 2-3 Field campaign – fuel field measurements			
Personnel/ Instrument/Other	**Number**	**Cost**	**Justification**
Principle Investigator / Lead Scientist field measurements	1	$60K	0.4 FTE (total): Plan / lead field measurement design, conduct field measurements
Crew Boss	1	$160K	1.6 FTE (total): Lead field crew to prepare / support /conduct field work and analyses
Field Crew	4	$320K	4.0 FTE (total): Field fuel sampling, sample processing
Post-doctoral researcher	1	$128K	1.6 FTE (total): Data reduction and analysis
Travel		$300K	7 personnel travel to collect pre- and post-fuel data and collecting moisture samples at the time of each fire
Sample shipment		$20K	Field sample shipment back to lab
Supplies		$20K	Field equipment
Years 2-3 Total		**$1008K**	

Table D1. Continued.

Years 4-5 Post-analysis, publication, integrating results into models			
Personnel/ Instrument/Other	**Number**	**Cost**	**Justification**
Principle Investigator / Lead Scientist field measurements	1	$30K	0.2 FTE (total): Data analysis, reports & peer review publication, support of model evaluation/integration
Crew boss	1	$40K	0.4 FTE (total): Data analysis
Crew	1	$37K	0.5 FTE (total): Data reduction and analysis
Post-doctoral researcher	1	$32K	0.4 FTE (total): Data analysis, reports & peer review publication, support of model evaluation/integration, data management and data placement into archive
Travel		$30K	PI / post-doc and crew boss travel to integration workshop and to professional meetings
Years 4-5 Total		**$169K**	
Total 5½ Years		**$1403K**	

Table D2. Estimated costs for airborne LiDAR fuels sampling.

Years 0-1 Experiment logistics, detailed planning, modeling exercises, etc.			
Personnel/ Instrument/Other	**Number**	**Cost**	**Justification**
Principle Investigator / Lead Scientist airborne LiDAR and ash	1	$60K	0.4 FTE (total): Site visit, field campaign planning, administrative tasks, organization and logistical planning
Crew leader/Technician	1	$40K	0.4 FTE (total): Site visit, field campaign planning.
Field crew	1	$32K	0.4 FTE (total): Site visit, field campaign planning.
Travel	1	$20K	Travel and airfare for 2 personnel for site visits and planning meetings
Years 0-1 Total		**$152K**	

Years 2-3 Field campaign – fuel field measurements			
Personnel/ Instrument/Other	**Number**	**Cost**	**Justification**
Principle Investigator / Lead Scientist airborne LiDAR and ash	1	$60K	0.4 FTE (total): Plan / lead field measurement design, conduct field measurements
Crew leader/Technician	1	$100K	1.0 FTE (total): lead field crew to prepare / support /conduct field work and analyses
Field Crew	1	$80K	1.0 FTE (total): Field fuel sampling, sample processing
Travel		$160K	3 personnel travel to collect pre- and post-fuel ash and fuels data and LiDAR imagery
Supplies		$24K	
Equipment purchase/LiDAR/Imagery		$200K	Field sample shipment back to lab
Supplies		$24K	Field equipment
Years 2-3 Total		**$648K**	

Table D2. Continued.

Years 4-5 Post-analysis, publication, integrating results into models			
Personnel/ Instrument/Other	**Number**	**Cost**	**Justification**
PI / lead scientist airborne LiDAR and ash	1	$30K	0.2 FTE (total): Data analysis, reports & peer review publication, support of model evaluation / integration
Crew Leader/Technician	1	$27K	0.3 FTE (total): Data analysis
Field crew	1	$21K	0.3 FTE, Data reduction and analysis
Travel		$25K	PI / post-doc and crew boss travel to integration workshop and to professional meetings
Supplies		$5K	Paper charges, other supplies
Years 4-5 Total		**$108K**	
Total 5½ Years		**$908K**	

Table D3. Estimated costs for terrestrial LiDAR fuels sampling.

Years 0-1	**Experiment logistics, detailed planning, modeling exercises, etc.**		
Personnel/ Instrument/Other	**Number**	**Cost**	**Justification**
PI / Lead Scientist Airborne LiDAR	1	$60K	0.4 FTE (total): Site visit, field campaign planning, administrative tasks, organization and logistical planning
Research assistant	1	$40K	0.4 FTE (total): Site visit, field campaign planning.
Field crew	2	$32K	0.4 FTE (total): Site visit, field campaign planning.
Travel		$20K	Travel and airfare for 2 personnel for site visits and planning meetings
Years 0-1 Total		**$142K**	

Years 2-3	**Field Campaign**		
Personnel/ Instrument/Other	**Number**	**Cost**	**Justification**
Principle Investigator / Lead Scientist field measurements	1	$180K	1.2 FTE (total): Plan / lead field measurement design, conduct field measurements
Research assistant	1	$140K	1.4 FTE (total): Lead field crew to prepare / support /conduct field work and analyses
Field Crew	2	$160K	2.0 FTE (total): Field fuel sampling, sample processing,
Travel		$140K	4 personnel travel to collect pre- and post-fire terrestrial LiDAR imagery
Supplies		$10K	
Equipment purchase/LiDAR/Imagery		$300K	Field sample shipment back to lab
Supplies		$20K	Field equipment
Years 2-3 Total		**$950K**	

Table D3. Continued.

Years 4-5 Post-analysis, publication, integrating results into models			
Personnel/ Instrument/Other	**Number**	**Cost**	**Justification**
PI / Lead Scientist field measurements	1	$75K	0.5 FTE: Data analysis, reports & peer review publication, support of model evaluation / integration
Research assistant	1	$33K	0.3 FTE (total): Data reduction and analysis
Field crew	2	$27K	0.3 FTE (total): Data analysis
Travel		$30K	PI / research assistant travel to integration workshop and to professional meetings
Supplies		$6K	Paper charges and other supplies
Years 4-5 Total		**$171K**	
Total 5½ Years		**$1263K**	

Table D4. Estimated costs for ground based fire behavior quantification.

Years 0-1 Experiment logistics, detailed planning, modeling exercises, etc.			
Personnel/ Instrument/Other	**Number**	**Cost**	**Justification**
Lead Scientist	1	$40K	0.2 FTE: Site visit, Instrument prepartion, field campaign planning, administrative tasks
Travel		$20K	Travel for site visits of 5 days
Years 0-1 Total		**$60K**	

Year 2-3 Field Campaign			
Personnel/ Instrument/Other	**Number**	**Cost**	**Justification**
Lead Scientist, Measurements: Ground based sensors			
Principle Investigator	1	$140K	1.0 FTE: Plan / organize measurements, lead instrument installation, conduct field measurements
Research Assistant	1	$100K	1.0 FTE: Instrument preparation, testing, calibration, logistic support, analyses
Wind and Video Characterization			
Co-Investigator	1	$120K	1.2 FTE: Prepare / support field work and analyses
Post-Doctoral Researcher	1	$160K	1.0 FTE: conduct field measurements and analyses of local wind fields
Equipment Upgrades	10	$150K	Construction of 10 additional sensor packages @ 7.5K each.
Videography upgrades	20	$100K	Purchase and install 20 new video boxes
IR imagery		$160K	Acquire IR camera and develop system to deploy on fires.
Travel		$200K	70 days per diem for 8 persons plus airfare for 8 persons
Equipment Shipment		$40K	Ship equipment to site instrument installation in aircraft
Supplies		$60K	Support gear needed to deploy instruments and effect field repairs.
Years 2-3 Total		**$1230K**	

Table D4. Continued.

Years 4-5 Post-analysis, publication, integrating results into models			
Personnel/ Instrument/Other	**Number**	**Cost**	**Justification**
PI / Lead Scientist	1	$70K	0.5 FTE: Data analysis, reports & peer review publication, support of model evaluation / integration
Co-Investigators	2	$80K	0.3 FTE: Data analysis, reports & peer review publication, support of model evaluation / integration
Post-doctoral researchers	2	$93K	0.7 FTE: Data analysis, reports & peer review publication, support of model evaluation / integration
Graduate Assistants	1	$27K	0.7 FTE: Data analysis, reports & peer review publication, support of model evaluation
Research Assistant	2	$53K	0.3 FTE: Data analysis
Travel		$30K	PI / Co-I travel to project data analysis / integration workshop and to professional meetings
Years 4-5 Total		**$353K**	
Total 5½ Years		**$1643K**	

Table D5. Estimated Costs for Meteorological Measurements.

Years 0-1	**Experiment logistics, detailed planning, modeling exercises, etc.**		
Personnel/ Instrument/Other	**Number**	**Cost**	**Justification**
Principle Investigator	1	$30K	0.4 FTE: Site visit, field campaign planning, administrative tasks
Graduate Assistant	1	$80K	2.0 FTE: Organize and prepare equipment, processing routines
Travel		$16K	Travel for site visits of 5 days
Years 0-1 Total		**$126K**	

Years 2-3	**Field Campaign**		
Personnel/ Instrument/Other	**Number**	**Cost**	**Justification**
Meteorological measurements: boundary layer meteorology and plume measurements			
Principle Investigator	1	$150K	1.2 FTE: Plan / organize field measurements, lead instrument installation, conduct field measurements
Post-Doctoral Researcher	2	$280K	2.0 FTE: conduct field measurements and tri-Doppler analyses
Graduate Assistant	2	$160K	2.0 FTE: Instrument preparation, testing, calibration, logistic support, analyses, field deployment
Meteorological measurements: micrometeorology			
Co-Investigator	1	$100K	1.0 FTE: conduct field research and analyses
Post-Doctoral Researcher	1	$140K	2.0 FTE: conduct field measurements and analyses
Graduate Assistant	1	$80K	2.0 FTE: conduct field measurements and analyses
Equipment: Doppler LiDAR	1	$200K	Second LiDAR acquisition for dual/tri-LiDAR plume scans
Equipment lease: Doppler LiDAR	1	$30K	Third LiDAR for triple-LiDAR, 3-d plume dynamics studies
Equipment: GHG fast flux analyzer	1	$100K	Acquisition of GHG fast flux CRDS for in situ flux measurements on tower
Travel		$120K	50 days per diem for 8 persons plus airfare for 7 persons
Equipment Shipment		$24K	Ship equipment to site, storage rental.
Supplies		$40K	Radiosondes, towers, parts, cabling
Years 2-3 Total		**$1424K**	

Table D5. Continued.

Years 4-5 Post-analysis, publication, integrating results into models			
Personnel/ Instrument/Other	**Number**	**Cost**	**Justification**
Principle Investigator	1	$80K	0.5 FTE: Data analysis, reports & peer review publication, support of model evaluation / integration
Co-Investigator	1	$33K	0.3 FTE: Data analysis, reports & peer review publication, support of model evaluation / integration
Post-doctoral researchers	2	$186K	0.7 FTE: Data analysis, reports & peer review publication, support of model evaluation / integration
Graduate Assistants	2	$107K	0.7 FTE: Data analysis, reports & peer review publication, support of model evaluation
Travel		$30K	PI / Co-I travel to project data analysis / integration workshop and to professional meetings
Years 3-5 Total		**$436K**	
Total 5½ Years		**$1986K**	

Table D6. Estimated costs for airborne meteorological measurements.

Years 0-1 Experiment logistics, detailed planning, modeling exercises, etc.			
Personnel/ Instrument/Other	**Number**	**Cost**	**Justification**
Principle Investigator / Lead Scientist Unmanned Aircraft Systems (UAS)	1	$100K	0.6 FTE (total): Site visit, field campaign planning, administrative tasks, organization and logistical planning
Crew leader/Technician	1	$40K	0.6 FTE (total): Site visit, field campaign planning.
Field crew (students)	2	$80K	0.8 FTE (total): Site visit, field campaign planning.
Travel	1	$20K	Travel 2 personnel for site visits and planning meetings
Years 0-1 Total		**$240K**	

Years 2-3 Field campaign – meteorological field measurements			
Personnel/ Instrument/Other	8 sUAS	$2K/each $16K/16 flights = $256K	Cost of each sUAS flight, includes student labor
Principal Investigator	1	$60K	0.4 FTE: On field site, admin., organization, etc.
Instrument – Large UAS or Heavy Aircraft	$7.5K/hour	300 hrs of flight = $2,250K	Includes all flight personnel, PI and meteorological instruments
Years 2-3 Total		**$2250K**	

Years 4-5 Post-analysis, publication, integrating results into models			
Personnel/ Instrument/Other	**Number**	**Cost**	**Justification**
PI / lead scientist UAS	1	$45K	0.3 FTE (total): Data analysis, reports & peer review publication, support of model evaluation / integration
Crew Leader/Technician	1	$27K	0.3 FTE (total): Data analysis
Field crew	1	$27K	0.3 FTE: Data reduction and analysis
Travel		$25K	PI / post-doc and crew boss travel to integration workshop and to professional meetings
Supplies		$5K	Paper charges, other supplies
Years 4-5 Total		**$129K**	
Total 5½ Years		**$2619K**	

Table D7. Estimated costs for airborne chemical measurements.

Year 1 Experiment logistics, detailed planning, modeling exercises, etc.			
Personnel/ Instrument/Other	**Number**	**Cost**	**Justification**
Lead Flight Scientist	1	$28K	0.2 FTE: Site visit, aircraft acquisition, field campaign planning, administrative tasks
Travel		$6K	Travel for site visits of 5 days
Years 0-1 Total		**$34K**	

Table D7. Continued.

Years 2-3 Field Campaign			
Personnel/ Instrument/Other	**Number**	**Cost**	**Justification**
Lead Flight Scientist, Measurements: CRDS, nephelometer, aethalometer, meteorology probe			
Principle Investigator / Lead Flight Scientist	1	$140K	1.0 FTE: Plan / organize aircraft measurements, lead instrument installation, conduct field measurements
Research Assistant	1	$80K	1.0 FTE: Instrument preparation, testing, calibration, logistic support, analyses
FTIR measurements			
Co-Investigator	1	$100K	Summer salary/ Release Time to prepare / support field work and analyses
Post-Doctoral Researcher	1	$140K	FTE, conduct field measurements and analyses
AMS measurements / SP2 measurements			
Co-Investigator	1	$100K	Summer salary/ Release Time to prepare / support field work and analyses
Post-Doctoral Researcher	1	$140K	2.0 FTE: conduct field measurements and analyses
Graduate Assistant	1	$80K	2.0 FTE: conduct field measurements and analyses
Canister Samples			
Research Assistant	1	$120K	1.5 FTE: conduct field measurements, laboratory analysis of canisters, analyses
Equipment Shipment		$20K	Ship equipment to site instrument installation in aircraft
Aviation			
Twin Otter Flight Hours		$1,560K	120 flight hours at $1300/hour
Aircraft Mechanic	1	$8K	Instrument installation support, 80hours at $100/hour
Installation Costs		$20K	Misc. installation costs (e.g. shop fabrication time labor and materials to construct aircraft equipment racks)
Travel		$108K	50 days per diem for 8 persons plus airfare for 6 persons
Equipment Shipment		$20K	Ship equipment to site instrument installation in aircraft
Supplies		$20K	Calibration gases
Years 2-3 Total		**$2676K**	

Years 4-5 Post-analysis, publication, integrating results into models			
Personnel/ Instrument/Other	**Number**	**Cost**	**Justification**
PI / Lead Flight Scientist	1	$70K	0.5 FTE: Data analysis, reports & peer review publication, support of model evaluation / integration
Co-Investigators	2	$80K	0.3 FTE: Data analysis, reports & peer review publication, support of model evaluation / integration
Post-doctoral researchers	2	$93K	0.7 FTE: Data analysis, reports & peer review publication, support of model evaluation / integration
Graduate Assistants	1	$27K	0.7 FTE: Data analysis, reports & peer review publication, support of model evaluation
Research Assistant	2	$80K	0.3 FTE: Data analysis
Travel		$53K	PI / Co-I travel to project data analysis / integration workshop and to professional meetings
Years 4-5 Total		**$403K**	
Total 5½ Years		**$3113K**	

Table D8. Estimated costs for ground-based chemical measurements.

Years 0-1 Experiment logistics, detailed planning, modeling exercises, etc.			
Personnel/ Instrument/Other	**Number**	**Cost**	**Justification**
PI / Lead Scientist Ground-based Chemical Measurements	1	$28K	0.2 FTE: Site visit, aircraft acquisition, field campaign planning, administrative tasks
PI / Lead Scientist Ground-based smoke characterization	1	$28K	0.2 FTE: Site visit, aircraft acquisition, field campaign planning, administrative tasks
Travel		$16K	Travel for site visits of 5 days
Years 0-1 Total		**$72K**	

Table D8. Continued.

Years 2-3 Field Campaign			
Personnel/ Instrument/Other	**Number**	**Cost**	**Justification**
Open Path FTIR Measurements			
Principle Investigator / Lead Scientist ground-based chemical measurements	1	$140K	1.0 FTE: Plan / organize aircraft measurements, lead instrument installation, conduct field measurements
Principle Investigator / Lead Scientist Ground-based smoke characterization	1	$140K	1.0 FTE: Plan / organize aircraft measurements, lead instrument installation, conduct field measurements
Research Assistant	1	$80K	1.0 FTE: Instrument preparation, testing, calibration, logistic support, analyses
Post fire front RSC point measurements (CO2, CO, CH4, NMOC)			
Co-Investigator	1	$100K	0.8 FTE: prepare / support /conduct field work and analyses
Post-Doctoral Researcher	1	$140K	1.0 FTE, conduct field measurements conduct field measurements, laboratory analysis of canisters, analyses
Downwind fixed point measurements (PM10, PM2.5, OC/EC, BC, CO2, CO, CH4, NMOC)			
Co-Investigator	1	$100K	0.8 FTE: prepare / support /conduct field work and analyses
Research Assistant	1	$80K	1.0 FTE: Instrument preparation, testing, calibration, logistic support, analyses
Downwind and far-field fixed point array (PM10, PM2.5, CO)			
Co-Investigator	3	$240K	6 x 0.3 FTE: prepare / support /conduct field work and analyses
Research Assistant	2	$128K	0.8 FTE: Instrument preparation, testing, calibration, logistic support, analyses
Field crew	8	$140K	16 x 0.2FTE: Instrument preparation, testing, calibration, logistic support, analyses
Travel		$240K	50 days per diem plus airfare for 8 persons
Equipment Shipment		$80K	Ship equipment to experiment site
Supplies		$40K	Calibration gases
Years 2-3 Total		**$1532K**	

Years 4-5 Post-analysis, publication, integrating results into models			
Personnel/ Instrument/Other	**Number**	**Cost**	**Justification**
PI / Lead Scientist Ground-based chemical measurements	1	$70K	0.5 FTE: Data analysis, reports & peer review publication, support of model evaluation / integration
PI / Lead Scientist Ground-based smoke characterization	1	$47K	0.3 FTE: Data analysis, reports & peer review publication, support of model evaluation / integration
Co-Investigators	5	$166K	0.3 FTE: Data analysis, reports & peer review publication, support of model evaluation / integration
Post-doctoral researchers	1	$47K	.7 FTE: Data analysis, reports & peer review publication, support of model evaluation / integration
Research Assistant	3	$80K	0.3 FTE: Data analysis
Travel		$60K	PI / Co-I travel to project data analysis / integration workshop and to professional meetings
Years 4-5 Total		**$470K**	
Total 5½ Years		**$2074K**	

Table D9. Estimated costs for satellite data analysis and integration.

Years 0-1 Experiment logistics, detailed planning, modeling exercises, etc.			
Personnel/ Instrument/Other	**Number**	**Cost**	**Justification**
Principal Investigator	1	$40K	0.2 FTE: Site visit, field campaign planning, administrative tasks
Data Analyst	1	$30K	0.2 FTE: Organize and prepare existing satellite data for planning purposes
Travel		$10K	Travel to one or two team meetings/site visits of 5 days each at $2.5K per travel (airfare, hotel, per-diem, car rental, etc.) anywhere in North America
Years 0-1 Total		**$80K**	

Years 2-3 Field Campaign			
Personnel/ Instrument/Other	**Number**	**Cost**	**Justification**
Satellite data analysis and integration with airborne and ground-based measurements			
Principal Investigator	1	$80K	0.4 FTE: Plan/organize satellite data and coordinate with field measurements and associated scientific research
Post-Doctoral Researcher/Programmer	1	$240K	2.4 FTE: Formulate scheme for ground/airborne/satellite/modeling integration and upscaling for regional studies. Develop all software codes and actively process all satellite measurements of fires, smoke aerosol and trace gases in coordination with the ground-based and aircraft measurements and modeling components
Travel	2	$40K	PI and Postdoc travel ($10K each) to measurement site(s) for 25 days for participation in field campaign (planning, measurement, and analysis)
Years 2-3 Total		**$360K**	

Table D9. Continued.

Years 4-5 Post-analysis, publication, integrating results into models			
Personnel/ Instrument/Other	**Number**	**Cost**	**Justification**
Principal Investigator	1	$120K	3 x 0.2 FTE: Coordinate scientific research of regional biomass burning patterns informed by field measurements, and generate reports & peer review publication, support of model evaluation / integration
Post-doctoral researcher	1	$200K	3 x 0.7 FTE: Conduct in-depth data analysis, and perform upscaling from local to regional domains, linking ground/air/satellite measurements to models, supporting model evaluation / integration, and generating reports & peer review publications
Travel		$15K	PI and Postdoc travel to project data analysis / integration workshop and to professional meetings, once each per year for 3 years (i.e., 6 travels at $2.5K each)
Years 4-5 Total		**$335K**	
Total 5½ Years		**$775K**	

Table D10. Data Management

Years 0-5 Data Management			
Personnel/ Instrument/Other	**Number**	**Cost**	**Justification**
Data Manager	1	$70K	0.75 FTE starting in Year 1: Manage data management system, ensure data quality
Programmer	1	$20K	0.2 FTE:
Travel		$5K	Travel to one or two team meetings/site visits of 5 days each at $2.5K per travel (airfare, hotel, per-diem, car rental, etc.) anywhere in North America
Per Year Total		**$95K**	
Total 5½ Years		**$475K**	

Table D11. Model Sensitivity Analyses

Years 0-1 Model Sensitivity Analyses			
Personnel/ Instrument/Other	**Number**	**Cost**	**Justification**
Lead Researchers for various modeling systems	5	$180K	0.3 FTE each
Programmers	5	$180K	0.4 FTE each
Data Analysts	5	$225K	0.4 FTE each
Travel		$15K	2 Meetings of 3 days each in North America
Total 5½ Years		**$600K**	**All in Years 0-1**

Appendix E. International role

Canada provides an opportune location for a large-scale wildfire smoke field experiment. In Canada, large extents of wildland forest are available for study. If carefully picked out, large experimental burns can be conducted in remote areas with minimal impact on communities and forest resources. Moreover, large fires are a common event in Canada. A typical year sees 5,000-6,000 fires burn 2 million hectares, compared to the US where in 2013 where 47,579 fires burned 4.3 million acres (~2 million hectares). Canada may be the last place in North America where fires can be burned at high thresholds with little risk to population or significant values.

The Canadian Forest Service is experienced in running large-experimental burn projects. The Canadian Forest Fire Danger Rating System (CFFDRS) is largely based on experimental burns conducted in Ontario (Matheson, Thessalon, White River), Alberta (Darwin Lake, Big Fish Lake) and the Northwest Territories (Porter Lake). The International Crown Fire Modeling Experiment, conducted between 1995 and 2001 involved 18 experimental high-intensity crown fires. Over 100 participants from 30 organizations and 14 countries participated in that study.

Some provincial and territorial agencies are routinely conducting large-scale prescribed burns. Parks Canada uses prescribed burns to maintain forest health and biodiversity. Provinces, including British Columbia, Alberta and Ontario, use prescribed burns to mitigate fire hazard to communities and forest resources. It may be possible to link with the above partners to pair prescribed burns with experimental smoke observations, though such burns typically occur under moderate fire weather conditions not as conductive to crown fire and smoke production.

The 2014 fire season was severe with over twice the annual average area being burned (mostly in western Canada). There may be many unburned islands that could be used as isolated pockets to burn in a large-scale experiment. The landscape may be set up for large-scale experiments, where island of unburned forest may be found, that are accessible and likely to pose any threat to communities. The CFS will be compiling maps of the 2014 wildfires and their associated unburned islands in order to create a short list of candidate sites by early 2015.

While Canada has appropriate fuels for a smoke measurement field campaign, conducting experiments in Canada are not without potential issues. In Canada, forest management and protection are a provincial/territorial jurisdiction (with the exception of the National Parks). An experiment would require buy-in from the host agency. Large fire experiments may require environmental impact assessments and consultations with First Nations. There are habitats that have been impacted by recent fire activity (e.g., caribou habitat in Saskatchewan) and many First Nations people use the forest for their livelihood. Accessibility is also a concern. Distances are great in Canada and remote airports capable of receiving transported, scientific equipment are few. To conduct a large-fire experiment in Canada, finding a location with road access and a reasonable distance from an airport may be a challenge. Finally, research dollars are limited in the current environment of Canadian government fiscal restraint – both federally and provincially. It would be important to establish alliances between agencies, provincial, federal and international, to share costs and opportunities. Further, there could be travel issues and extra expenses for U.S. researchers to transport equipment across the border.

However, if a large-scale smoke modeling experiment were to be conducted in Canada, the first step would be to bring the proposal forward to the Canadian Interagency Forest Fire Centre (CIFFC). A joint provincial/federal agency, the CIFFC Council of Directors provides guidance to research projects and priorities to Canadian fire research. A proposal could also be presented to the Canadian Council of Forest Ministers (CCFM). Functioning at a higher level than CIFFC, the CCFM may allocate funds directly from provincial and federal budgets. The Natural Sciences and Engineering Research Council of Canada may be another agency to approach. This agency focuses on funding university projects and post-doctoral fellowship and so this avenue may be limited given the governmental science direction this project is following.

Appendix F. Workshop participants

Table F1. Workshop participants, associated organization, and position and workshop role.

Participant	Organization	Position/workshop role
Dr. Kerry Anderson	Northern Forestry Centre, Canadian Forest Service	Fire research officer (fire growth modeling)
Dr. Bret Butler	USFS Missoula Fire Sciences Lab	Research mechanical engineer (fire behavior)
Dr. Timothy Brown	Desert Research Institute	Professor (Project organizer; facilitator)
Dr. Craig Clements	San Jose State University	Associate Professor, (Fire Weather and Meteorology)
Dr. Scott Goodrick	USFS Southern Research Station	Research meteorologist (mesoscale/dispersion modeling)
Dr. Charles Ichoku	NASA	Research physical scientist (fire remote sensing; emissions)
Dr. Brian Lamb	Washington State University	Professor (air quality, atmospheric modeling)
Dr. Narasimhan (Sim) Larkin	USFS Pacific Wildland Fire Sciences Lab	Research physical climatologist (BlueSky; measurements/modeling)
Dr. Ruddy Mell	USFS Pacific Wildland Fire Sciences Lab	Research combustion engineer (WFDS)
Roger Ottmar	USFS Pacific Wildland Fire Sciences Lab	Research forester (fuel characterization; consumption)
Sher Schranz	NOAA ESRL and CSU/CIRA	CIRA Assoc. Director (UAV/Fire Weather)
Gail Tonnesen	US Environmental Protection Agency	Research scientist (atmospheric modeling)
Dr. Shawn Urbanski	USFS Missoula Fire Lab	Research physical scientist (smoke chemistry; emissions)
Dr. Adam Watts	Desert Research Institute	Assistant professor (Fire ecologist/UAV)

Appendix G. Data Management

It is expected that each experiment discipline lead would have a fair degree of autonomy, and that widely varied data would be generated (e.g., excel spreadsheets, meteorological files, infrared imagery, still photographs and video, and LiDAR). However, these results should be collected in a common place to allow unrestricted access by researchers. Thus, 1) there should be a central project-sponsored facility to collect all project-sponsored data, and 2) facilitation of the transfer of project-sponsored data to an archive. To manage data within the project, a separate data management component task is planned (Appendix B.o). It would be reasonable to encourage that newly collected field experiment data at the end of the project be archived with data from previous campaigns such as RxCADRE (i.e., the Forest Service R&D Data Archive).