Data Set for Fuels, Fire Behavior, Smoke, and Fire Effects Model Development and Evaluation – the RxCADRE Project

PI: Roger Ottmar, U.S. Forest Service, Pacific Northwest Research Station, Seattle, WA

I. Overview

The availability of integrated, quality-assured fuels, fire, and atmospheric data for development and evaluation of fuels, fire behavior, smoke, and fire effects models is limited. The lack of co-located, multi-scale measures of pre-fire fuels, active fire processes, and post-fire effects hinders our ability to tackle fundamental fire science questions. The lack of such datasets became clear following discussions within the Core Fire Science Caucus, a group of 30 scientists that meet periodically to discuss fire behavior research, identify knowledge gaps, and outline a strategic direction for continued research. Consequently, the Caucus pooled their own operational and in-kind resources and collaboratively instrumented and collected fire and fuels data on prescribed fires in the southeastern United States in a research effort called the Prescribed Fire Combustion and Atmospheric Dynamics Research Experiment (RxCADRE)[1]. 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.

In 2008, 15 RxCADRE scientists demonstrated the capacity for making collaborative measurements by characterizing fire-atmospheric dynamics on 5 prescribed fires in several southern pine fuelbed types (longleaf pine/grass, longleaf pine/saw palmetto, and longleaf pine sandhills) at Eglin Air Force Base, FL and the Joseph W. Jones Ecological Research Center, GA. The RxCADRE teams collected data on pre-burn fuel loading, fuel consumption, fuel moisture, ambient weather, *in situ* convective dynamics, plume dynamics, radiant heat release, *in situ* fire behavior, and selected fire effects. This effort created linkages between data generation and data use for fire and fire effects model development and evaluation, and provided important practical experience coordinating data collection among different disciplines and deploying diverse arrays of field measurement devices. Data and results from the 2008 experiments were presented at the 4th International Fire Ecology and Management Congress in December, 2009. Lessons learned were documented and incorporated into future RxCADRE experiments (Macholz et al. 2010a; 2010b; Kremens et al. 2010). In 2011, RxCADRE monitored 3 prescribed fires in fuelbed types composed of longleaf pine, grass, turkey oak, and saw palmetto, refining logistics and sampling protocols as a collaborative and integrated research team. Twenty additional scientists from NOAA, NASA, EPA, and DoD SERDP also participated, providing prospects for diversifying expertise and funding sources in future years. Relevant grants, one-time discretionary funds, and in-kind support from RxCADRE participants for the 2008 and 2011 research campaigns were estimated at $2.5 million. Many of the resulting datasets can be made available for data repository placement.

This proposal presents a series of research plans to build and improve upon RxCADRE efforts, focusing on integrated, fine-scale (5 ha) and operational-scale (500 ha) measurements of fuel characteristics, fuel consumption, meteorology and plume dynamics, fire behavior, heat release, emissions, and fire effects in southeastern grasslands. This is a larger, more coordinated, and robust effort that will target the critical data needs as outlined by members of the fire modeling community. Ruddy Mell, Rod Linn, Gary Achtemeier, Scott Goodrich, Mark Finney and others have identified the kinds of coordinated measurements of the fuel, atmospheric, and fire environment that they require for evaluation and further development of fire and smoke models and systems such as the WUI Fire Dynamics Simulator (WFDS), FIRETEC, Rabbit Rules, FOFEM, Consume, BlueSky, Daysmoke, and others.

This proposal includes participants from the Forest Service's Southern, Rocky Mountain, Pacific Northwest,

[1] *Primary acronym definitions are listed in Appendix 2.*

Pacific Southwest, and Northern Research Stations; San Jose State University, University of Montana, Rochester Institute of Technology, University of Rochester, and other research entities with operational support from the Department of Defense (DoD), and the Remote Sensing Applications Center (RSAC). Participants offer a wide range of fuel, fire behavior, meteorology, smoke, and fire behavior monitoring expertise and equipment, and propose to instrument a minimum of 3 replicated 5-ha prescribed fires and two 500-ha operational prescribed fires in grasslands in the southeastern U.S. The small replicate fires are designed to provide a detailed and robust dataset that can be used to develop or validate fine-scale fire behavior and fire effects models. The operational prescribed fires will provide a data set to develop, modify, or test large scale fire behavior, plume generation, smoke production, and other fire effects models. These burns will leverage data and expertise derived from the seven operational burns already instrumented by RxCADRE. Specifically, we propose to: 1) quantify fuel characteristics and consumption across scales using standard methods, and with aerial and ground-based LiDAR, 2) measure fire-atmosphere interactions, plume dynamics, and ambient meteorological conditions, 3) measure surface fire behavior including radiant and convective energy release, fire rate of spread and progression, fire shape, and flame characteristics, 4) approach closure of the fire heat budget from measurements and estimates of total and effective heat of combustion and key modes of heat dissipation, 5) characterize smoke emissions at the source and downwind from the fire, and 6) characterize first order fire effects (Fig. 1). All data from the research will be quality assured by internal peer review and stored in a centrally managed repository such as the JFSP recommended Forest Service Research Data Archive, and/or Smoke and Emission Model Intercomparison Project (SEMIP, JFSP 09-1-01-7), and/or the Fire Research and Management Exchange System (FRAMES). Peer-reviewed results from these experimental fires will be multi-authored and integrated across the various disciplinary aspects of the project, providing comprehensive assessment of fire as a physical process.

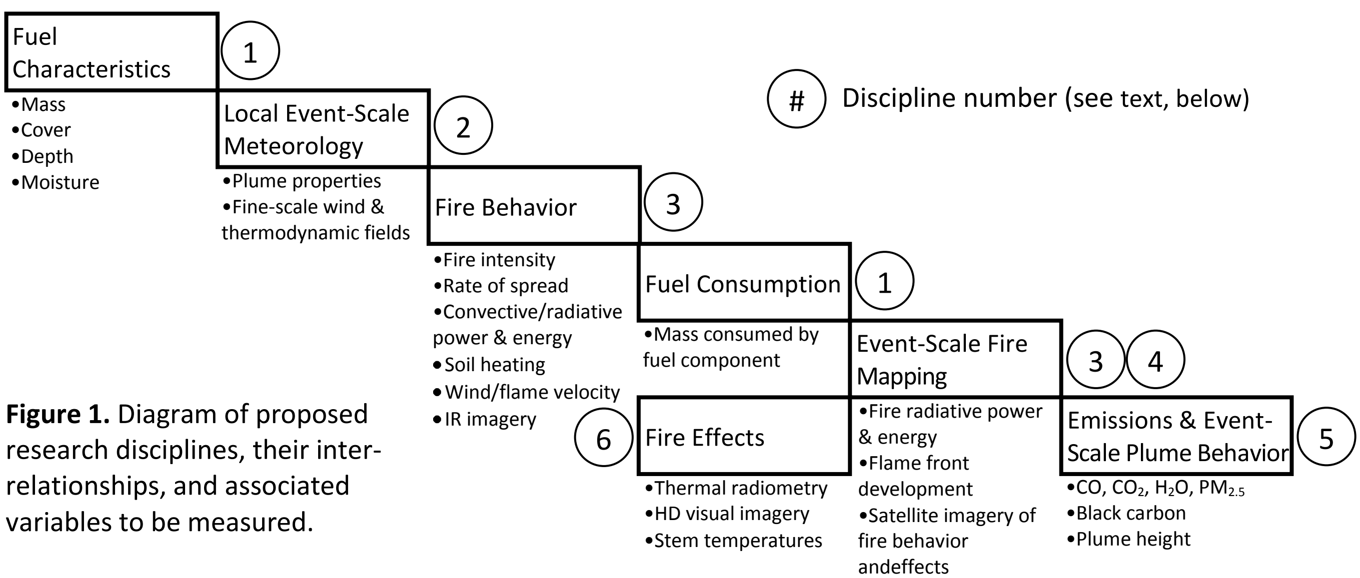

Figure 1. Diagram of proposed research disciplines, their inter-relationships, and associated variables to be measured.

1. Project Justification & Expected Benefits

Small- and large-scale field research data sets that document integrated fire behavior, emissions, and other fire effects, and that focus on individual aspects of fire dynamics (i.e., fuel characteristics, wind, surface fire behavior, fuel consumption, fire effects, emissions) are, at present, inadequate to help understand the complex interactions of fire and the atmosphere. Advancement in the core fire sciences requires an integrated research approach to further our understanding of fire and atmospheric dynamics that may vary by the scale of the burn. The experiments proposed herein will study these complex interactions on small replicate and large operational prescribed fire that range from 5 to 500+ hectares. Small replicate (≈5 ha) fires will occur in a simple grass fuelbed and will be hand lit with a single, uniform strip head fire and monitored from both the air and the ground to produce a unit-scale, high resolution fire progression and heat release data set for validating fine scale fire behavior and fire effects models. We worked with Ruddy Mell to develop an experimental planthat will provide the kind of fires and monitoring data needed to validate computational fluid dynamics-based fire behavior simulators such as WFDS and FIRETEC, next generation fire models. This project will provide a quantum improvement over the Australian grassland fire experiments of Cheney et al.(1993), the only other comparable validation dataset (Mell et al. 2007). The operational prescribed fires will also be in a simple grass fuelbed but will provide data to develop, modify, and/or evaluate large scale fire behavior, plume generation, smoke production, and other fire behavior and fire effects models.

The RxCADRE approach offers the ability to compare *in situ* and remotely sensed heat and energy; document coupled fire-atmospheric interactions; produce validation datasets for coupled fire-atmospheric dynamic models, and relate fire behavior to smoke production and first order fire effects. Fully integrated datasets will document pre-burn fuel loading and fuel consumption by fuelbed category, ambient weather, *in situ* convective dynamics, plume dynamics, radiant heat release (both from *in situ* and remote sensors), *in situ* fire behavior including fire progression and fire shape, and select fire effects, including smoke generation and soil heating. RxCADRE has already produced synergies among researchers and across scientific disciplines that have led to several new JFSP, SERDP and NSF proposals and technological developments. For example, IR data collected by a novel system devised by RxCADRE scientists from the 2011 campaign has already validated some first principles in a rule based cellular automaton model (Rabbit Rules, Achtemeier, 2003). The cross-agency and -disciplinary nature of the experiments has been fertile ground for the development of new measurement techniques, the identification of critical fire science questions, and the experiments to address these questions. Each iteration has been more successful and, with dedicated funding, should be even more fruitful. All data, once quality assured, will be placed in a centrally managed data repository for future model development and validation. Methods and results will be documented in a series of manuscripts that describe the linkages between fire behavior, fire weather, fuels, and fire effects. RxCADRE represents a unique and unprecedented collection of research capacity; it is highly likely that this effort, like previous self-funded campaigns, will leverage support from other sources, such as NOAA, EPA, NASA, and DoD (ESTCP and SERDP), which have participated actively and shown interest in this collaborative research project. Further, the project will develop methodologies and techniques for making integrated measurements that will be portable to other fire environments, thereby facilitating collection of consistent and comparable data by other researcher in other locations.

2. Rationale for Selection of Measurement Variables

Participants in RxCADRE and discussions with fire behavior and fire effects modelers including Ruddy Mell, Rod Linn, Mark Finney, the Core Fire Science Caucus, and others identified six core scientific disciplines, including: 1) fuels, 2) meteorology, 3) surface fire behavior, 4) event-scale fire mapping, 5) smoke, and 6) fire effects (Fig. 1). Datasets from each of these core disciplines will provide the integrated measurements necessary for future fire model development and evaluation. All variables that will be collected, along with their associated units, their spatial and temporal scales, and justifications for their inclusion in the experimental plan are found in Appendix 1.

1. Fuels – Fuels are often defined as the physical characteristics (e.g., loading, depth, coverage, height, bulk density) of the live and dead biomass that provide the material which is burned in combustion and contributes to wildland fire (Davis 1959). If we are to modify and validate both simple and complex systems that predict fuel consumption, fire behavior, energy release, plume and emission generation, and other fire effects, the physical characteristics, composition, distribution, and condition of each of fuelbed element needs to be described at the appropriate spatial and temporal scales. Characteristics (i.e., loading, coverage), conditions (i.e., moisture content), and spatial arrangement of all fuelbed categories (i.e., trees, shrubs, grasses, woody fuels, litter, and duff) will be measured using: 1) standard inventory protocols including non-destructive sampling and 2) aerial and ground-based LiDAR before and after each research burn. Aerial and ground LiDAR can characterize fuels in three dimensions and will be critical for integrating across different spatial scales (Hiers et al. 2009). The use of aerial and ground-based LiDAR to evaluate fuels is a new process, however, so collecting both standard and LiDAR measurements will provide a valuable data set for evaluating these new methods while also providing the data needed for modification and validation of fire models.

2. Meteorology – Measurements of meteorological fields (upper-level wind and temperature, in-plume temperature, moisture, turbulence, plume height and geometry, plume dispersion) are critical as they affect fire behavior and plume formation and will be essential in developing new and improved models for predicting these phenomena. Intense and detailed measurements of fine-scale wind and thermodynamic fields are required to determine fire-atmosphere interactions (turbulence, fire-induced circulation). These are key variables required for developing and validating fully coupled fire behavior and smoke dispersion models (Clements et al. 2007, Kochanski et al. 2011). A suite of meteorological instrumentation will be deployed within, upwind, and downwind of each burn unit. *In situ* tower measurements and remote sensing platforms will be used simultaneously to measure the atmospheric conditions in and around each experimental fire. The combination of *in situ* and remote sensing platforms will provide high temporal and spatial resolution and coverage measurements. The key measurement system to be deployed is the California State University-Mobile Atmospheric Profiling System (CSU-MAPS) that consists of a trailer-mounted, extendable 32-m micrometeorological tower with six levels of meteorological sensors, a Doppler scanning wind LiDAR, radiosonde system, and a microwave profiling radiometer that measures tropospheric profiles of temperature and humidity.

3. Surface Fire Behavior – Quantitative measurements of flame front behavior, fire progression, fire shape, and key components of the fire heat budget will be conducted using the Fire Behavior Package (FBP; Butler et al. 2004), airborne nadir high resolution infrared thermography, and deployment of cameras, spotting poles, and temperature sensors. The FBP provides local measurements of radiative and convective energy released by the fire, fluid dynamics associated with the fire passage, and fire imagery. While the FPB provides oblique, spatially integrated fire measurements, the IR thermography provides a nadir, high resolution (both spatial and temporal) imagery (see description of the FHBP, below). Associated instruments will include downward-looking radiometers and soil-heat flux sensors. Detailed field measurements of convective and radiative energy release will address current and relevant questions about how energy is released from fires and how fires spread providing an important validation data set for developing and testing fire behavior and smoke production models. Ocular estimation, temperature sensor deployment, and HD video for measuring fire progression and fire shape will provide back-up measurement for this critical variable (W.A. Mell, personal communication) and provide the ability to evaluate each method.

4. Event-Scale Fire Mapping – Fire progression, fuel consumption, and fire heat dissipation (radiative, convective, and soil heating) will be mapped on both Unmanned Aerial Systems (UAS) and manned, fixed-wing platforms. Fire progression at high temporal resolution is essential for fire behavior model validation (W.A. Mell, personal communication) and will be mapped on the small, replicate fires using two UAS platforms. Using two UAS platforms is required because fire progression is fundamental to validating fire behavior modeling. Fire progression will also be provided from the manned fixed-wing aircraft during the operational fires.

Ground-based measurements of key components of the fire heat budget are critical for mapping event-scale fire behavior and effects. The Fire Heat Budget Package (FHBP) is a new initiative, based on several generations of technology development, that brings together a set of (mostly) tower-mounted instruments that will allow us to close the instantaneous and integrated fire heat budget (Kremens et al. 2011). With our

FHBP and airborne infrared data, we will be able to map fuel consumption (after accounting for combustion efficiency), unit-scale soil heating, radiative heat release, and convective heat release, which will provide the means of linking fire behavior emissions and soil and vegetative heating and, thus, fire effects. The FHBPs will be deployed in concert with fuel and FBP sampling (see Surface Fire Behavior, above) and results will be compared and used to provide comprehensive descriptions of the fires. Satellite imagery (e.g., MODIS, LANDSAT, and available higher-resolution sensors) collected before and after the fire will be related to our event-scale fire behavior and effects maps, providing an unprecedented opportunity to evaluate satellite products.

5. Smoke – Smoke measurements will include surface and airborne measurements on the two operational burns. No smoke measurements will be taken on the small, replicate burns. Surface measurements will include $PM_{2.5}$ and black carbon downwind of the burn area and CO, CO_2 and H_2O (using CSU-MAPS) within the fire's perimeter. Airborne measurements in the smoke plume will include CO, CO_2 H_2O, CH_4, NO_x, $PM_{2.5}$, black carbon, and C1-C3 hydrocarbons. In addition, visible video will be recorded from multiple angles on each burn so that smoke puff velocities can be reconstructed. The measurements included reflect the quantities that are necessary for understanding fuel emissions and smoke chemistry, as well as the operating environment limitations of available instruments.

6. Fire Effects – Fine-scale fire radiative power (FRP) and fire radiative energy (FRE will be collected using a multispectral FLIR SC660 imaging system and related to fuelbed characteristics determined from non-destructive fuel sampling and ground-based LiDAR data. These data, in conjunction with fire heat budget measurements are critical for validating and refining physical models of heat transfer into the soil (FIRETEC; R.R. Linn, personal communication) and plant tissue (Butler and Dickinson 2010), for predicting plant injury and mortality, and providing fire spread and fire shape back-up data for evaluating fire spread models at different scales (e.g., FIRETEC, WFDS, Rabbit Rules).

II. Methods

1. Study Site and Time Frame

Data will be collected on prescribed fires in grasslands at Eglin Air Force Base in northern Florida. Jackson Guard, Eglin Air Force Base's Natural Resource Branch, has agreed to host the proposed RxCADRE integrated measurement project. Jackson Guard has the logistical and operational capacity to execute our proposed study design, can accommodate a large contingent of fire researchers, and understands our needs since RxCADRE monitored burns at Eglin in 2008 and 2011. Jackson Guard burns more than 45,000 hectares of southern pine forests with grass, turkey oak and saw palmetto understories annually between November and April. The active burning program, wide prescription windows, and excellent burning weather will provide a near 100% probability that the proposed fires will be accomplished.

The research will be conducted on a large military range with a uniform mixture of pure grass and grass with turkey oak shrubs. This will provide sufficient area to select locations for two large operational burns and a minimum of 3 smaller replicate burns. The burns will be conducted during a two-week campaign scheduled in November, 2012 following the first hard frost, which will cure the grass and shrub leaves. If a delay occurs due to weather or logistics, the remaining research burns will be conducted in January or February of 2013.

2. Sampling Design

RxCADRE participants understand the need for comprehensive, high-quality data collection and propose to intensively instrument three small burn units (5 ha) in simple, uniform grassland fuels and two operational burn units (500 ha) with both uniform grass and a mixture of grass and turkey oak shrub fuels in 2012 (Fig. 2). Fuel and fire behavior sampling will be concentrated in 250 m^2 plot areas established in relatively uniform fuels in each unit, and meteorological and smoke sampling will occur in and adjacent to each unit

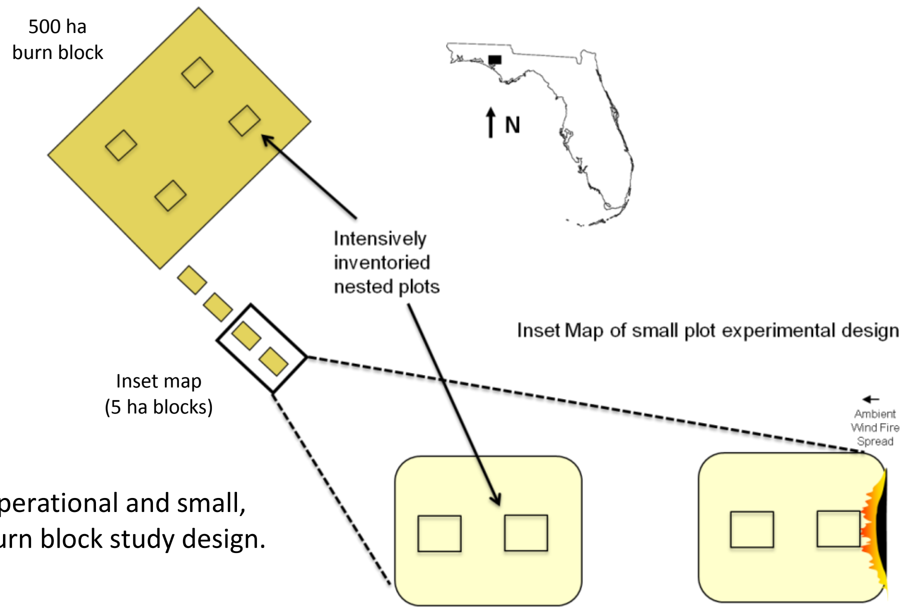

Figure 2. Operational and small, replicate burn block study design.

to measure critical inputs required for evaluation of fire behavior, fuel consumption, and smoke models. This design will allow integration of fuels, meteorological, fire behavior, fire effects, and smoke data across spatial scales. With six disciplines and up to 40 scientists participating, this research effort will generate large datasets requiring creative and sophisticated analysis, so year two (2013) has been set aside for completing additional burns if needed, data reduction, quality assurance, analysis, management and archiving, and manuscript preparation.

3. Variables and Field Measurements by Discipline Group

<u>Fuels</u> – The fuels discipline will measure pre- and post-fire fuel loading, depth, coverage, and other characteristics using standard ground-based inventory techniques (e.g., Brown 1974) and pre- and post-fire ground and aerial LiDAR on all research fires. Fuel consumption will be determined by subtracting post-fire fuel loading from pre-fire loading. In addition, fuel moisture prior to ignition will be measured for all fuelbed components. The fuels data will be available for entry into a national fuel and fuel consumption validation data set sponsored by the Joint Fire Science Program (JFSP 08-1-06-10) for use to evaluate or modify fuel characterization, fuel consumption, fire behavior, fire effects and smoke dispersion models.

Ground-based Inventory – Vegetation coverage and height by lifeform, and litter and duff coverage and depth will be measured in 20 pre-fire plots (1 m^2 each) located around the perimeter of the 250 m^2 sample area (Fig. 3). All biomass in these plots will then be clipped or gathered, sorted into categories (grass, herbs, , and as appropriate, woody vegetation, saw palmetto, litter, and duff), oven dried at 100°C, and weighed to determine mass. The relationship between coverage and height/depth and biomass for each lifeform will be used to estimate pre-fire fuel loading for 5m x 5m non-destructive (ND) plots located in each 250 m^2 sample area (Fig. 3). ND plots are divided into a 1-m^2 grid; coverage and height by lifeform, and litter and duff coverage and depth will be measured as above for each grid cell. In addition, where present pre-fire woody fuel loading by size class will be assessed on two 1.4-m long planar intersect transects (Brown 1974) in each of the 1-m^2 grid cells. Post-fire loading by fuel category will be determined by clipping or collecting remaining biomass in each 1-m^2 grid cell. Fuel consumption in ND plots will be calculated as the difference between pre-fire and post-fire loading. Similar measurement techniques will be used to assess highly instrumented 4m x 4m plots (HIPs) over which thermal imagery and radiative energy equipment will be deployed to assess fine-scale fire behavior and energy flux (Fig. 3). ND plots and HIPs will provide an undisturbed fuelbed in which to measure fire behavior and radiative energy flux. Up to four additional areas within each burn unit will be assessed non-destructively for fuel characteristics. Finally, a minimum of five grab samples of turkey oak shrub leaves, grasses, forbs, litter, and duff will be collected immediately before ignition for estimating fuel moisture.

Ground and Aerial LiDAR – A multi-scale, multi-technology approach will be used to link traditional ground-based field sampling with terrestrial and airborne remote sensing (Fig. 3). A terrestrial laser scanner (TLS) will be used to quantify the three-dimensional structure of fuels at micro-plot (16-25 m^2) and macro-plot (250 m^2) scales, co-located with fuels sampling, *in situ* heat flux measurements, and thermal imaging. The TLS provides the basis for spatial scaling of micro-plots, establishes precise scene geometry with respect to instrumentation and fuels, and facilitates scaling to the fire event domain via assimilation of surface roughness and tree crown data obtained from concurrent airborne laser scanning (ALS). The feasibility of this sampling approach was demonstrated by RxCADRE during the 2011 campaign.

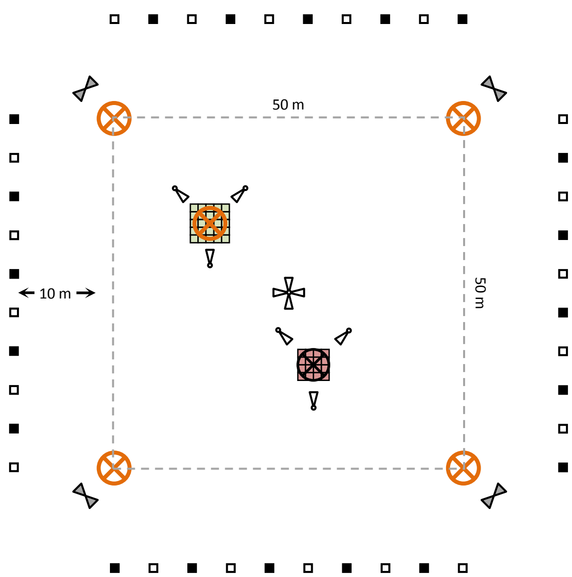

Figure 3. Fuel and fire behavior sampling layout. Additional non-destructive fuel sampling plots and radiant energy sampling equipment will be located outside of the core 50 m x 50 m sampling area.

We will refine sampling procedures tested at RxCADRE in2011 to produce integrated fuels datasets that scale from micro-plot to fire event. Data from the TLS will allow us to precisely characterize the vertical variations in fuels at very fine grain across large enough spatial domains to facilitate direct, quantitative comparisons between ALS and TLS.

Fractional cover of soil, ash, residual green and non-photosynthetic vegetation, and litter will be estimated ocularly at the same fuel plots as measured by standard ground inventory techniques. A digital photograph will be taken at nadir to further classify the fuels in each plot and to aid in TLS interpretation. These reference images will be used to refine fuel classifications as needed.

Meteorology – Measures of fire-induced atmospheric circulations, and ambient meteorological conditions will be made during the burn experiments. Comprehensive instrumentation will be deployed in order to document the fire-behavior and micrometeorology of the fire environment (Fig. 4). This will include *in situ* towers, remote sensing platforms such as a Doppler Wind LiDAR (DWL), a microwave temperature profiler, and balloon soundings for profiling the atmosphere. Key variables to be measured include:

1. Ambient wind and thermodynamic fields for background conditions affecting the fire behavior and plume, including: (a) upper-level wind and temperature up-and down-wind of the plume, (b) plume thermodynamic properties (temperature and water vapor concentration), (c) plume height and geometry, (d) plume wind field, including horizontal winds surrounding the plume, and (e) plume turbulence statistics, and
2. Fire environment, fine-scale wind, and thermodynamic fields to determine fire-atmosphere

interactions, including: (a) turbulence, heat, and moisture fluxes, (b) fire-induced circulations in and around the fire front, and (c) near-surface thermodynamic properties including temperature profiles.

The CSU-MAPS will be deployed during both the small-scale replicate fire behavior burns and the larger operational burns (Fig. 4). During the operational burns, the CSU-MAPS will be deployed in the interior of the burns while smaller (10 m) towers will be located near the downwind edge of the unit. During the smal-scalce replicate plot experiments, the CSU-MAPS will be deployed between adjacent plots, and will act as either an upwind or downwind site depending on which unit is ignited. The CSU-MAPS will then be moved 'leap-frog' to the next plot quickly in order to conduct as many burns as possible in a short timeframe to maintain consistent ambient conditions. Both the CSU-MAPS tower and the guyed towers will measure 3-D wind fields, air temperature, water vapor, and radiative heat flux at 10 Hz. Additionally, the CSU-MAPS will measure CO and CO_2 for emissions calculations. Fine-wire thermocouples sampled at 5-10 Hz will be used to measure temperature profiles of the near-surface plume environment. Winds will be measured on the *in situ* towers at 2 and 10 m above ground level (AGL) and at 2, 10, 20, and 32 m AGL on the CSU-MAPS allowing fire-induced circulations and convergence to be diagnosed. Wind profiles will be provided by both a Doppler wind LiDAR and Doppler SoDAR. The SoDAR will provide 10 min averaged, upwind profiles from 15 to 200 m AGL while the scanning LiDAR will scan across the entire experimental area with a resolution of 24 m. The LiDAR also provides vertical profiles from 80 m AGL to the top of the boundary layer (~2000 m AGL) at 3 Hz data output for u, v, w, and backscatter intensity. The combination of tower and remote sensing measurements will provide for direct quantitative data for determining the wind field characteristics of fire plumes.

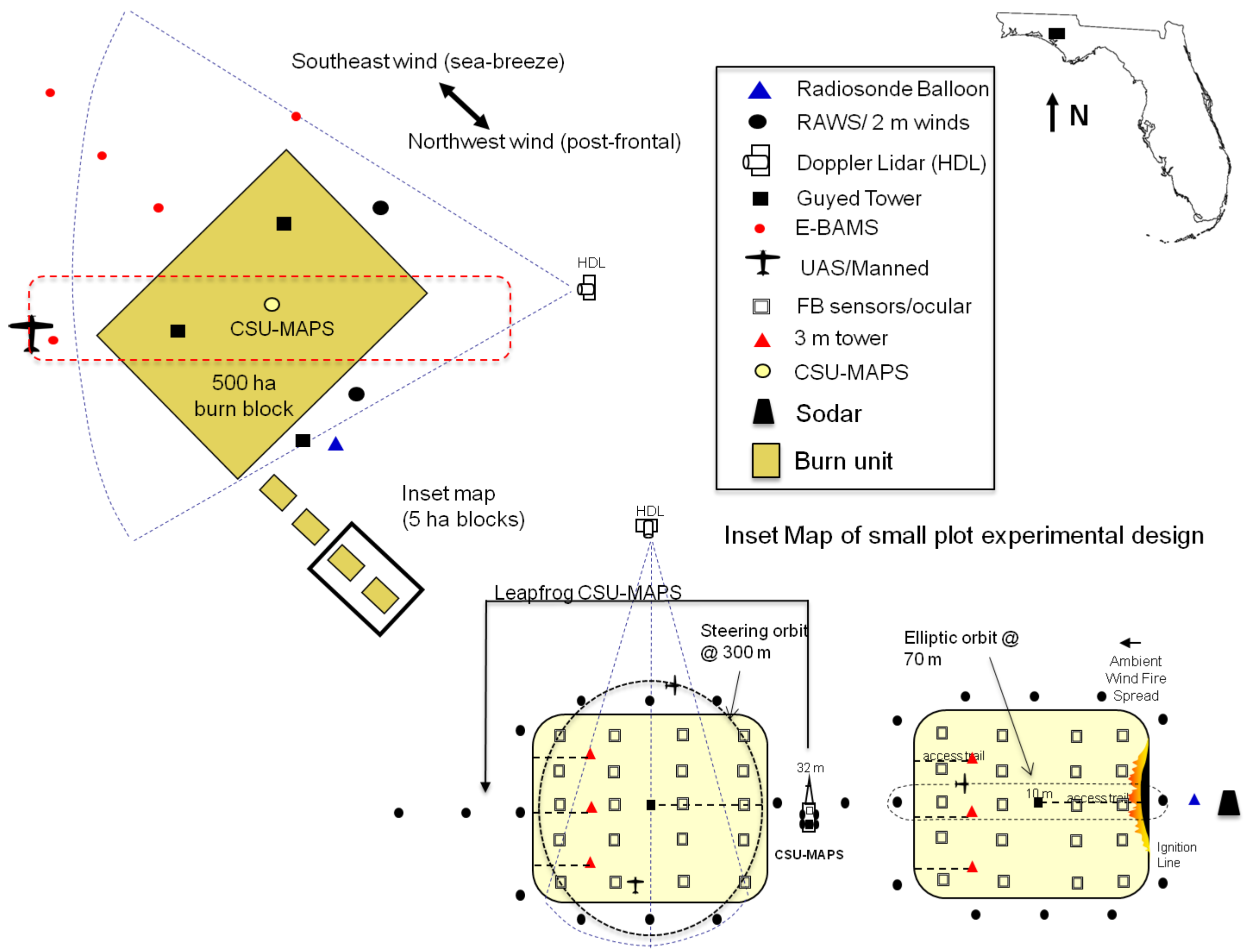

Figure 4. Experimental design for meteorological and smoke sampling.

Unmanned Aerial System (UAS) – An UAS platform flying at low altitude (approximately 70 m) will be used to sample the plume properties including temperature, humidity, wind, and black carbon concentration at a frequency of 1 Hz. Data from the UAS will be used to verify the Microwave Profiler Radiometer (MPR) profiles obtained from the plume (MPR located on CSU-MAPS platform). These data will provide a good comparison of both platforms and will allow for estimates of plume spread and extent to be compared with the Doppler wind LiDAR measurements. The UAS will also be equipped with an infrared camera sensor for mapping the progression of the fire front and will be operated by the Eglin AFB Test Wing.

The time series of each meteorological field will be subjected to a consistent quality assurance check. Sharp increases in velocities and sonic temperature associated with the plume and fire front passage (FFP) are often interpreted as spikes. The time series data will be processed using a quality control procedure to flag and remove spikes (defined as points larger than four times the standard deviation of the time series). Spikes will be replaced with the mean value of the ten preceding and following points. The process is conducted three times to ensure erroneous spikes are removed, after which, tilt corrections will be applied by use of the planar-fit method. Once the time series data from all the sonic sensors are quality assured, turbulence statistics will be calculated.

<u>Surface Fire Behavior</u> – Surface fire behavior will be characterized using the Fire Behavior Package (FBP), which has been proven to be a field deployable, fire resistant, programmable platform with a wide range of sensors, including *in situ*, short range and long range remote sensors (Fig. 3). Direct measurements of fire intensity and behavior at the flame scale include: total energy released by the fire as sensed by incident flux, radiant energy flux equivalent to blackbody emissive power, kinetic air temperature, flame emissive energy, 2-D and 3-D air flow, soil temperature gradients in the top 20 cm of the soil, CO and/or CO_2 emissions, and video images of fire burning in the sensor locations. This suite of measurements provides direct quantitative data on the temporal aspects of the ignition and burning process. The difference between total and radiant energy flux provides an estimate of convective energy heating rates in the vicinity of the fire. Measurements of air temperature history and air flow provide additional data on convective energy transport. Soil temperature measurements provide a means for estimating the energy absorbed by the soil and are relevant to determination of fire effects in terms of plant mortality and soil chemistry. Emissions of CO and CO_2 are critical as estimates of the source term used in smoke emission modeling. Additional related measurements of fire behavior will be collected by the Event-Scale Fire Mapping, Fire Effects, Smoke, and Meteorology teams referenced in this proposal. The additional measurements include fire radiometric temperatures, fire and emitting surface radiance, wind velocity and direction around the periphery of the burn unit, upper atmosphere flow and thermal gradients, and infrared images of burning vegetation from near scale (<10m) and far scale (>100 m).

Fire behavior monitoring will be concentrated in the 250-m^2 sample areas located in each burn unit. Sensors consisting of overhead infrared images, *in situ* measurements of total and radiant energy release, air flow, and air temperature will be collected as well as video images of fire behavior. Vertically oriented multi-band downward-facing radiometers will be located at the corners of the 250 m^2 sample areas and also over the 4m x 4m HIP and the 5m x 5m ND plot. Additionally, CO and/or CO_2 sensors will be tested in the aforementioned sensor package.

All sensors will be calibrated and raw data files will be converted to engineering units for characterization of fire and environment conditions. Video images will be evaluated to determine local flame geometry and local fire rate of spread. Measurements of total energy release and radiant energy release will be converted to radiant and convective energy heat fluxes and integrated to obtain estimates of fire radiative power (FRP) and fire convective power. Heat flux and temperature data will be evaluated to obtain flaming and smoldering residence times. Flow data will be evaluated to obtain estimates of local turbulence and flow characteristics in the vicinity of the spreading fire front. Fire energy release rates and power estimates will be correlated with fuel consumption, plume flow, plume temperature, and spatial estimates of surface radiance from infrared sensors.

In conjunction with the FBP, cameras, spotting poles, temperature sensors, oblique infrared videos, and infrared camera equipped UAS will be deployed to acquire fire shape and fire progression measurements as requested by fire behavior modelers. Spotting poles will be positioned at 30-m intervals for ocularly measuring fire progression while infrared cameras located on a ground based boom and the UAS/manned aircraft will provide georeferenced video for fire progression and fire shape. An array of thermocouple probes will be established in each of the small-scale units to further characterize fire rate of spread and residence time.

Event-Scale Fire Mapping – Each prescribed fire burn unit will be flown with an infrared mapping camera on an airborne platform. The two operational units (>500 ha) will be flown with a manned fixed-wing aircraft deploying the WASP system (Ononye et al. 2007) while the 3 smaller units (5 ha) will be flown with two UAS. All flights described here are independent of the low-altitude UAS making plume measurements on the operational burns (Fig. 4). The UAS support "staring" image capture by deploying gimbal-mounted sensors and flying in a circular orbit. The platforms will be flown at sufficient altitude (~300 m) to provide continuous imagery of fire development and shape over entire units. As mentioned before, fire progression and fire shape are critical for fire behavior model validation on small units and the RxCADRE feel that duplicate UAS missions were required to adequately capture these variables. One UAS system will be operated by the Eglin AFB Test Wing while the other will be operated by the University of Alaska Scan Eagle). The UAS imagery will consist of Long Wave Infrared detector (LWIR) and concurrent visible imagery. The minimum product from these flights will be maps of fire progression and flame front dimensions. Quantitative Fire Radiative Fux Density (FRFD, Kremens et al. 2010 and 2011) will also be mapped on the larger burns from WASP data. Quantitative FRFD is obtained from a combination of laboratory calibration, internal sensor calibration, ground calibration (from FHBP measurements, see below), and a large dataset of field measurements (see Kremens et al. 2010). Flame fronts (locations of peak FRFD) will be identified and FRFD and time-integrated fire radiated energy density (FRED) will be mapped for flame front pixels. In this way, a very large sample (>10,000) of time- and space-resolved FRFD and FRED estimates will be obtained across each of the operational burn units. WASP images will be captured over the center of a burn unit (a nadir perspective) at the shortest return interval possible (~5 minutes). The UAS will be operated in "staring mode" (through use of a gimbal mount) to provide near-nadir and continuous imagery. Raw image data will be orthogeorectified and co-registered using tools developed through the WASP program and by Department of Defense Test Wing staff using TerraSight, a high-end commercial software package used in mapping drone imagery for the military. TerraSight mapping will be contributed to this project.

A crucial component of event-scale fire mapping will be ground measurements. We will use the Fire Heat Budget Package (FHBP) and associated measurements (fuel and FBP, see above) to characterize the fire heat budget (Kremens et al. 2011). Having measurements of the key components of the fire heat budget will be the basis for extrapolating from event-scale maps of FRFD to event-scale maps of fuel consumption, soil heating, convective heat release, emissions, and effects on vegetation. That is, ground measurements with the FHBP will provide quantitative links between radiative heat release and other components of the fire heat budget. The FHBP instruments are tower-mounted and include CO and CO_2 sensors (for estimating combustion efficiency, e.g., Ward and Radke 1993), downward-viewing dual-band radiometers (Kremens et al. 2010 and 2011), and 3-D flow sensors for convective flux measurements (McCaffrey and Heskestad 1976). Coincident arrays of imbedded and surface soil heat flux probes will be used for estimating fire rate of spread and soil heat flux (e.g., Bova and Dickinson 2008 and 2009). Latent heat fluxes will be estimated from emission factors and measured on associated meteorological towers to fully close the heat budget. The FHBP is a new suite of instruments based on established and tested technology, although they have never been deployed in concert in this configuration on wildland fires.

<u>Smoke</u> – Electronic Beta Attenuation Monitor (EBAMS) $PM_{2.5}$ monitors will be arrayed downwind of both operational burns, in an arc across the wind as well as a line along the wind downwind of that arc (Fig. 4). These will measure $PM_{2.5}$, temperature, humidity and wind speed and direction every 5 minutes. A black carbon monitor will also be located with one of the EBAMS. Within the burn, one of the meteorology towers will also have $PM_{2.5}$ and black carbon sensors for *in situ* measurements.

In addition to these chemical emissions measurements, surface-based measurements will also include visible video from multiple angles to allow analysis of vertical and horizontal smoke velocities. This video, combined with LiDAR and *in situ* tower measurements of velocities, will provide an extensive record of the plume dynamics relevant to smoke and fire behavior. The use of video to determine plume movement was demonstrated in Reid and Vines (1972), significant advances in video technology increase the potential value of this approach.

Airborne measurements on the operational burn will complement the surface based observations. The airborne measurements will be taken using 3 sampling modes:

1. Fresh smoke samples of plume at source taken at multiple elevations to determine emission factors and combustion efficiency, validate emission models, provide initial emission profiles for initialization of smoke dispersion and atmospheric chemistry transport models.

2. Vertical profiles with spiral or step increase (Fig. 5) centered on the plume, immediately downwind of the source, are taken from above the plume to the lowest practical elevation (minimum 150 m AGL). Step increase vertical profiles involve short (~10 km) horizontal transects, perpendicular to the long-axis of the smoke plume (i.e., the direction of smoke transport), taken at 150- to 300-m increments from above the plume to the lowest practical elevation. This sampling mode provides vertical concentration profiles at the source that are used to initialize the vertical emission profiles used in dispersion and atmospheric chemistry models. Vertical concentration profiles downwind of the fire provide total column smoke and concentration fields to evaluate smoke transport models. The vertical smoke profile also provides a measurement of plume rise height. When executed upwind of the fire this sampling mode will provide vertical profiles of temperature, relative humidity, pressure, and a 3-D wind vector that can be used to initialize plume rise models. Downwind vertical profiles of these meteorological variables, when coupled with the upwind profiles, will provide observations of the fire's impact on the local atmospheric environment (e.g., changes in stability).

3. Concentration fields measured 1 to 100 km downwind of the fire will be made by traversing the plume horizontally, perpendicular to the direction of smoke transport in an S-shaped pattern downwind of the updraft core. This mode of sampling provides the observations needed to evaluate the concentration fields and chemical evolution simulated by smoke dispersion and atmospheric chemistry transport models. This sampling mode will also provide tracer concentration fields (CO, CH_4) that can be used in inverse modeling studies to provide "top-down" emissions estimates.

<u>Fire Effects</u> – Fine-scale instantaneous FRP and time integrated FRED will be measured for validation and refinement of physical models of heat transfer into the soil and plant tissue (O'Brien et al. 2008, Butler and Dickinson 2010, Stephan et al. 2010) and provide detailed fire behavior measurements for model evaluation and identification of fire behavior phenomena. Variables to be collected include: 1) detailed spatially explicit fire radiative power at a resolution of 1 cm^2 at a rate up to 30 Hz taken from nadir at a height of 7 m, 2) fire radiative power integrated over a circular area 3.5 m in radius over the same scene as imaged by the system described above collected at 0.25 Hz, 3) high definition visual images collected at 15 Hz from nadir at a height of 7 m time integrated to estimate FRE, 4) FRFD collected over a standard fuel bed (excelsior) at 0.25 Hz time integrated to estimate FRE, and 5) high-resolution stem surface temperatures at millimeter scales and at high frequency (up to 30 Hz).

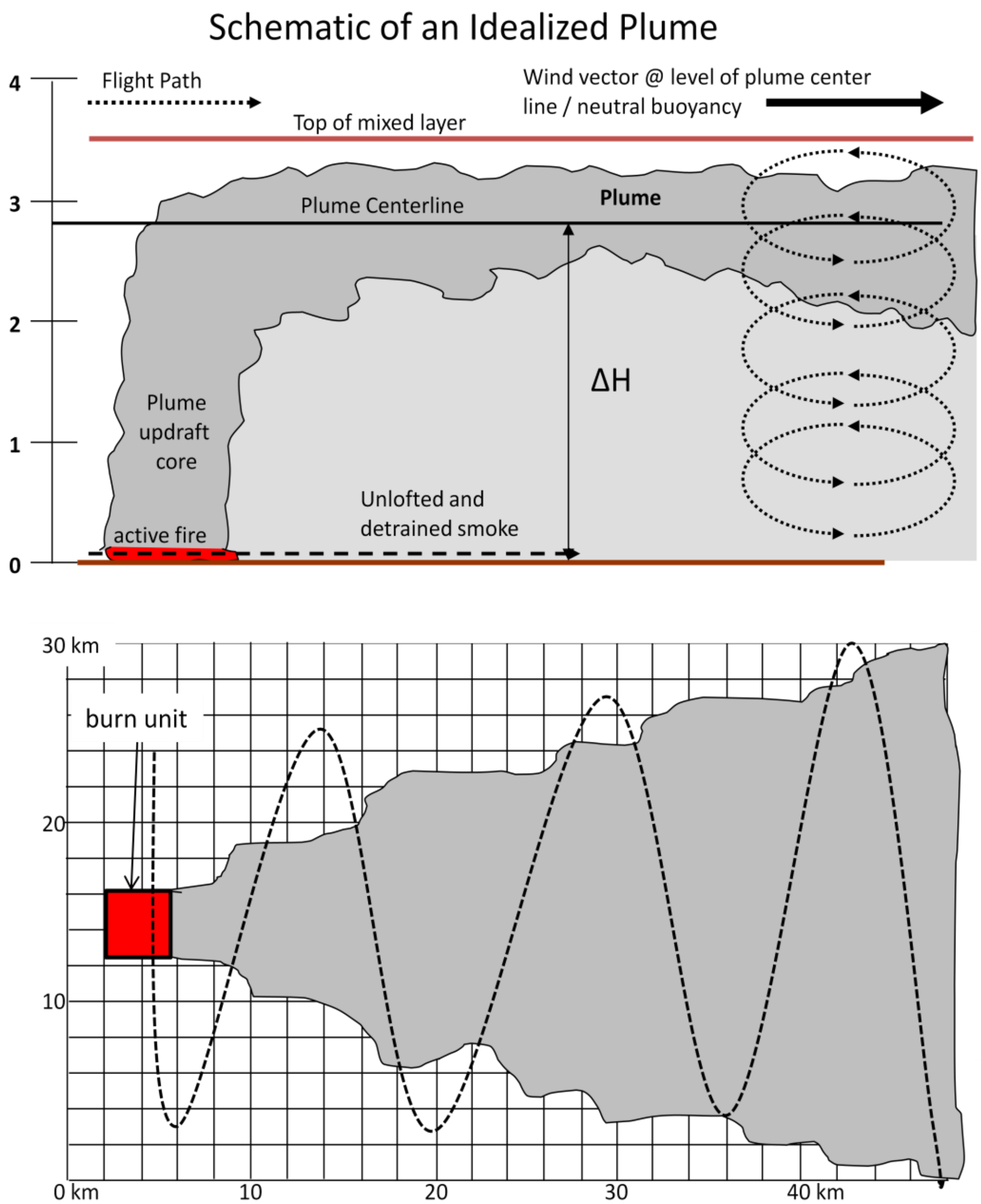

Figure 5. Aircraft flight trajectory for sampling smoke.

We will measure fine scale fire behavior using an in-fire measurement system composed of a tripod with a FLIR SC660 imaging system and a co-located dual band radiometer positioned 7 m above 16m^2 highly instrumented plots (i.e., the HIPs) where spatially explicit fuel structure and characteristics will be measured by using multispectral and LiDAR imagery (Fig. 3). We will deploy a fire hardened, fine-scale thermal imaging package for in-fire oblique measurements of radiative energy transfer into shrub stems and deploy an *in situ* excelsior fuel bed useful as a fire behavior standard and a means for synthetically evaluating the combined effects of relative humidity, wind speed, insolation, fuel moisture, etc. on fire behavior on different burn days.

4. Data Management, Archival, Documentation, Access

Project-level data management must accomplish the general objectives of: 1) centralizing data storage for a large, distributed team and 2) facilitating the assembly of data files into documented data sets. Each scientist bears the responsibility for describing the data they contribute, as well as any processing algorithms relevant to contributed reduced datasets. These descriptions, which form the bulk of the content of the metadata, will be worked into the actual metadata document using a web-based software package (preferred), or by leveraging the manual effort of the designated data manager. In either case, the data manager will be responsible for developing training on the metadata documentation process and aiding the scientists as necessary. We intend to accomplish both the storage and documentation functions on a server rented from a commercial hosting service for the duration of the project.

The prescribed fire data collection campaign is scheduled to be completed by December 1, 2012. Each discipline will have all raw data stored by April 1, 2013 and reduced data products uploaded by September 1, 2013. All annotated data will be uploaded to the specified repository by December 1, 2013 and public access granted after manuscripts are published.

RxCADRE has assigned Bryce Nordgren to facilitate data management, including quality assurance and control, archiving, documentation, formatting, sharing and coordinating data delivery from each discipline. Jim McIver and Marty Alexander, both experienced managers of large data sets, will be consulted during the planning process. A data management plan is presented as a separate document as requested by JFSP.

5. Materials

Rebar, plot poles, flagging, sample collection bags, and other disposable materials will be purchased as necessary to establish grid-points, measure plots, collect fuels samples, record, measure, and proof data. Most measurement equipment is in the inventory of the participating scientists and will be provided by the supporting institutions, although a sodar, sonic anemometers, black carbon sensor, towers, camera rental, expendable supplies for sensors, maintenance and repairs, and shipping will need to be purchased. Radisonde deployment and remote sensing aerial over-flights will be contracted.

III. Project Duration and Timeline

This project will last 24 months, assuming a start date of 1 April 2012 and an end date of 31 March 2014 (Table 1).

Table 1. List of project milestones and delivery dates.

Project Milestone	Description	Delivery Dates
Fire behavior modeling research needs assessment	The PI and several co-PIs will participate in meetings conducted by JFSP to discuss data gaps and informational needs for improving and evaluating fire behavior models with principle fire behavior experts	30 September 2012
Prescribed fires	Complete 3 small, replicate burns and 2 operational burns	1 December 2012
Data reduction and analysis	Quality assure and summarize/analyze data from winter 2012-2013 fires	1 September 2013
Data reduction and analysis	Quality assure and summarize/analyze data from 2008 and 2011 RxCADRE fires	31 December 2013
Present findings	Present results at local, regional, and national meetings conferences	31 December 2013
Prepare manuscripts	Submit papers for publication in a special section of *Forest Ecology and Management, International Journal of Wildland Fire, Canadian Journal of Forest Research,* or similar outlet	31 March 2014
Submit data	Submit documented data to USFS R&D data archive, SEMIP, and/or FRAMES	31 March 2014
Final Report	Submit final report to JFSP	31 March 2014

IV. Project Compliance - NEPA and other clearances.

NEPA has been conducted by Jackson Guard for Eglin Air Force Base to cover the prescribed burning and subsequent research for all sites selected for this research effort.

V. Research Linkage

The PI is the lead scientist for the original RxCADRE project which was initiated in 2008. RxCADRE is a concept developed by the Core Fire Science Caucus that has successfully monitored five prescribed fires in 2008 and three prescribed fires in 2011. The project has been an unfunded, *ad hoc* effort to date; participating scientists have contributed their own equipment, time, research funds, and grants that aligned with the RxCADRE effort to verify the feasibility and value of the RxCADRE research approach. A special session at the 4th International Fire Ecology and Management Congress was convened to transfer knowledge gathered from the work in 2008 (Hiers, 2010; Ottmar and Vihnanek, 2010; Butler and Jimenez, 2010; Clements et al., 2010; O'brien et al., 2010; Hudak et al., 2010). NOAA, NASA, EPA, and DoD (ESTCP and SERDP) have shown interest in participating with RxCADRE and contributing financial and in-kind resources because of the appeal of collaborating with a scientific cadre with the depth and breadth of expertise of the participating scientists. Several participating scientists have ongoing JFSP projects that are closely linked with this proposed project (Table 2).

Table 2. Current and pending research grants.

Grant Program	Project or Proposal Description/Identification	Funding Amount	Project Completion Date
Joint Fire Science Program	**JFSP-07-2-1-20** Characterizing the effect of terrain and slope on firefighter safety zones	$428,322	15 June 2012
Joint Fire Science Program	**JFSP: 08-1-6-01** Validation of fuel consumption models for smoke management planning in the Eastern Regions of the United States	$516,000	31 December 2011
Joint Fire Science Program	**JFSP: 08-1-06-10** Creation of a Smoke and Emissions Model Intercomparison Project (SEMIP) and evaluation of current models	$479,935	30 September 2011
Joint Fire Science Program	**JFSP: 09-1-01-2** Does season of burning affect fuel dynamics in southeastern forests?	$331,581	30 September 2012
Joint Fire Science Program	**JFSP: 09-1-01-7** Fuel life-cycle and long term fire behavior responses to fuel treatment in southeastern U.S. pine ecosystems	$297,024	30 September 2012
Joint Fire Science Program	**JFSP: 09-1-04-2** Sub-canopy transport and dispersion of smoke: a unique observation dataset and model evaluation	$670,988	30 September 2012
Joint Fire Science Program	**JFSP: 12-1-06-52** Probabilistic risk assessment of heat and gas effects on burrow and cavity- using threatened and endangered wildlife during wildland fires	$537,810	1 June 2015

VI. Deliverables and Science Delivery

The program manager and senior and co-PIs will be active in preparing deliverables and conducting outreach (Table 3). An informational exchange website will be established. The primary deliverable will be publication of the scientific results in a special issue of *Forest Ecology and Management*, the *International Journal of Wildland Fire*, the *Canadian Journal of Forest Research,* or another similar outlet. Preceding special issue publication, all key participants will present results in person at local, regional, and national meetings and conferences. All data from the study will be quality assured, reduced as appropriate, documented, and stored in a centrally managed repository such as the U.S. Forest Service Research and Development Data Archive, SEMIP, and/or FRAMES.

Table 3. List of deliverables and their description and delivery dates.

Deliverable Type	Description	Delivery Dates
Fire behavior modeling research needs assessment	The PI and several co-PIs will participate in meetings conducted by JFSP to discuss data gaps and informational needs for improving and evaluating fire behavior models with principle fire behavior experts	30 September 2012
RxCADRE website	Establish RxCADRE website for informational exchange	30 April 2012
Special session at a major fire conference	PIs and scientists will present preliminary results at a major Fire Conference in 2014	Date to be determined
Workshop for managers	Program manager and senior and co-PIs will present findings to managers in the southern U.S.	Prior to 31 March 2014
Final Report	Summary description of findings to JFSP	31 March 2014
Documented data sets	Fully quality assured and documented data sets, posted on USFS R&D data archive, SEMIP and/or FRAMES	31 March 2014
Scientific papers	Manuscripts describing all primary findings; drafts to be ready for publication in journal special issue	Draft by 31 March 2013

VII. Roles of Investigators and Associated Personnel

The curricula vitae of the PI and discipline leads are included in Attachment 2. A summary of the project personnel and their responsibilities is noted in Table 4. All parties have extensive experience making field measurements in their respective disciplines.

Table 4. Roles and responsibilities of associated personnel.

Personnel	Role	Responsibility
Roger Ottmar (USFS - PNW)	Principal Investigator	PI and Fuels discipline lead
Dan Jimenez (USFS - RMRS)	Program Manager	Overall project management of the RxCADRE research
Craig Clements (San Jose State University)	Co-principal Investigator	Meteorology discipline lead
Bret Butler (USFS - RMRS)	Co-principal Investigator	Fire Behavior discipline lead
Matt Dickinson (USFS - NRS)	Co-principal Investigator	Event-Scale Fire Mapping discipline lead
Brian Potter (USFS - PNW)	Co-principal Investigator	Smoke discipline lead
Joe O'Brien (USFS - SRS)	Co-principal Investigator	Radiative Energy and Fire Effects discipline lead
Kevin Hiers (Eglin Air Force Base)	Cooperator	Prescribed fire program manager for Jackson Guard; prescribed fire operations and planning
James Furman (Eglin Air Force Base)	Cooperator	Fire management officer for Jackson Guard; operations oversight and coordination with military command

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Appendix 1

This table presents the discipline, variable name, data type or instrument used, sampling median, measured units, spatial and temporal scales, field description, justification, and lead scientists of variables that will be measured during the fires.

Integrated Monitoring Data Table

General Data Category	Data Name Variable	Instrument/sensor /data type	Ground, Tower, Balloon, Aircraft	Units	Spatial Scale	Temporal Scale/Freq.	Field Description	Justification	Lead Scientist(s)
Fuel Characteristic Measurements									
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	Ottmar Seielstad
Fuels	Live and dead nonwoody mass	Nonwoody based on clip plots and airborne and terrestrial LiDAR.	Ground	Mg/ha	$1m^2$	Pre- and post fire	Unit and plot average nonwoody load from clip plots/ terrestrial LiDAR. Statistical and integrated techniques to map.	Identify/Quantify nonwoody loads and map spatially to support fire behavior, smoke, and fire effects modelling	Ottmar Seielstad
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 modelling	Ottmar Seielstad

General Data Category	Data Name Variable	Instrument/sensor /data type	Ground, Tower, Balloon, Aircraft	Units	Spatial Scale	Temporal Scale/Freq.	Field Description	Justification	Lead Scientist(s)
Fuel Characteristic Measurements									
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 modelling	Ottmar Seielstad
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 modelling	Ottmar Seielstad
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 modelling	Ottmar Seielstad
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 modelling	Ottmar Seielstad

General Data Category	Data Name Variable	Instrument/sensor /data type	Ground, Tower, Balloon, Aircraft	Units	Spatial Scale	Temporal Scale/Freq.	Field Description	Justification	Lead Scientist(s)
Fuel Characteristic Measurements									
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 modelling	Ottmar Seielstad
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 modelling	Ottmar Seielstad
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	Ottmar
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	Hudak

General Data Category	Data Name Variable	Instrument/sensor /data type	Ground, Tower, Balloon, Aircraft	Units	Spatial Scale	Temporal Scale/Freq.	Field Description	Justification	Lead Scientist(s)
Meteorology Measurements									
Meteorology	WS	CSU-MAPS tower	Tower	m/s	2, 10, 20, 32 m AGL	1 Hz	Wind speed	Wind profile	Clements
Meteorology	WD	CSU-MAPS tower	Tower	m/s	2, 10, 20, 32 m AGL	1 Hz	Wind direction	Wind profile	Clements
Meteorology	Press	CSU-MAPS tower	Tower	mb	2, 10, 20, 32 m AGL	1 Hz	Pressure	Pressure field	Clements
Meteorology	3-D winds, u,v,w	*In situ* tower	Tower	m/s	10 m AGL	10 Hz	3-D winds, u,v,w	Turbulence profile	Clements
Meteorology	T	*In situ* tower	Tower	°C	10 m AGL	10 Hz	Temperature	Plume temperature	Clements
Meteorology	Ts	*In situ* tower	Tower	°C	10 m AGL	10 Hz	Sonic Temperature	Calculate sensible heat flux	Clements
Meteorology	Hr	*In situ* tower	Tower	kW/m^2	1 m	10 Hz	Radiative heat flux	Radiative heat flux	Clements
Meteorology	3-D winds, u,v,w	*In situ* tripod	Tower	m/s	3 m AGL	10 Hz	3-D winds, u,v,w	Turbulence profile	Clements
Meteorology	T	*In situ* tripod	Tower	°C	3m AGL	10 Hz	T emperature	Air temperature	Clements
Meteorology	Ts	*In situ* tripod	Tower	°C	3 m AGL	10 Hz	Sonic Temperature	Sensible heat flux	Clements
Meteorology	Press	*In situ* tripod	Tower	mb	3 m AGL	1 Hz	Pressure	Pressure field	Clements
Meteorology	T	Radiosonde	Balloon	°C	2 m	1 Hz	Temperature	Sounding profile	Clements
Meteorology	Td	Radiosonde	Balloon	°C	2 m	1 Hz	Dewpoint temperature	Sounding profile	Clements
Meteorology	RH	Radiosonde	Balloon	%	2 m	1 Hz	Relative humidity	Sounding profile	Clements
Meteorology	WS	Radiosonde	Balloon	m/s	2 m	1 Hz	Wind speed	sounding profile	Clements
Meteorology	WD	Radiosonde	Balloon	degree	2 m	1 Hz	Wind direction	sounding profile	Clements
Meteorology	Pres	Radiosonde	Balloon	mb	2 m	1 Hz	Pressure	sounding profile	Clements

General Data Category	Data Name Variable	Instrument/sensor /data type	Ground, Tower, Balloon, Aircraft	Units	Spatial Scale	Temporal Scale/Freq.	Field Description	Justification	Lead Scientist(s)
Meteorology Measurements									
Meteorology	3-D winds, u,v,w	Doppler wind LiDAR	Ground	m/s	80-9600 m range, 24 m gate	3 Hz	uvw	3-d wind profile	Clements
Meteorology	B	Doppler wind LiDAR	Ground	dB	80-9600 m range, 24 m gate	3 Hz	Backscatter	Aerosol profile	Clements
Meteorology	Vr	Doppler wind LiDAR	Ground	m/s	24 m, 80-9600 m	3 Hz	Radial velocity	Scanning Velocity measurements	Clements
Meteorology	T	Microwave profiling radiometer	Ground	°C	100 m, 50 - 10,000 m	3 min	Temperature	Tropospheric profiles	Clements
Meteorology	RH	Microwave profiling radiometer	Ground	%	100 m, 50 - 10,000 m	3 min	Relative humidity	Tropospheric profiles	Clements
Meteorology	Ql	Microwave profiling radiometer	Ground	g/m^3	100 m, 50 - 10,000 m	3 min	Liquid water content	Tropospheric profiles	Clements

General Data Category	Data Name Variable	Instrument/sensor /data type	Ground, Tower, Balloon, Aircraft	Units	Spatial Scale	Temporal Scale/Freq.	Field Description	Justification	Lead Scientist(s)
Fire Behavior Measurements									
Fire Behavior	Total incident flux	FBP total heat flux	Ground	kW/m^2	Point	1-10 Hz	Total incident energy emitted by fire arriving at sensor	Characterize fire intensity and energy release	Butler
Fire Behavior	Radiant incident flux	FBP incident radiant heat flux	Ground	kW/m^2	Point	1-10 Hz	Radiant incident energy emitted by fire arriving at sensor	Characterize fire intensity and energy release	Butler
Fire Behavior	Flame radiative power	FBP narrow angle radiometers	Ground	kW/m^2	Point	1-10 Hz	Energy emitted by flames in specific direction	Characterize the energy source term.	Butler
Fire Behavior	Air temperature	FBP air temperature	Ground	°C	Point	1-10 Hz	Air temperature	Characterize the energy source term	Butler
Fire Behavior	Air velocity	FBP air flow	Ground	m/s	Point	1-10 Hz	Horizontal and vertical air flow	Characterize the convective heating environment around and in spreading flames	Butler
Fire Behavior	Fire images	FBP video footage	Ground	n/a	Point	30 Hz	Flame video	Characterize the fire environment.	Butler
Fire Behavior	Soil temperature	Soil heating	Ground	°C	Point	1-10 Hz	Soil temperature	Characterize the heating of the soil below a spreading fire front.	Butler
Fire Behavior	Fire progression	Hobo temperature sensors	G	°C, m/s	10m	Sec.	Temperature sensors positioned in grid to provide rate of spread	Record of fire behavior phenomena; used as back-up to other fire progression data	Ottmar
Fire Behavior	Fire progression	Poles/ocular estimation	G	m/s	10m	Sec.	Pole observation markers positioned in grid to ocular estimate rate of spread	Visual record of fire behavior phenomena; used as back-up to other fire progression data	Ottmar

General Data Category	Data Name Variable	Instrument/sensor /data type	Ground, Tower, Balloon, Aircraft	Units	Spatial Scale	Temporal Scale/Freq.	Field Description	Justification	Lead Scientist(s)
Airborne and Terrestrial Radiative Flux Variables									
Fire Behavior	ROS	Rate of spread	Ground	m/s	10 m	Seconds	Local fire rate of spread	Basic fire behavior description, fireline intensity calculation	Dickinson
Fire Behavior	ROS	Rate of spread	Aircraft	m/s	10 m	Minutes	Local fire rate of spread. Based on infrared FRFD mosaics collected from UAS and manned fixed-wing platforms	Basic fire behavior description at unit scale used for model evaluation and fire intensity calculation	Dickinson
Fire Behavior	I	Fireline intensity	Ground	kW/m	10 m	Minutes	Frontal heat release from product of heat of combustion, fuel consumption, and ROS	Variable that links fire behavior with ecological effects and plume models	Dickinson
Fire Behavior	L	Flame dimensions (length)	Ground	m	10 m	Minutes	From video analysis	Modeling fire effects on trees	Dickinson
Fire Behavior	H	Flame dimensions (height)	Ground	m	10 m	Minutes	From video analysis	Modeling fire effects on trees	Dickinson
Fire Heat Budget	CE	Combustion efficiency	Tower	Fraction	10 m	Seconds	CO/CO_2 ratio	These measurements are part of the Fire Heat Budget Package (FHBP) sensor array. The arrays are a 3rd-generation, integrated set of instruments designed to balance the instantaneous and integrated fire heat budget, interpret remotely sensed data, and predict fire effects	Dickinson
Fire Heat Budget	FRFD	Fire radiative flux density (nadir)	Tower	kW/m^2	10 m	Seconds	Dual-band radiometer	These measurements are part of the Fire Heat	Dickinson

General Data Category	Data Name Variable	Instrument/sensor /data type	Ground, Tower, Balloon, Aircraft	Units	Spatial Scale	Temporal Scale/Freq.	Field Description	Justification	Lead Scientist(s)
Airborne and Terrestrial Radiative Flux Variables									
Fire Heat Budget	FCFD	Fire convective flux density	Tower	kW/m^2	10 m	Seconds	3-D flow sensor	Budget Package (FHBP) sensor array. The arrays are a third-generation, integrated set of instruments designed to balance both the instantaneous and integrated fire heat budget, interpret remotely sensed data, and predict fire effects	Dickinson
Fire Heat Budget	FSHFD	Fire soil heat flux density	Ground	kW/m^2	10 m	Seconds	Soil thermocouple probe arrays associated with tower		Dickinson
Fire Heat Budget	FLHFD	Fire latent heat flux density	Tower	kW/m^2	10 m	Seconds	Inferred from fuel combustion and combustion efficiency		Dickinson
Fire Heat Budget	FRFD	Fire radiative flux density (nadir)	Aircraft	kW/m^2	10 m	Seconds to minutes	Infrared FRFD mosaics collected from UAS and manned fixed-wing platforms	Unit scale FRFD and FRED (Fire Radiated Energy Density, integrated FRFD) maps of entire burn units used to extrapolate local fire heat budget measurements to the unit scale and estimate unit-scale fuel consumption and fireline intensity.	Dickinson

General Data Category	Data Name Variable	Instrument/sensor /data type	Ground, Tower, Balloon, Aircraft	Units	Spatial Scale	Temporal Scale/Freq.	Field Description	Justification	Lead Scientist(s)
Smoke Measurements									
Smoke	Particulate matter	EBAMS, Particle scattering, $PM_{2.5}$mass density	Ground	µg/m^3	50 m to 10 km, TBD	5 min	Concentration of $PM_{2.5}$ down wind.	Determine smoke concentrations at various distances to validate smoke dispersion and transport models	Potter
Smoke	Black carbon	Athalometer, Black carbon aerosol mass density	Ground	µg/m^3	Single point	5 min	Concentration of black carbon aerosol	Determine smoke composition	Potter
Smoke	Temperature, Relative humidity, wind	Meteorological data (EBAMS-based)	Ground	°C, %, m/s	50 m to 10 km, TBD	5 min	Meteorology variables collocated with smoke concentrations	Determine smoke transport and dispersion. Also supports overall meteorology measurements.	Potter
Smoke	Video	Visible video and time lapse images	Ground	m/s	10 m	0.1 to 10 sec	Statistical description of near-ground vertical and horizontal air motions within the visible plume	Plume dynamics reconstruction based on puff motion and tracking.	Potter
Smoke	Gases	Trace gas analyzer, mixing ratios of CO_2, CO, CH_4, NO, NO_2, C_2-C_3 hydrocarbons, H_2O	Aircraft	ppm	130 m horiz-ontal, 5 m vertical	2-sec continuous, NO/NO_2 30-sec C_2-C_3 hydro-carbons discrete samples. Fresh smoke at source, downwind (smoke aged 0.1 to 4 hours)	Concentration fields of trace gases at the source and down wind.	Concentration of trace gases for vertical profiles and horizontal transects of the downwind smoke plume	Potter

General Data Category	Data Name Variable	Instrument/sensor /data type	Ground, Tower, Balloon, Aircraft	Units	Spatial Scale	Temporal Scale/Freq.	Field Description	Justification	Lead Scientist(s)
Smoke Measurements									
Smoke	Particulate matter	Nephelometer, particle scattering, $PM_{2.5}$ mass density	Aircraft	µg/m^3	130 m horiz-ontal, 5 m vertical	2-sec continuous. Fresh smoke at source, downwind (smoke aged 0.1 to 4 hours)	Concentration fields of $PM_{2.5}$ at the source and down wind.	Concentration of $PM_{2.5}$ for vertical profiles and horizontal transects of the downwind smoke plume	Potter
Smoke	Black carbon	Athalometer, black carbon aerosol mass density	Aircraft	µg/m^3	1300 m horiz-ontal, 50 m vertical	30-sec continuous. Fresh smoke at source, downwind (smoke aged 0.1 to 4 hours)	Concentration fields of black carbon aerosol at the source and down wind.	Concentration of black carbon aerosol for vertical profiles and horizontal transects of the downwind smoke plume	Potter
Smoke	Temperature, Relative humidity, Pressure, Wind	Airborne Meteorological Probe	Aircraft	°C, %, Pa, m/s	65 m horizontal, 2.5 m vertical	2-sec continuous data. Fresh smoke at source, downwind 50-100 km (smoke aged 0.1 to 4 hours)	Meteorology variables at the source and down wind.	Vertical profiles and horizontal transects of meteorology variables upwind and downwind of fire	Potter

General Data Category	Data Name Variable	Instrument/sensor /data type	Ground, Tower, Balloon, Aircraft	Units	Spatial Scale	Temporal Scale/Freq.	Field Description	Justification	Lead Scientist(s)
Fire Effect Measurements									
Fire Effects	Fire radiative power and energy, fireline geometry, rate of spread, flame depth	Tower based Infrared thermal imagery using FLIR SC660 (307,200 pixels per image). Data consists of native format IR file and CSV matrix of temperature data.	Tower	MW, MJ, m/s, m	1-50 ha	During Fire, maximum frame frequency 60Hz. Pixel size $20mm^2$-$50mm^2$	Pixel coordinates, temperature, time stamp.	Fire line characterization, synoptic observations of fire intensity and fire behavior. Also will provide redundancy for UAS data	O'Brien
Fire Effects	Fire radiative power and energy, fine scale fire behavior and spread	Nadir Infrared imagery using FLIR S60 (76,800 pixels). Data consists of native format IR file and CSV matrix of temperature data.	Tower	MW, MJ, m/s, m	16 m^2	During Fire, maximum frame frequency 60Hz. $4mm^2$ pixel size.	Pixel coordinates, temperature, time stamp.	Fine scale fire behavior, fine scale fire spread, detailed spatial data of flaming and glowing combustion phases.	O'Brien
Fire Effects	Fire Radiative power, energy	Standardized Fuel Beds. Infrared radiometry of in situ excelsior fuel bed.	Ground	MW, MJ	$1m^3$	During fire	Time, power.	Account for temporal variation in fuel moisture, temperature and fire weather.	O'Brien
Fire Effects	Rate of spread, flame depth, fire behavior, fire shape	Synoptic and nadir visual imagery of fire behavior using HD digital video in MPEG4 format	Tower	m/s, m	Up to 50 ha	During fire	Time, location, rate of spread, flaming depth, fire shape	Visual record of fire behavior phenomena; used as back-up to other fire progression data	O'Brien

Appendix 2

Primary acronym list found in the text and definition.

Acronym	Definition
AGL	Above Ground Level
ALS	Airborne Laser Scanner
CSU-MAPS	California State University Mobile Atmospheric Profiling System
DoD	Department of Defense
DWL	Doppler Wind LiDAR
EBAMS	Electronic beta Attenuation Monitor
EPA	Environmental Protection Administration
ESTCP	Environmental Security Technology Certification Program
FB	Fire Behavior
FBP	Fire Behavior Package
FHBP	Fire Heat Budget Package
FHBS	Fire Heat Budget System
FOFEM	First Order Fire Effects Model
FRAMES	Fire Research and Management Exchange System
FRE	Fire Radiative Energy
FRFD	Quantitative Fire Radiative Flux Density
FRP	Fire Radiative Power
HD	High Definition
HIP	Highly Instrumented Plots
IR	Infrared
JFSP	Joint Fire Science Program
LiDAR	Light Detection And Ranging
LWIR	Long Wave Infrared Dector
MODIS	Moderate Resolution Imaging Spectroradiometer
MPR	Microwave Profiler Radiometer
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
RAWS	Remote Automatic Weather Station
RxCADRE	Prescribed Fire Combustion and Atmospheric Dynamics Research Experiment
SEMIP	Smoke and Emission Model Inter-comparison Project
SERDP	Strategic Environmental Research and Development Program
SoDAR	Sonic Detection And Ranging
TLS	Terrestrial Laser Scanner
UAS	Unmanned Aerial System
WASP	Wildfire Airborne Sensor Program
WFDS	WUI Fire Dynamics Simulator