RxCADRE Integrated Research Project

Project Title: Data set for fuels, fire behavior, smoke, and fire effects model development and evaluation—the RxCADRE Project

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Project Websites:

http://firelab.org/project/rxcadre-project
http://www.fs.fed.us/pnw/fera/research/rxcadre/index.shtml
http://www.fs.usda.gov/rds/archive

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Executive Summary

Outputs from fire models play a critical role in natural resource management decision making. However, most of the models used today have not been scientifically evaluated nor have their outputs been verified because of a lack of quality-assured data. This lack of integrated, quality-assured datasets across key fire-related disciplines, including fuels, meteorology, fire behavior, radiative power and energy, emission, and fire effects information, reduces both our ability to evaluate fire and smoke models and to answer fundamental fire science questions.

The Prescribed Fire Combustion and Atmospheric Dynamics Research Experiment (RxCADRE) was planned to provide an opportunity for leading scientists to come together and collect these fire datasets on 7 large operational prescribed fires in 2008 and 2011 at Eglin Air Force Base and the Joseph W. Jones Ecological Research Center in the southeastern United States. In 2012, the Joint Fire Science Program sponsored continuation and expansion of this effort to include 6 small replicate and 3 operational prescribed burn blocks in longleaf pine ecosystems on Eglin Air Force Base.

During 2013 and 2014, the quality of the data was assured, and it reduced and formatted for placement into the Forest Service Research Data Archive which is accessible to all. Data collection and preliminary results have been presented at several conferences, workshops, training courses and in a 10-paper special issue of the International Journal of Wildland Fire that will be published in 2015.

Abstract

The availability of integrated, quality-assured datasets is limited, reducing our ability to evaluate fire models and tackle fundamental fire questions. To help fill this gap, the Prescribed Fire Combustion and Atmospheric Dynamics Research Experiment (RxCADRE) evolved to collect reduce, and complete a preliminary analysis of data collected in 2008, 2011, and 2012 on small replicate and large operational prescribed fire burn blocks in longleaf pine ecosystems at Eglin Air Force base in Florida and at the Joseph Jones Ecological Research Center in Georgia. The goal was to develop synergies between fuel, atmospheric conditions, fire behavior, radiative energy, smoke generation, and fire effects measurements for fire model development and verification. Over 90 scientists and technicians from 15 different federal agencies, universities, and other organizations participated during the campaign. The RxCADRE project organized its data collection around a stepwise, hierarchical structure with 6 major discipline areas of fuels, meteorology, fire behavior, radiative power and energy, emissions, and fire effects. The burn block selection targeted grass, grass/shrub, and managed southern pine forest fuelbeds at both fine- and operational scales. Each discipline employed data collection techniques ranging from in-situ instrumentation to mapping fire progression with manned and unmanned aircraft. Once collected, data were reviewed, reduced, analyzed and linked to metadata. Over 125 datasets and accompanying metadata are being uploaded and stored in the US Forest Service Research Data Archive and will be available to all scientists and managers for purposes of evaluating and improving fire models, and advancing knowledge in the area of wildland fire science. Ten papers have been submitted for review and publication as a special issue of the International Journal of Wildland Fire.

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I. Background by Discipline and Purpose

Many fire models are routinely used to make critical nature resource decisions. These models predict a variety of variables and phenomena including estimations of biomass loading (Weise and Wright 2014), fuel consumption (Ottmar 2014), fire behavior (Rothermel 1972, Van Wagner 1977, Linn et al. 2010, Mell et al. 2010), emissions and the dispersion of those emissions (Heilman et al. 2014, Larkin et al. 2014, Urbanski 2014) and fire effects (DeBano et al. 1998). However, evaluation of model results has been limited by the lack of integrated, quality-assured datasets (Cruz and Alexander 2010, Alexander and Cruz 2012). A lack of datasets for evaluating models also hinders our ability to tackle fundamental fire science questions. To help fill this void, the Core Fire Science Caucus—an ad hoc group of 30 scientists that met periodically to discuss fire behavior research, identify knowledge gaps, and outline a strategic direction for continued research. We pooled our operational and in-kind resources to collaboratively instrument and collect fire data on seven operational prescribed fires in 2008 and 2011 at Eglin Air Force Base in Florida and the Joseph W. Jones Ecological Research Center in Georgia. This effort was termed the Prescribed Fire Combustion and Atmospheric Dynamics Research Experiment (RxCADRE). The collaboration enabled scientists to integrate processes for collecting complementary research data across fire-related disciplines before, during, and after the active burning periods of prescribed fires. The goal was to develop synergies among the fuel, atmospheric conditions, fire behavior, radiative energy, smoke generation, and fire effects measurements for fire model development and evaluation.

In 2012, the Joint Fire Science Program (JFSP) validated and formalized this effort by funding a continuation and expansion of RxCADRE to include six small replicate (~2 ha) and three operational (~200 ha) prescribed burn blocks in longleaf pine ecosystems on Eglin Air Force Base in northern Florida (Joint Fire Science Program 2012). The six small replicate sites for 2012 were selected to represent relatively simple fuelbeds at the request of noted fire behavior modelers. The three operational fires were requested by smoke modelers so that enough heat and smoke could be generated to produce a strong plume that could be followed downwind. Besides the data collection effort in 2012, the JFSP supported data reduction and analysis for the 2008, 2011 and 2012 RxCADRE campaigns; design of a data management system; and the storage of the data into a permanent data archive for all clients to access. Thirty scientists and technicians participated in the 2008 and 2011 campaigns while over 90 scientists and technicians participated in the 2012 campaign. Eglin Air Force Base was selected for the much larger 2012 RxCADRE project because of its history of management support of such projects, availability of appropriate research sites, a high probability that experimental fires would actually occur, local control of air space for deployment of remotely-piloted aircraft systems (RPAS), and support for data acquisition and processing.

The RxCADRE project organized data collection in a thematic stepwise structure with six major research discipline areas and their associated variables (Fig. 1). This final report follows the outline suggested by the Joint Fire Science Program, with each section organized around the six research discipline areas (fuels, meteorology, fire behavior, radiative power and energy, emissions and fire effects). Datasets and the management of the data, a critical outcome of this project, are also discussed.

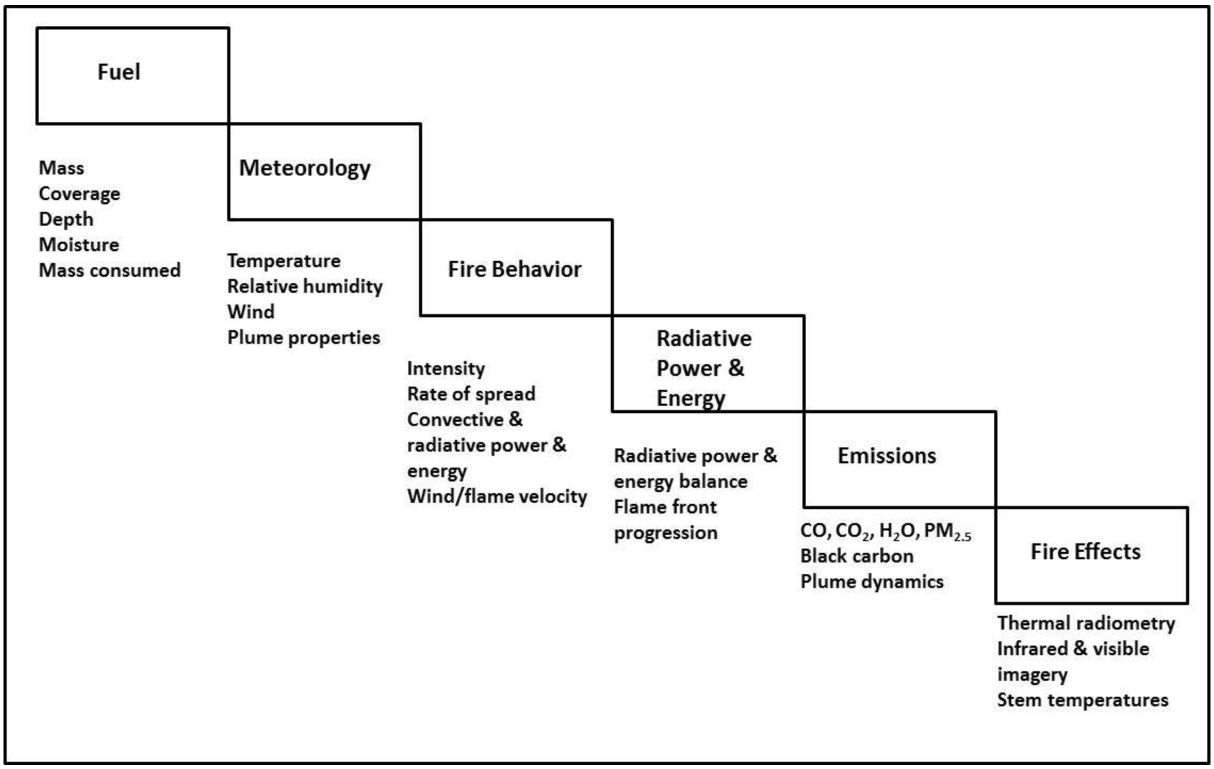

Figure 1. Research discipline areas and associated target variables.

Fuels

The emergence of next-generation wildland fire models that simulate fire propagation, energy transfer, and emissions has placed new demands on fuels data (Linn et al. 2002, Morvan and Dupuy 2004, Mell et al. 2007, Pickett et al. 2009, Prince et al. 2010). Although statistical distributions of fuel properties and consumption characteristics from field plots remain fundamental to understanding fire behavior and effects, the very high spatial variability observed in even fairly simple fuelbeds (Keane et al. 2012) highlights the need to map the actual arrangement of materials as an addition to statistical abstraction. However, distributing fuels realistically across landscapes is difficult, and measuring three-dimensional locations of fuels in the field accurately is time consuming and hard to replicate. Few experiments have collected conventional fuels data pre- and postfire in parallel with systematic measurements of residual ash and 3-dimensional fuel structure. The purpose of collecting RxCADRE fuels measurements was to provide robust fuels data for model validation from standard field sampling, and to extend those measurements experimentally through application of terrestrial and airborne laser scanning. The potential near-term advantage of laser scanning for providing improved fuels data is in mapping characteristics of the fuelbed such as height, shape, and arrangement of vegetation across landscapes, with the goal of explicitly characterizing some of the spatial variability in fuels that may affect fire behavior and effects.

Pre- and postfire measurements of fuels were also focused on characterizing consumption because consumption of fuel during wildland fire is the basic process that leads to heat generation and emissions, driving fire behavior and accounting for fire effects such as smoke effects on communities, carbon reallocation, tree mortality, and soil heating (Agee 1993, Hardy et al. 2001, Ottmar 2014). To assist managers in planning for wildland fire, consumption studies of shrubs, forbs, grasses, woody fuel, litter, and duff in forests and rangelands have been conducted in temperate, tropical, and boreal regions of the world and offer datasets that include fuel characteristics, fuel moisture, fuel consumption, and environmental variables from both wildfires and prescribed fires (Ottmar 2014). These datasets have been used to develop fuel consumption models for software systems in use today such as Consume (Prichard et al. 2007), FOFEM (Reinhardt et al. 1997), CanFIRE, and BORFIRE (de Groot et al. 2007, 2009). Although mainstays of fire effects modeling, the aforementioned modeling systems have not been quantitatively evaluated because independent, fully-documented, and quality-assured fuel consumption data are lacking (Alexander and Cruz 2012; Cruz and Alexander 2010). One way to acquire an independent dataset is by collecting ground measurements of pre- and postfire fuel characteristics and conditions during prescribed fires (Macholz et al. 2010, Ottmar et al. 2013). Fuel consumption measurements are difficult and costly, however, and more efficient methods to measure fuel consumption on the ground are desired, including residual ash remaining or terrestrial laser scanning (lidar).

Meteorology

Fire–atmosphere interactions are defined as the interactions between presently burning fuels and the atmosphere, as well as interactions between fuels that will eventually burn in a given fire and the atmosphere (Potter 2012). Currently, most meteorological sampling for fire behavior applications and research is performed at coarse resolution (i.e., hundreds of meters to kilometers) with widely-spaced remote automated weather station (RAWS) networks in existence throughout the United States (Horel and Dong 2010). However, there is an increasing need to measure fire–atmosphere interactions at finer scales to better understand the role of near-surface wind and thermodynamic structures of flames and plume (Clements et al. 2007), and to provide evaluation datasets for new-generation coupled fire–atmosphere modeling systems (Coen et al. 2013, Filippi et al. 2013, Kochanski et al. 2013).

To date, few field experiments have focused on simultaneous measurements of fire behavior and fine-scale meteorology. The FireFlux experiment (Clements et al. 2007, 2008; Clements 2010), provided the first dataset of in situ micrometeorological measurements during a fire front passage. Although the FireFlux dataset remains the standard for the evaluation of coupled fire–weather models (e.g., Kochanski et al. 2013; Filippi et al. 2013), it is limited by a lack of comprehensive fire behavior measurements. Therefore, more comprehensive field experiments are required to better understand the role of fire-atmosphere interactions in fire spread. To that end, an extensive set of meteorological instruments was deployed simultaneously with a comprehensive suite of fire behavior measurements from multiple airborne and in situ ground-based platforms.

Fire behavior

Energy transfer drives wildland fire intensity and rate of spread (Anderson 1969, Yedinak et al. 2006, Anderson et al. 2010). Quantification of energy transport on wildland fires is a critical yet poorly documented element of wildland fire science, especially the variability in space and time and as the proportion released through radiant and convective heating modes (Frankman et al. 2012). To understand and accurately predict the behavior of forest fires (Albini 1996), model fire emissions (Wooster et al. 2005, Freeborn et al. 2008), and improve public and wildland firefighter safety (Butler and Cohen 1998, Butler 2014), it is critical to understand how energy is released from burning wildland fires, and to provide both laboratory and in situ measurements of fire behavior and the transfer of energy in fires burning natural fuels. RxCADRE provided such an opportunity.

RxCADRE addressed these questions through use of integrated airborne, oblique, and ground measurements of energy production and transport and fire movement. The use of piloted aircraft to collect infrared and visible passive imagery for monitoring fire behavior has long been recognized as critical for wildland fire research. However, despite their promise, RPAS use has not been evaluated extensively. The RxCADRE project provided an opportunity to evaluate several types of RPAS.

Radiative power and energy

Characterizing radiation from wildland fires is important because such radiation relates directly to the combustion process. Satellites that measure power and energy from wildland fires hold great promise for use in monitoring long-term active fires, helping to characterizing fuel consumption, and to estimate smoke production (e.g., Coen and Schroeder 2013; Schroeder et al. 2013, 2014; Peterson et al. 2013; Peterson and Wang 2013; Freeborn et al. 2014). Satellite measurements, however, are subject to limitations and these can be explored and quantified through ground (e.g., Kremens et al. 2012) and airborne (e.g., Riggan et al. 2004; Peterson et al. 2013, 2014) measurements at higher spatial and temporal resolution. Ground and airborne measurements, however, also have their challenges, including limitations on replication and spatial extent and the lack of fundamental knowledge of fire radiation (Kremens et al. 2010).

There is no “gold standard” wildland fire radiative power (FRP) measurement, only measurements of fire radiation for which we more or less understand accuracy, precision, and uncertainty. Only recently has a comparison among ground, airborne, and satellite data from an active fire been achieved in which ground radiometer measurements of FRP were similar to airborne measurements and, in turn, airborne measurements coincided with measurements from four spaceborne sensors, including the GOES geosynchronous imagers (East and West) (Schroeder et al. 2013). Geostationary satellite imagers (GOES) provided data at a temporal resolution similar to that of an airborne sensor making repeated passes over a fire, albeit at a much coarser spatial resolution (> 6 km). Understanding the accuracy and precision of fire radiation measurements and improving those measurements is paramount to the future use of airborne and satellite measurements for fire behavior characterization and ecological effects prediction (Kremens et al. 2010). RxCADRE intended to characterize radiative power and energy through multi-scale simulation measurements from ground, aircraft and satellite platforms.

Emissions

In many regions around the world, fire is an essential ecological process. It emits particulate (i.e., Hodzic et al. 2007, Strand et al. 2011) and gaseous compounds (i.e., Goode et al. 1999, Aurell and Gullett 2013) into the atmosphere on a wide variety of spatial and temporal scales, driven by both natural forces and human management decisions. Particulate emissions strongly affect regional visibility (McMeeking et al. 2006), can cause a positive or negative climate forcing (Hobbs et al. 1997), and can cause inhalation health effects (Wegesser et al. 2009). The black carbon fraction of particulates has been found to accelerate Arctic and Greenland ice sheet melting (Bond et al. 2013). The strong spectral variation in light absorption of biomass burnings’ organic carbon fraction (i.e., brown carbon) contributes to atmospheric warming (Chung et al. 2012) and affects photochemistry (Li et al. 2011). Gaseous compounds emitted during biomass burning include greenhouse gases, tropospheric ozone precursors, and other air quality pollutants (Andreae and Merlet 2001). Understanding the effects of these emissions on global climate and regional air quality requires quantifying biomass burning emissions.

Predicting wildland fire emissions requires prediction of fire occurrence and growth, fuel type consumed, and combustion phase such as flaming or smoldering, and each prediction compounds uncertainty (French et al. 2011). Emission factors associated with a fuel type, combustion phase, or both, are used to estimate emissions when combined with mass of fuel consumed. Emission factors have varying ranges of uncertainty depending on the emitted chemical species (Urbanski et al. 2009, Akagi et al. 2011). Several studies have derived emission factors for a variety of North American fuel types, including southeast United States fuels, by using excess concentration data collected from prescribed fires, wildfire measurements, and laboratory studies (i.e., Akagi et al. 2013, Yokelson et al. 2013, Burling et al. 2011). Collectively, these studies have provided reasonable estimates of emission factors for the primary gas species— carbon dioxide, carbon monoxide, methane (CO_2, CO, CH_4, respectively)—emitted during biomass burning, and the fuel type with which they are associated. In contrast, for other emitted species, such as particulate matter (PM), uncertainty remains large or unknown (Larkin et al. 2014).

To improve our capability to predict smoke emissions and to model smoke plume concentrations we need to develop a full understanding of the plume's suite of gas and particulate species and their concentrations both near the ground and aloft. RxCADRE combined smoke concentration observations with measurements of fire behavior and fuel consumption to allow for a full time-lapse view of the shift in biomass emissions as it relates to the fire behavior.

Fire effects

Measuring wildland fire is inherently difficult, especially in ways that are important for understanding the ecological effects of fire. For many years, the technology available for measuring wildland fire intensity was limited to qualitative descriptions, visual estimates, point measurements, or relative indices of intensity (Kennard et al. 2005). This hindered the ability to accurately capture fire in ways that could mechanistically link fire behavior (energy release) with fire effects (energy transfer), especially in a spatial manner. Direct measurements of energy transfer are critical for predicting and understanding both first- and second-order fire effects (Van Wagner 1971, Johnson and Miyanishi 2001, Dickinson and Ryan 2010). Recent advances in technology have made it possible to measure the fire energy environment across time and space using infrared thermography. Long-wave infrared thermography (LWIR) is a well-established measurement technique (Maldague 2001, Melendez et al 2010) and especially useful because the long-wave portion of the infrared spectrum is most sensitive to radiation emitted by surfaces heated by fire such as fuels, plants, woodland creatures, and soils. Furthermore, the system can have high spatial and temporal resolution and does not require sensor contact with the object being measured. LWIR thermography is especially useful for fire effects research because the LWIR radiation emitted by an object represents the collective effect of radiative, convective, and conductive heating impinging on the object of interest. The system used in the research reported here employed a focal plane array designed to detect

LWIR, a band especially useful for smoky environments because part of the bandpass is minimally affected by fine particulates, hot gas emissions, and infrared absorption by gases (Rogalski and Chrzanowski 2002).

Data recorded by LWIR thermography is spatially explicit, and examining spatial dependencies or autocorrelation of the fire radiation environment can be useful in many ways. First, one can decouple spatial trends to better understand the underlying mechanisms that either drive fire behavior (e.g., fuel type and arrangement) or how fire behavior influences subsequent fire effects (Hiers et al. 2009; Loudermilk et al. 2009, 2012) These spatial trends can also be used to evaluate fire spread models (e.g., Berjak and Hearne 2002, Achtemeier et al. 2012) created for similar systems to determine if they capture the appropriate scale of variability measured in the field. A spatio-temporal analysis could be performed using simultaneously recorded wind data (e.g., with anemometers) to isolate direct wind effects from other fire behavior characteristics.

II. Location and Study Description by Discipline

General description and location

The RxCADRE experiment was designed to collect fuels, meteorological, fire behavior, energy, emissions, and fire effects data to evaluate and advance fire models and further our understanding of fire. The project covered 28 sample units within six small replicate grass burn blocks, two large operational grass and shrub fires burn blocks, and eight large operational forested burn blocks. Burn blocks were located in longleaf pine (*Pinus palustrus*) ecosystems of the southeastern United States at Eglin Air Force Base in Florida and at the Joseph W. Jones Ecological Research Center in Georgia (Fig. 2), and were ignited in 2008, 2011, and 2012. Sample units located within the burn blocks ranged in size from 400 m^2 to covering the entire burn block. The small replicate grass fires burned in 2012 were named S3, S4, S5, S7, S8, and S9. The two operational grass and shrub fires burned in 2012 were named L1G and L2G. Eight operational forested units were named: Dubignon East, North Boundary, Turkey Woods, 307B, and 608A (burned in 2008); 608A and 703C (burned in 2011); and L2F (burned in 2012) (Table 1). Although the RxCADRE project had campaigns in 2008, 2011 and 2012, not all the discipline areas collected data for each of the three years. Table 2 presents each discipline and sub-disciplines, lead scientist, and the year data was collected. Study descriptions for each discipline and sub-discipline are presented in the next section.

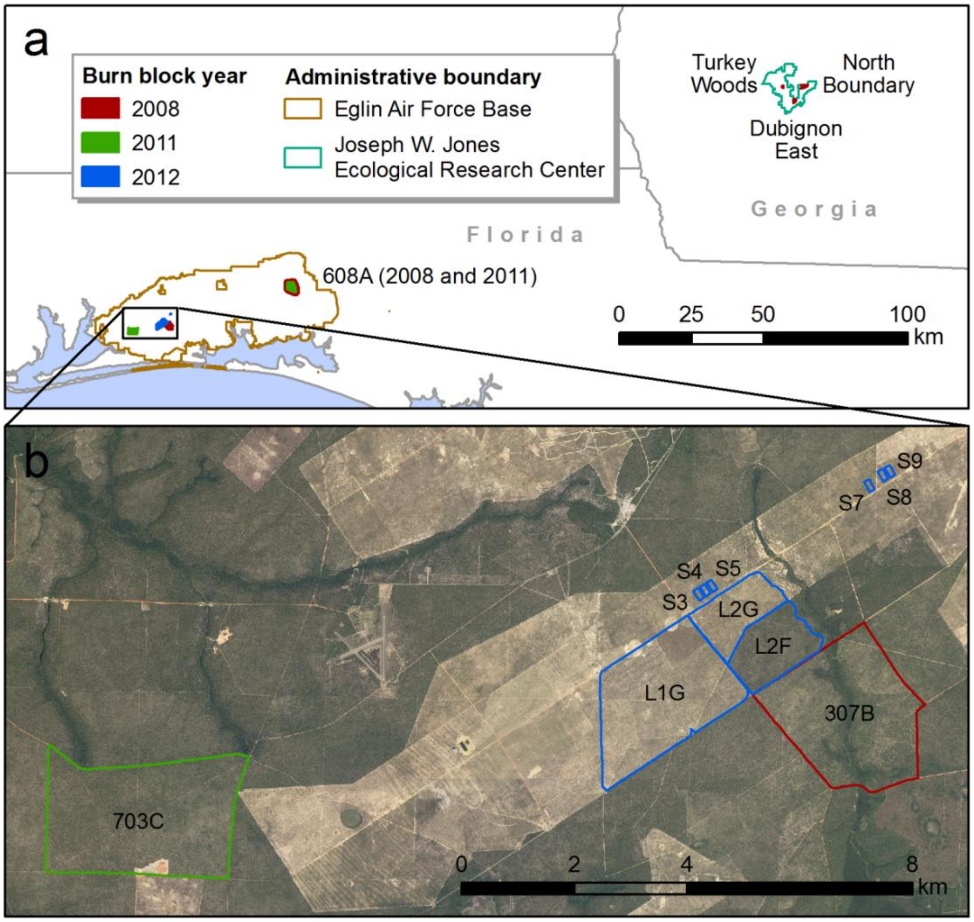

Figure 2. (a) Location of the 16 RxCADRE experimental prescribed fires conducted in 2008, 2011, and 2012. **(b)** Small replicate (*S*) and large operational (*L*) burn blocks established for the 2012 RxCADRE research project were located on the B-70 bombing range of Eglin Air Force Base, Florida. Only large operational burn blocks were established for the RxCADRE research burns in 2008 and 2011.

Table 1. Burn block name, location, number of sample units within each burn block, and year sampled for the RxCADRE campaigns

Burn block	Location	Burn type	Number of sample units	Vegetation type	2008	2011	2012
307B	Eglin AFB[a]	Operational	1	Grass/forb/shrub/woody debris	X		
608A	Eglin AFB	Operational	1	Grass/forb/shrub/woody debris	X		
Dubignon East	JJERC[b]	Operational	1	Grass/forb/shrub/woody debris	X		
North Boundary	JJERC	Operational	1	Grass/forb/shrub/woody debris	X		
Turkey Woods	JJERC	Operational	1	Grass/forb/shrub/woody debris	X		
608A	Eglin AFB	Operational	3	Grass/forb/shrub/woody debris		X	
703C	Eglin AFB	Operational	2	Grass/forb/shrub/woody debris		X	
S3	Eglin AFB	Replicate	1	Grass/forb/shrub			X
S4	Eglin AFB	Replicate	1	Grass/forb/shrub			X
S5	Eglin AFB	Replicate	1	Grass/forb/shrub			X
S7	Eglin AFB	Replicate	1	Grass/forb/shrub			X
S8	Eglin AFB	Replicate	1	Grass/forb/shrub			X
S9	Eglin AFB	Replicate	1	Grass/forb/shrub			X
L1G	Eglin AFB	Operational	4	Grass/forb/shrub			X
L2G	Eglin AFB	Operational	4	Grass/forb/shrub			X
L1F	Eglin AFB	Operational	4	Grass/forb/shrub/woody debris			X

[a] Eglin Air Force Base, Niceville FL
[b] Joseph W. Jones Ecological Research Center at Ichauway, Newton GA

Table 2. Discipline, sub-discipline, lead scientists, and years when the data were collected

Discipline	Sub-discipline	Lead scientist	2008	2011	2012
Fuel	Pre-and postfire	Ottmar	X	X	X
	Ash	Hudak	X	X	X
	Fuel-lidar	Seielstad		X	X
Weather	Ground	Clements			X
Fire behavior	In situ	Butler		X	X
	Aerial	Zajkowski			X
Radiative power and energy	Energy	Hudak		X	X
	Power	Dickinson			X
Emissions	Ground	Potter			X
	Airborne	Urbanski			X
Effects	Thermography	O'Brien			X

Study Description by Discipline

Fuels

Pre-and postfire fuel characteristics

Multi-scale measurements of pre-, active, and postfire fuel and white ash variables were collected on 28 sample units associated with six small replicate (grass, forb and shrub) and ten large operational prescribed fires (two grass/forb/shrub and eight forested) conducted during the RxCADRE research campaigns in 2008, 2011, and 2012. Pre- and postfire surface fuel loadings were characterized in alternating pre- and postfire clip plots and transect lines that were established systematically within burn blocks. Loadings summarized at the plot level were aggregated to estimate absolute consumption (Mg ha^{-1}) and relative consumption (%) for each sample unit (Fig. 3).

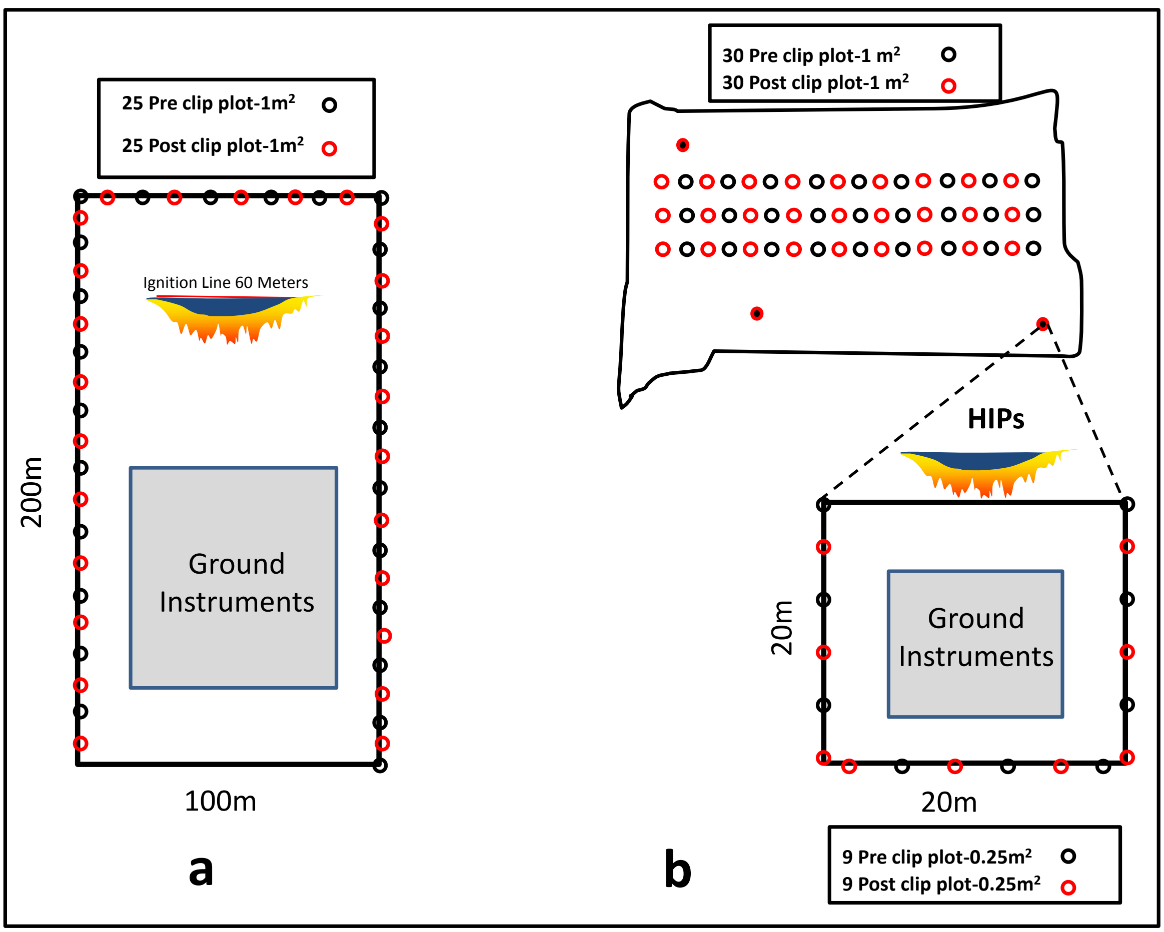

Figure 3. Plot layout for (a) replicate experimental fire sample units, and (b) large operational burn blocks with sample units for the 2012 RxCADRE burns. Only large operational burns with one to three sample units were established in the 2008 and 2011 research burns. Surface cover fractions were estimated at the postfire clip plots.

Ash

Fuel loading and consumption measurements were examined to assess the potential for using white ash cover as a surrogate for prefire surface fuel loading and consumption. Percentage cover of green vegetation, litter, black char, white ash, and mineral soil were estimated ocularly in prefire fuel plots co-located with the postfire fuel plots and aggregated to the same 28 sample units. Spearman correlations were calculated between the non-normal distributions of surface cover fractions (%) and both surface fuel loading and consumption. The hypothesis that the first-order fire effects and direct result of complete combustion, white ash cover, is a significant indicator of fuel consumption was tested.

Airborne laser scanning to characterize fuels

Airborne laser scanning (ALS), or airborne lidar, was collected to characterize prefire fuels in all burn blocks in 2008, 2011, and 2012, with the exception of small replicate blocks S3, S4, and S5 which were burned before airborne lidar collection. Height and density metrics were calculated from the lidar returns within the flame zone, or between 0 and 2 m above ground. These were associated with prefire clip plot fuel measures in a multiple linear regression model to predict total surface fuel loads.[1] The model was then applied to map surface fuels across the 2011 and 2012 burn blocks. A simple canopy cover correction based on the proportion of airborne lidar returns reflected from the overstory canopy (above breast height) was developed and applied to correct the two 2011 forested burn blocks and the L2F forested block in 2012 for canopy occlusion of the lidar signal.

Terrestrial laser scanning and fuels

Terrestrial laser scanning (TLS) was used to collect spatially continuous height measurements of fuelbeds across the plots and burn blocks of the 2012 RxCADRE experiments in Florida (Fig. 4). Fuel beds were scanned obliquely from plot/block edges at a height of 20 m above ground. Plots were scanned at ~8 mm spot-spacing from a single viewing position pre- and postfire while blocks were scanned from six perspectives prefire and four postfire at ~2-cm spot spacing. After processing, fuel height models were developed at one meter spatial resolution in burn blocks and 0.5-m resolution in plots and compared with field measurements of height. Spatial bias was also examined.

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[1] The 2008 metrics were excluded from the model because of poor plot geolocation accuracies.

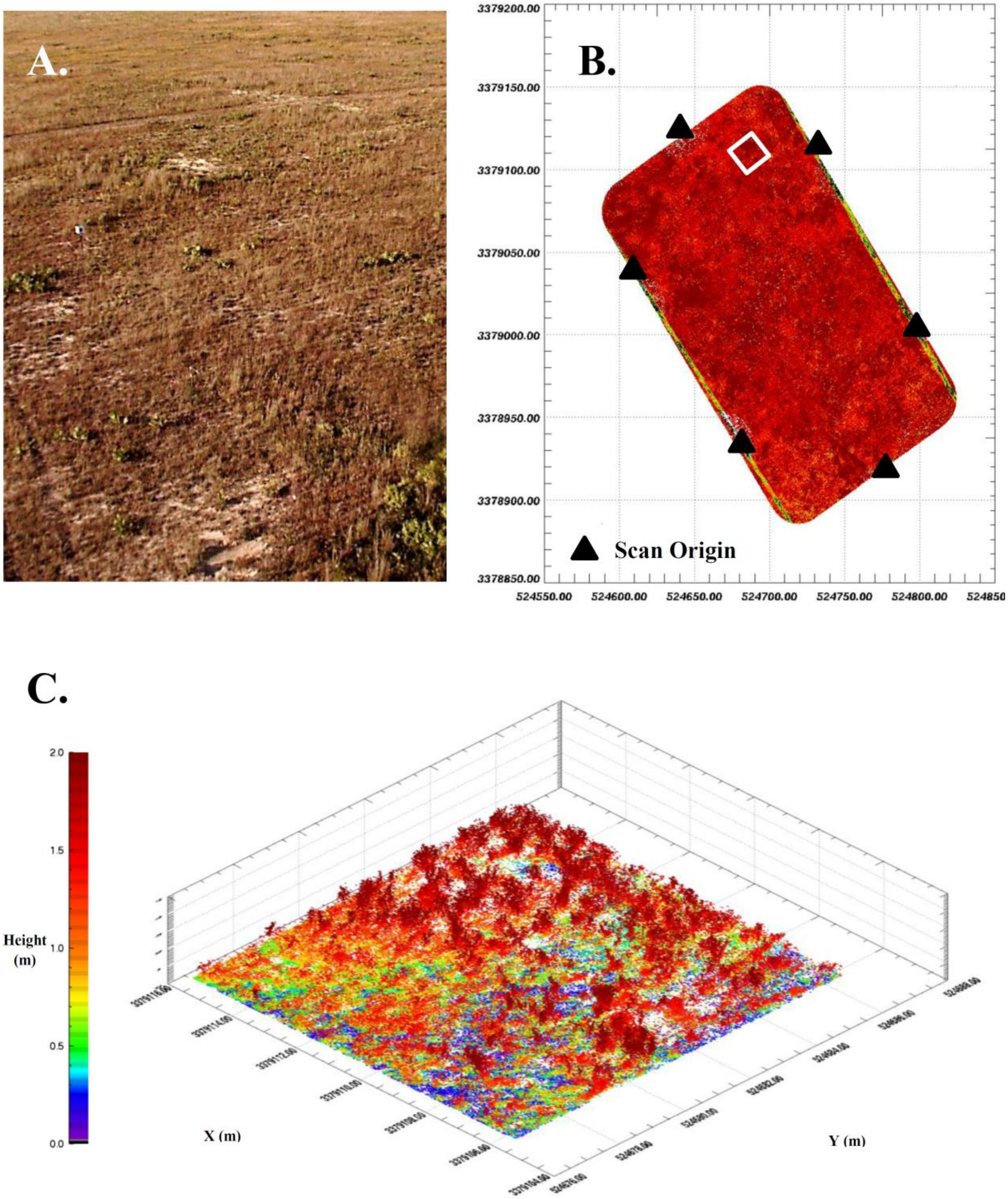

Figure 4. (a) An example of the fuelbed for block S3 from the boom lift, **(b)** TLS data clipped to the block boundary with scan locations, and **(c)** a three-dimensional graph demonstrating height variability for a 10 m x 10 m subset of the terrestrial lidar scanning (TLS) data.

Meteorology

The RxCADRE meteorological measurement campaign consisted of a variety of measurement platforms and instrument types during 2012. The experimental design was aimed at measuring both the ambient meteorological conditions surrounding each burn plot and the in situ fire-atmosphere interactions within the burn plots. The wind field was measured intensively using several instruments and platforms, including a scanning Doppler wind lidar, an array of cup-and-vane anemometers around each burn unit perimeter, an interior tower equipped with two sonic anemometers, a Doppler mini-Sodar wind profiler, and a portable, 30-m meteorological tower placed outside of all the burn units (except during the L1G burn on 3 November 2012, where the tower was placed in the middle of the burn unit). Fig. 5 displays the location of the instrumentation.

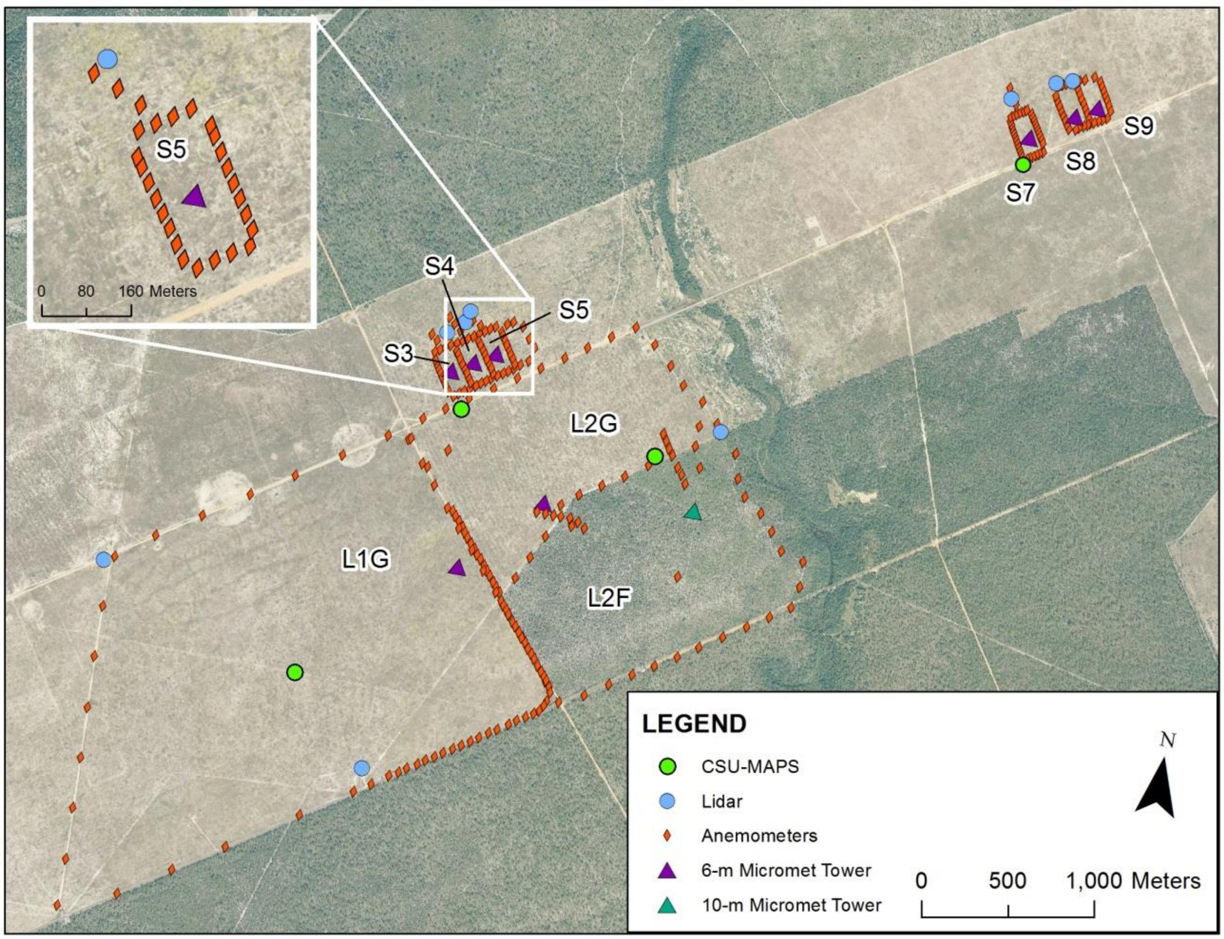

Figure 5. Location of meteorological instruments.

Fire behavior

Fire behavior packages (FBP) and in-fire video recorders were deployed on all burn blocks (Fig. 6). The FBPs were positioned to sense fire from the expected spread direction based on wind direction, terrain slope, and lighting procedures. The cameras were oriented to provide images of the fire as it approached and burned over the respective FBPs; that is, cameras “looked” toward an FBP in an angle perpendicular to expected fire spread. The thermocouples sensed air temperature nominally 1.0 m above ground level. Narrow angle radiometers were included that looked horizontally towards the direction faced by the FBP and sensed energy emitted from a 7° field of view.

Three RPAS were deployed on all burn bocks during the RxCADRE 2012 campaign including the relatively large catapult-launched ScanEagle (representing a long endurance system that could support large incidents), the hand-launched G2R (a hand-launched and belly-landing aircraft with moderate endurance), and the vertical takeoff and recovery Scout system (that must be operated by a crew near the fire line). The RPAS used several sensors based upon the scientific requirements of their mission. Sensors included: LWIR for flame-front description and progression mapping; natural color for characterizing pre- and postfire vegetation; meteorological for measuring air temperature, wind speed, wind direction (in three dimensions) and relative humidity; and particulate sensors for characterizing smoke. Even though the RPAS data have only been used in one study to date, in keeping the RxCADRE goals, RPAS data are archived for wide distribution and use in future studies.

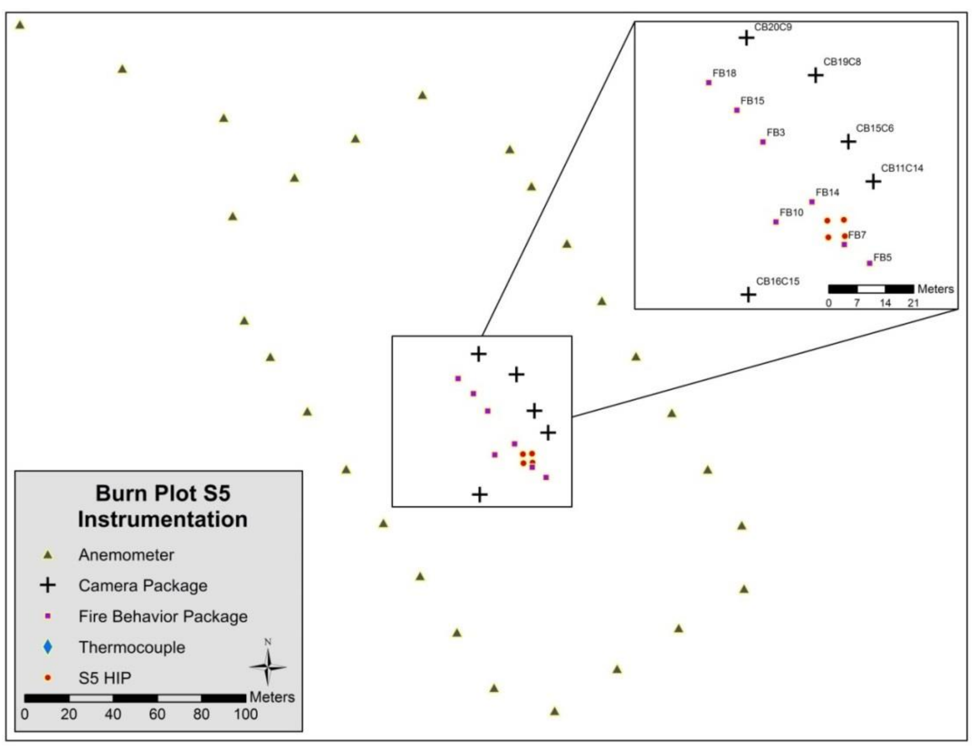

Figure 6. Location of anemometers, fire behavior and camera packages, and thermocouples on burn plot S5.

Radiative power and energy

Ground, airborne, and satellite retrievals of fire radiative power (FRP) over entire fires were completed during the RxCADRE project in 2012 (Fig. 7). This provided measurements for future evaluation of models and a better understanding of the measurement limitations. Here, we report the methods by which FRP for small and large burn blocks was derived.

Figure 7. Ground and airborne platforms used to collect fire radiation measurements for RxCADRE 2012. Clockwise from upper left: aircraft carrying the Wildfire Airborne Sensor Program package, G2R RPAS, Aeryon Scout quadcopter, ScanEagle RPAS, tower-mounted radiometer, boom lift with oblique infrared camera. Not shown are nadir (downward viewing) radiometers and infrared cameras positioned on large tripods (see *Fire Effects*). Satellite platforms used during the study but not shown include bearing—and visible infrared imaging radiometer suite (VIIRS) sensors.

Fire radiative power from RPAS and nadir-viewing radiometers

FRP was calculated as the product of perimeter length (m) estimated from RPAS imagery and frontal radiant intensity (kW m^{-1}) estimated from radiometers. Nadir-viewing, dual-band radiometers (termed radiometers hereafter) were distributed at 10-m intervals from a central meteorological tower. Radiometers were attached to a 0.5-m arm and elevated to 5.5 m on telescoping poles anchored to steel fence posts. Voltages were logged at 5-s intervals from which average fire radiative flux density (FRFD) (W m^{-2}) was calculated. The sensors used in the radiometers were built by Dexter Research. The longwave sensor (detector ST60 DX-0852) has a silica window with a nominal bandpass of 6.5 to 20 µm (spectral transmission described by DC-6186-L2). The midwave sensor (detector ST60 DX-0852) has a calcium fluoride window with nominal bandpass of 3 to 5 µm (spectral transmission described by DC-6100-CaF_2-U8). The field of view of the sensors was 24 ° at 50% response (i.e., full width at ½ maximum response) (FWHM). FRP was calculated from peak FRFD through multiplication by the sensor's FWHM field of view on the ground (m^2). Flame fronts were assumed to be linear within the field of view, and FRP was divided by the diameter of the field of view to estimate average fire radiant intensity in Wm^{-1} in analogy to frontal fire intensity.

Flame-front perimeters were estimated from RPAS LWIR data. Frames encompassing entire blocks were captured by a FLIR Tau 640 camera (nominal 8- to 14-µm bandpass) mounted obliquely on a small RPAS (the G2R) that orbited the block. The frames were orthorectified with reference to infrared "hot" targets and features visible on high resolution aerial orthophotos. The RPAS frames were used to identify flame fronts whose perimeters were manually delineated after image classification. It was found that RPAS images from a similar perspective (collected as the G2R aircraft orbited the fire) were required to obtain consistent perimeters from orthorectified frames as fires spread. Perimeters were somewhat ambiguous when flame fronts were not continuous, that is, when the flame front extinguished in certain areas. In these cases, discontinuous perimeters were added to estimate total perimeter.

Fire radiative power estimated from oblique LWIR data

A LWIR camera elevated on a boom lift (FLIR SC660) with a nominal bandpass of 7.5 to 13 µm was used to measure fire progression and FRFD from an oblique perspective. Thermal images were captured at 1Hz, emissivity was set at 0.98, and temperature range was set to 300 to 1500°C. Further information on FLIR specifications and image rectification and processing are found in Hiers et al. (2009), and Loudermilk et al. (2012). Orthorectified image data were rendered at 1-m^2 scale and these data were integrated spatially to provide whole-fire radiated power (FRP) (MW). A 25-m boom lift, fully extended and located 10 to 25 m outside of each block's boundary, was used to elevate the camera.

Fire radiative power estimated from airborne LWIR data

Longwave infrared imagery was captured by Rochester Institute of Technology's Wildfire Airborne Sensor Program (WASP) sensor during repeated passes over each of the three large burns. Midwave infrared imagery are also available from the WASP system, but saturation and reflected solar radiation limit their use. The WASP system is described in McKeown et al. (2004), and its utility is described in Ononye et al. (2007). The WASP Indigo Phoenix LWIR camera (model IA126 LWIR) was built by Cantronic Systems Incorporated and has quantum-well, cooled detectors. Peak transmission is at 8.7 µm with a nominal bandpass of 8 to 9.2 µm. Flight altitude was determined in part by compromise between the goals of capturing entire blocks in a single mosaic of frames captured on a single pass and the need to fly below any existing cloud deck. Because atmospheric absorption varies with flight altitude and atmospheric conditions, we used the moderate resolution atmospheric transmission code (MODTRAN) to estimate spectral absorption, which was incorporated in the calibration process. An automated process based on Applanix inertial measurement unit data was used to orthorectify image frames. Canopy interception of radiation is a known limitation of both airborne and satellite measurements of fire radiation, but no correction was attempted for the L2F forested block.

FRP estimated from spaceborne sensors

Among the set of active fire imaging sensors (e.g., Schroeder et al. 2013), only the daytime (from midday to early afternoon) overpasses from a moderate resolution imaging spectroradiometer (MODIS) on the EOS/Aqua satellite, a standard in FRP retrieval in the fire science community, and the VIIRS sensor, borne on the S-NPP polar satellite (launched in 2011) provided sufficient opportunity to observe the experimental fires given RxCADRE research priorities and operational constraints. Both satellites follow a similar orbit (Justice et al. 2013, Csiszar et al. 2014) and their timing is convenient for coordination with prescribed fire operations.

MODIS

MODIS fire detection (e.g., Justice et al. 2002) is done using the spectral bands centered at ~4 µm (midwave) and ~11 µm (longwave), although data from several other spectral bands are also used for masking clouds, extremely bright surfaces, glint, and other potential sources of false detection (Giglio et al. 2003). The official MODIS fire data product provides datasets of detected fire pixels at 1 km resolution and their respective FRP values calculated only from the ~4 µm measurements (Kaufman et al. 1998; Justice et al. 2002, 2006; Giglio et al. 2003). MODIS overpasses were coincident with experiments S6, L1G, L2G and L2F on 31 October and 4, 10, and 11 November 2012, respectively (Table 1). The MODIS active fire product (MYD14) retrievals for these overpass events were collected, and the radiance data were corrected for atmospheric absorption using MODTRAN 4v3 (Berk et al. 2003) and atmospheric profiles derived from National Centers for Environmental Prediction 0.5 ° resolution 6-hourly data. An average atmospheric absorption weighted by sensor spectral response was used to correct top of the atmosphere values to give ground-leaving FRP (Table 1).

VIIRS

VIIRS is a multispectral instrument, launched in 2012, that supports Earth weather and climate applications. Full global coverage is completed every 12 hours or less using two distinct sets of spectral channels at 375-m (Schroeder et al. 2014) and 750-m nominal resolution. A unique data aggregation scheme was applied to the sensor's radiometric data to limit pixel area increase along scan, thereby resulting in greater image integrity compared to other wide-area orbital scanning systems (Wolfe et al. 2013). The 750-m dataset includes a dual-gain midwave infrared (MIR) channel with a high saturation temperature of 634 K designed to detect and characterize active fires (Csiszar et al. 2014).

VIIRS coincidently imaged S5, L1G, L2G, and L2F during firing operations (Table 2). Automated active fire detection data were produced for the 375-m and 750-m datasets using the methods described in Schroeder et al. (2014) and Csiszar et al. (2014), respectively. The 375-m active fire product detected all four fires, whereas the 750-m product detected only L2G. Omission errors in the 750-m product were mainly because of the small size of the S5 fire, resulting in weak radiative signal in the primary MIR detection channel, and to scattered opaque clouds over L1G and L2F causing partial fire obscuration with consequent classification of the area as cloud-covered. Because of the low saturation temperature (367 °K) of the 375-m MIR channel driving that active fire algorithm, the larger fires at L1G, L2G, and L2F resulted in saturated pixel radiances (Table 2). Meanwhile no pixel saturation was found in the higher saturation temperature (634 °K) 750-m data.

To overcome limitations imposed by fire omission errors and pixel saturation described above, VIIRS 375- and 750-m coincident data were used interchangeably. Fire-affected pixels omitted by the 750-m product were accounted for using co-located reference pixels detected by the 375-m product. Pixel-based FRP retrievals were derived using the method by Wooster et al. (2004) applied to unsaturated MIR (single-band) radiance data only. Hence, two separate FRP retrievals were produced using the 375- and 750-m data for block S5, whereas single retrievals based on 750-m radiance data were produced for blocks L1G, L2G, and L2F. VIIRS MIR radiance data were corrected for atmospheric attenuation using the MODTRAN code as described above.

Fire radiative energy density and surface fuel consumption

Fire radiative energy (FRE) was mapped on a per area basis (i.e., fire radiative energy density, or FRED) to allow straightforward comparison across multiple measurement scales. Per area measures of FRP (i.e., fire radiative power flux density, or FRFD) observed from the calibrated airborne WASP images were coregistered in an image cube and integrate over time to calculate total FRED observed. The objective was to demonstrate that FRED was linearly related to surface fuel consumption, regardless of measurement scale. A straightforward manner to demonstrate a 1:1 relationship was to convert the FRED measures to estimates of consumption, based on the published combustion equation of Reid and Robertson (2012) for longleaf pine fuels. This was confirmed for four types of heat sensing instruments deployed on the ground, but remained a challenge to demonstrate from the calibrated airborne WASP measures of FRED.

The gaps between WASP flight overpasses caused this observed FRED to be undersampled, so a simple correction was developed based on the proportion of time the burn block was not being imaged. The active fire within the burn block was usually undersampled spatially as well, due to the extent of the WASP frames typically being smaller than the burn block; a simple correction was developed based on the proportion of the burn block not imaged. A simple canopy cover correction based on the proportion of airborne lidar returns reflected from the overstory canopy (above breast height) was developed and applied to correct the two 2011 forested burn blocks and the L2F forested block in 2012 for canopy occlusion of FRED.

Emissions—ground and aerial

Smoke measurements were taken both on the ground and aloft. On the ground, electronic beta attenuation monitors (EBAMs) were placed along the downwind edge, and the downwind half of the flanks, on each large burn unit. On burn L2F, three EBAMs were placed along a short longitudinal transect downwind of the fire. Five digital SLR cameras and five digital video cameras were situated around the fire perimeter at various distances to capture time lapse and video imagery. This element of the project was an attempt to evaluate the use of photography for tracking smoke movements and velocities.

A flight-ready cavity ring-down spectroscopy (CRDS) trace-gas analyser (Picarro, Inc., CA, USA, model G2401-m) was used to take continuous measurements of CO_2, CO, and CH_4 with a data acquisition rate of 2 s. Urbanski (2013) provides details on the CRDS instrument and measurement technique. The measurement platform was a Cessna 337. The aircraft smoke sampling effort acquired measurements of fresh emissions, the smoke vertical profile, plume height, and smoke dispersion. Measurements of fresh emissions and smoke dispersion were obtained with horizontal flight transects (Fig. 8) in perpendicular and zigzag patterns at distances of up to 25 km downwind from the source. Measurements of the smoke concentration vertical profile and the maximum height of the smoke layer were obtained with corkscrew and parking garage flight profiles. Corkscrew profiles, centered on the plume downwind from the burn unit, were taken from above the smoke plume/smoke layer to 150 m above ground level. Parking garage vertical profiles involved short (~10 km) horizontal transects, roughly perpendicular to the long-axis of the smoke plume, taken at multiple elevations. The parking garage vertical profiles also provide measurements of spatial distribution of smoke emissions and dispersion. Emissions were determined from level-altitude flight segments that began in smoke-free background air, passed through the smoke plume, and then re-entered the background air. A section of each flight segment prior to plume entry provided the background measurements that were used to calculate the excess mixing ratios.

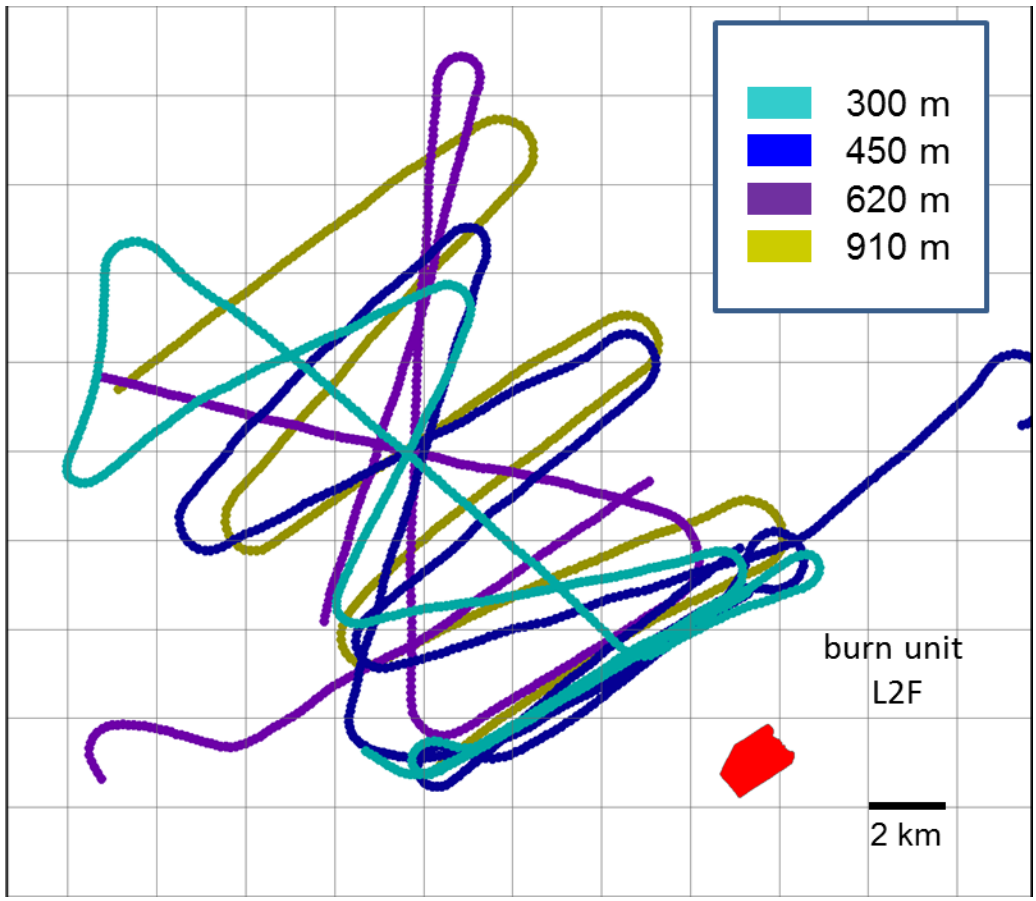

Figure 8. Airplane horizontal flight profile for fire L2F. The thick color lines denote the flight path at different elevations in meters above sea level (ASL) (m): aqua (300 m ASL), blue (450 m ASL), purple (620 m ASL), olive (910 m ASL). The L2F burn unit is shown as a red polygon and a 2 km x 2 km background grid is provided for reference.

Fire effects

Two measurement strategies were employed to capture thermal data at fine (1 to 4 cm^2) and moderate (1 m^2) resolutions. Fine-scale measurements were captured using an 8.2-m tall tripod (Fig. 7) designed to provide a nadir perspective, and the moderate-scale resolution data were collected at an oblique angle from a 25.9-m boom lift (Fig. 7). Nadir views were positioned over presurveyed 4 x 4 m super-highly instrumented plots (SHIPs) located randomly in each burn unit within each 20 m x 20 m highly instrumented plot (HIP). The SHIPs had 100-cm^2 square steel plates placed at 1-m intervals around the plot perimeter (Fig. 9). The low emissivity (ε) of the steel made them easily detectable in the thermal image and useful for geo-referencing and cropping the plots. The boom lift was located 10 to 25 m from the control lines demarcating the small units and positioned at the center of and perpendicular to the ignition line upwind of the units in all cases except S9. Locating the boom lift upwind lessened the likelihood of unburned fuels obscuring the LWIR signal from the fire. For both the nadir and oblique viewing LWIR cameras, an image of the ambient temperature range (0–300 °C) was collected just before ignition.

Figure 9. (a) Tripod system and **(b)** boom lift used to collected nadir and oblique Long-wave infrared (LWIR) thermographic measurements, respectively, of surface wildland fires.

The tripod system consisted of an equilateral triangular aluminum plate with 1-m sides positioned 8.2 m above the ground by three 3.175-cm diameter American National Standards Institute (ANSI) schedule 40 pipe legs. The legs consisted of four sections (the top three aluminum, the lowest steel) connected by ferrules locked in place with D-rings. They were attached to each apex of the triangular plate by an axle, allowing the legs to swivel in two dimensions. Steel was used for the lowest section because of its high melting point and high density which increased tripod stability. The LWIR camera was mounted inside a metal ammunition box with ports cut for optics and cabling that was raised to the bottom of the triangular plate via a 9.5-mm braided steel cable and winch. Cabling, if present, was armored by 2.5-cm diameter flexible aluminum conduit. The LWIR optics were positioned 7.7 m above the center of the small plots. For the nadir measurements, we used three thermal imaging systems from FLIR Inc.: the SC660, S60 and T640. Oblique imagery was collected with the SC660. The height of the tripod system provided a 4.8 m x 6.4 m field of view for the SC660 and S60, and 2.5 m x 3.3 m field of view for the T640. The field of view of the oblique imagery covered most of the area of the small burn blocks and captured the entire fire perimeter from ignition until the fire passed the central instrument cluster and/or reached the downwind control line. The SC660 and T640 focal-plane arrays have a resolution of 640 x 480 pixels and the S60 has a resolution of 320 x 240 pixels. The SC660 and T640 have a sensitivity of 0.03 °C whereas the S60 has a sensitivity of 0.06 °C. All systems have a spatial resolution of 1.3 mRad and a thermal accuracy of ± 2%. Data were captured at 1 Hz with the SC660 and T640, and 0.25 Hz for the S60. Emissivity was set at 0.98 and the air temperature and relative humidity were noted for post-processing. The temperature range for all cameras during the fires was set to between 300 and 1500°C for collecting active fire LWIR data. High-definition digital visual imagery was collected before and during the fire from video cameras located adjacent to the LWIR cameras.

Image processing

The FLIR systems gave radiometric temperatures in °C as raw output. For all LWIR imagery, the native file format was converted to an ASCII array of temperatures in °K with rows and columns representing pixel positions. Twelve ground control points for each small burn block were identified using surveyed positions of hot targets, instruments, and ignition points. LWIR images of the initial ignition point and ends of ignition lines, which were surveyed, provided three ground control points. Each image was rectified using a third-order polynomial (using the 12 control points), bilinear resampling, and the EPSG projection 26916 (NAD 83/UTM zone 16N) with an output resolution of 1 m x 1 m. Once rectified, each image was converted back to radiometric temperature values by back-calculating using the previous equations, and estimates of fire radiative power (FRP) by pixel were calculated using the Stefan-Boltzmann Law for a grey body emitter. Fire pixel values were summed across units at each time step to give whole fire total fire radiative energy (FRE).

Data management

The RxCADRE project is composed of a multidisciplinary and geographically distributed team of scientists. Organization is such that each discipline leader has a fair degree of autonomy in experimental design, instrument selection and the production of data products. Teams generate widely-varied data products: Excel spreadsheets, meteorological files, infrared imagery, still photographs and video, and lidar are some examples. The primary challenges envisioned at the beginning were:

1. Provide a central project-sponsored facility to collect all project-sponsored data, including data from previous campaigns.

2. Facilitate the transfer of project-sponsored data to the Forest Service Research Data Archive.

3. Support the distributed team.

Storage facility requirements

A centralized data storage facility was designed and constructed that was large enough to accommodate all the data from the 2012, 2011, and 2008 RxCADRE campaigns. The storage had a measure of tolerance for disk failures. It also had a wide bandwidth internet connection, so that participants with correspondingly high bandwidth connections at their home institutions could transfer their large datasets in a timely manner.

The project purchased data storage disks. These disks were attached to a "repurposed" computer at the U.S. Forest Service Research, Missoula Fire Science Laboratory, and organized as a 17TB RAID 5 array to provide a measure of tolerance for disk drive failure. This repurposed computer was connected to the lab's proof-of-concept network enclave to provide access to the Internet2 high-bandwidth research and education network.

Users were provided direct access to the storage server through the secure file transfer protocol (SFTP). Forest Service computers have a graphical client for this protocol installed by default, and did not require the installation of any new software. Clients for other platforms (Linux, Mac, etc.) are ubiquitous. Project-sponsored Web applications which facilitated the transfer of data to the archive also made use of the storage.

Facilitation of data transfer to the archive

Helping the team submit their data to the archive primarily involved the construction of metadata acceptable to the archive. Early discussions with the archivists led us to select the International Organization for Standardization (ISO) metadata style for use on the project. The desire for high quality metadata required that the scientists involved with the production of the datasets also create the descriptive metadata: no third party was to be interjected between the archivists and the scientists. A facilitation solution was required to make metadata production as painless as possible for casual users. We also required that the facilitation solution be ready "out of the box", needing no software development.

Web-based metadata editors were preferred, as this did not require the installation of software on each team member's computer, and therefore could not conflict with the various information technology regulations of the participating organizations.

An additional computer from the Missoula Fire Science Lab's inventory was repurposed and dedicated to running the metadata editor web application. The web application selected was Geonetwork Opensource (Geonetwork 2014) because it seemed a mature solution for the browser-based editing of metadata, and provided some support for attaching the dataset to the metadata entry.

Supporting the RxCADRE team

All support was provided virtually with the exception of interactions at scientific conferences where most of participants were present. There was no provision for individualized onsite support for locations remote from the data manager's duty station.

Support was provided primarily by email, phone conversations, web meetings, and screen sharing. The team member responsible for motivating discipline leads tested the software early, and composed a detailed "HOWTO" document for entering metadata. This document was the reference used by all other participants. The data manager focused on addressing specific technical issues experienced by the team and updated the "HOWTO" document based on lessons learned.

As the time of the campaign approached, the team speculated that it would be useful to have a data storage resource available during the collection. They expected to upload the day's data to a central location so that it could be reviewed by the entire team for completeness and correctness. In this manner, the next day's collection activities could be modified to correct any perceived deficiencies in protocol or instrumentation.

A third computer from the Missoula Fire Science Laboratory's inventory was repurposed for this task. The requirements for this function were to support uploading data, discussing the uploaded data, annotating the data in an informal manner, and ensuring that related data were associated. Due to its high degree of configurability and wide array of plugin modules, the software chosen was the Drupal content management system. The system was configured with a general purpose scientific campaign schema and became known as the "informal repository".

III. Key Findings by Discipline

Fuels

Pre- and postfire fuel characteristics

Fuel loading averaged 5.0 Mg ha^{-1} and ranged from 1.7 Mg ha^{-1} on a sparsely vegetated non-forest unit to 11.5 Mg ha^{-1} on a managed longleaf pine forest unit; fuel consumption averaged 3.2 Mg ha^{-1} and ranged from 1.1 Mg ha^{-1} to 8.5 Mg ha^{-1}. Relative consumption was generally lowest on forest units and highest on non-forest units, ranging from 30 to 93% (Fig. 10). The pre- and postfire fuel loading and consumption observed in the RxCADRE fell within the range found in the literature and can be used for evaluation or modification of current fuel consumption and other fire models.

Postfire ash and other ground cover material

There were highly significant correlations between many of the fuel characteristic variables measured, with postfire white ash cover (ranging from 1 to 28%) and exposed mineral soil cover (ranging from 4 to 81%) producing the highest correlations with pre- and postfire surface fuel loadings and consumption. White ash cover, the first-order fire effect hypothesized as the best direct indicator of consumption, explained slightly more than half of the variance in both prefire fuel loading and consumption.

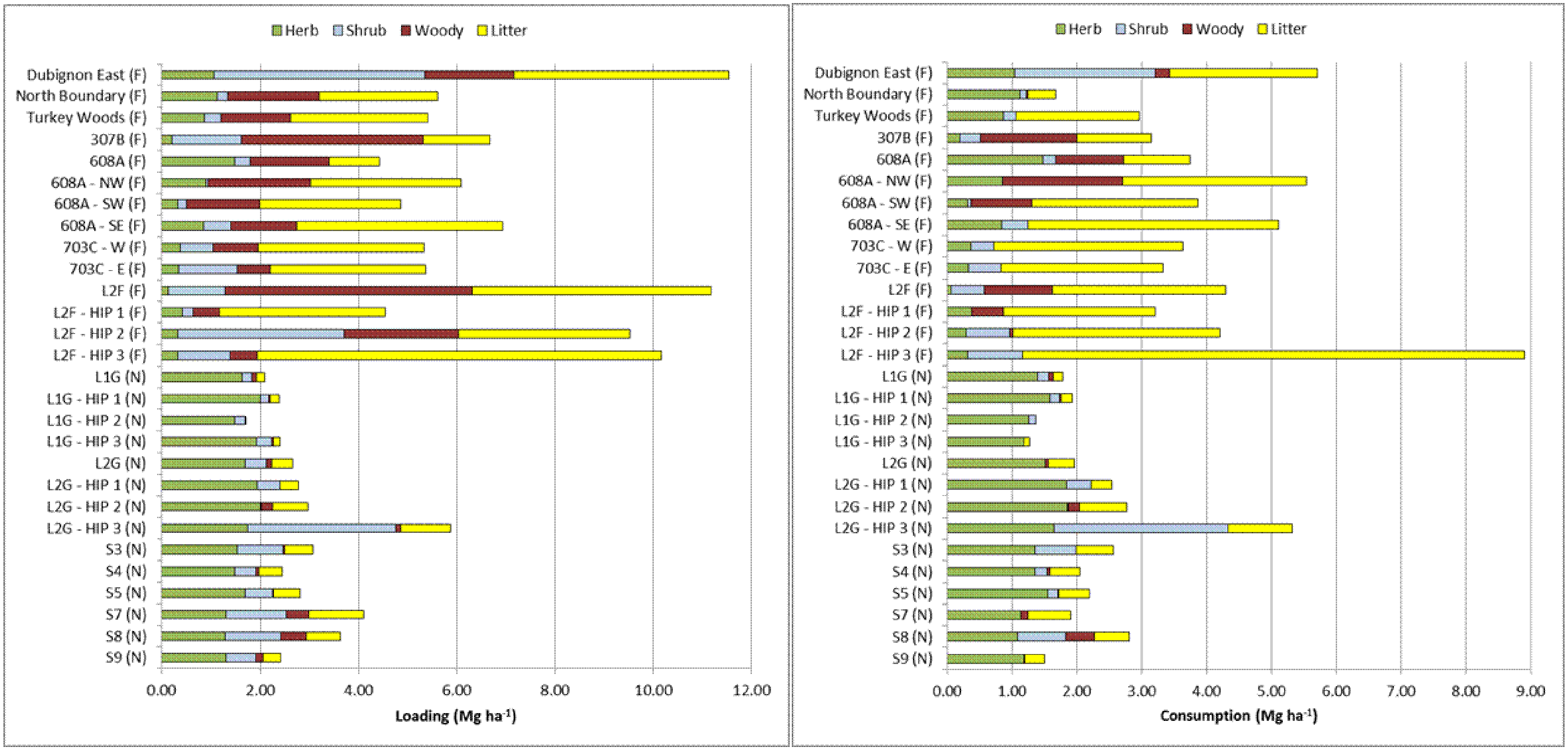

Figure 10. Fuel loading and fuel consumption by fuelbed strata for RxCADRE burn blocks, 2008, 2011, and 2012.

Terrestrial laser scanning and fuels

The resultant fuel height data corresponded closely with field measurements of height and exhibited low spatial bias. Average horizontal and vertical error associated with scan alignment was 12 mm and 9 mm, respectively. Maximum heights of field-collected and TLS-derived data correspond reasonably well ($r^2 = 0.70$, adjusted $r^2 = 0.70$, $p<0.0001$ (Fig. 11). Laser maximum heights are biased upward by 9 cm because of contamination of field plot point clouds due to both ghosting from the reflective corner posts, and subtle misalignment of plot boundaries due to uncertainty of the corner point used to anchor each 1-m^2 field plot polygon. Weak relationships were observed between TLS mean height and field-estimated center of mass height, yet it is not evident that relationships should be expected given how field estimation was executed. No consistent spatial bias was observed for maximum or mean heights, as characterized by trends in means from center of burn units to edges. Overall, the TLS measurements indicate considerably more height variability across the burn units than the field measurements suggest.

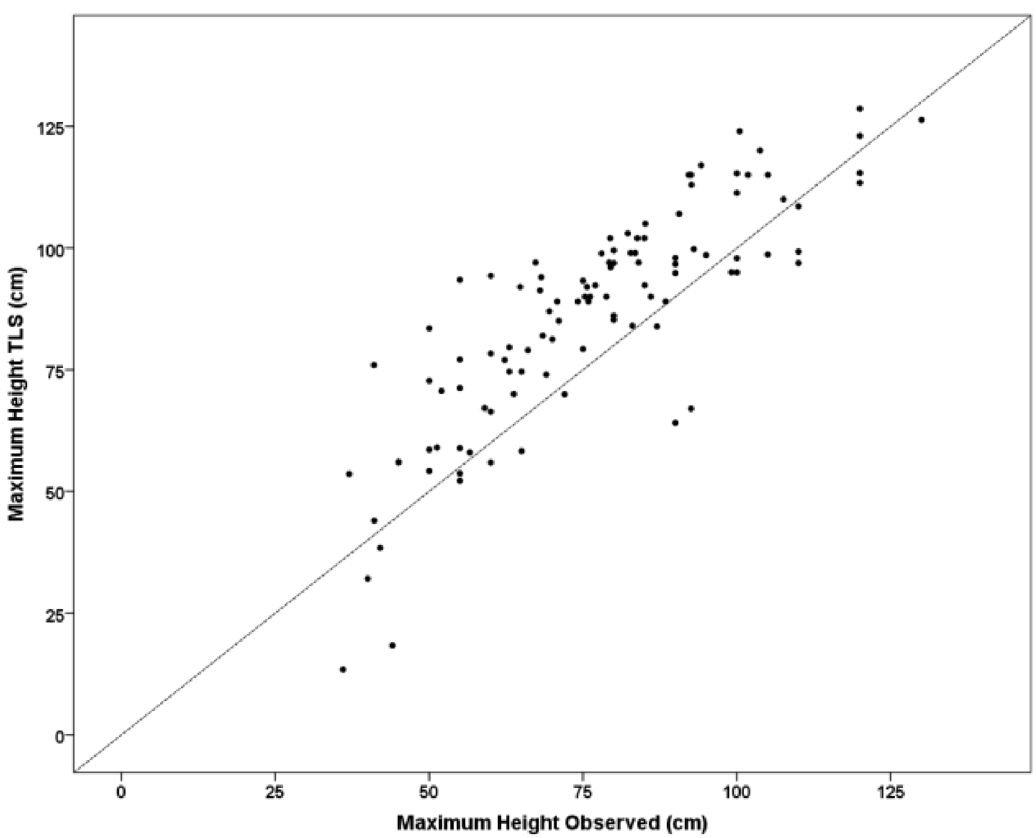

Figure 11. Scatter plot of observed and TLS-based maximum height for clip plots in the S-blocks demonstrating the overestimation of height from the terrestrial lidar scanning (TLS) estimate.

The validity of other TLS height metrics, such as mean and standard deviation, is unknown because of the absence of similar field measurements, although each of the TLS metrics appears spatially consistent across the blocks. The inability to match laser height distributions with similar field measurements is a chronic problem in lidar remote sensing. Direct reconciliation of TLS height measurements with field measured heights other than the maximum height will likely be unsuccessful. Therefore, developing models to translate lidar height metrics to specific fuels metrics is needed. A useful target starting point for modeling is biomass because field plot measurements of biomass are unequivocal. Initial investigation with scan data from the more richly-sampled HIPs showed that the surface area of meshed point clouds correlated well with prefire fuel mass, although the approach did not work well in the S-blocks. In the latter areas, reduced data density produced mesh volumes with artificially inflated surface areas due to excessively large triangulated facets. The application of convex hulls and mesh surface areas to fuel load estimation is the subject of ongoing research.

Airborne laser scanning to characterize surface fuels

Lidar metrics were calculated from lidar points collected within a 3-m radius of 354 prefire clip plots, as well as within 5-m x 5-m grid cells, scanned across the 2011 and 2012 burn blocks just before burning. A best subsets multiple linear regression model predicting fuel consumption from nine metrics calculated from the plot-level airborne lidar returns between 0 and 2 m height above ground (approximating the flame zone) explained 45% of variance and was highly significant ($p < 0.0001$). The model was then applied to the gridded metrics to produce a 5-m resolution surface fuels map across the 2011 and 2012 burn blocks (Fig. 12).

Canopy cover correction applied within the forested portions of the lidar surveys (Fig. 12) produced a strong linear relationship between predicted and observed fuel loads compared across all the 2011 and 2012 burn blocks surveyed prefire with airborne lidar and sampled by traditional destructive clip plots on the ground, respectively (Fig. 13).

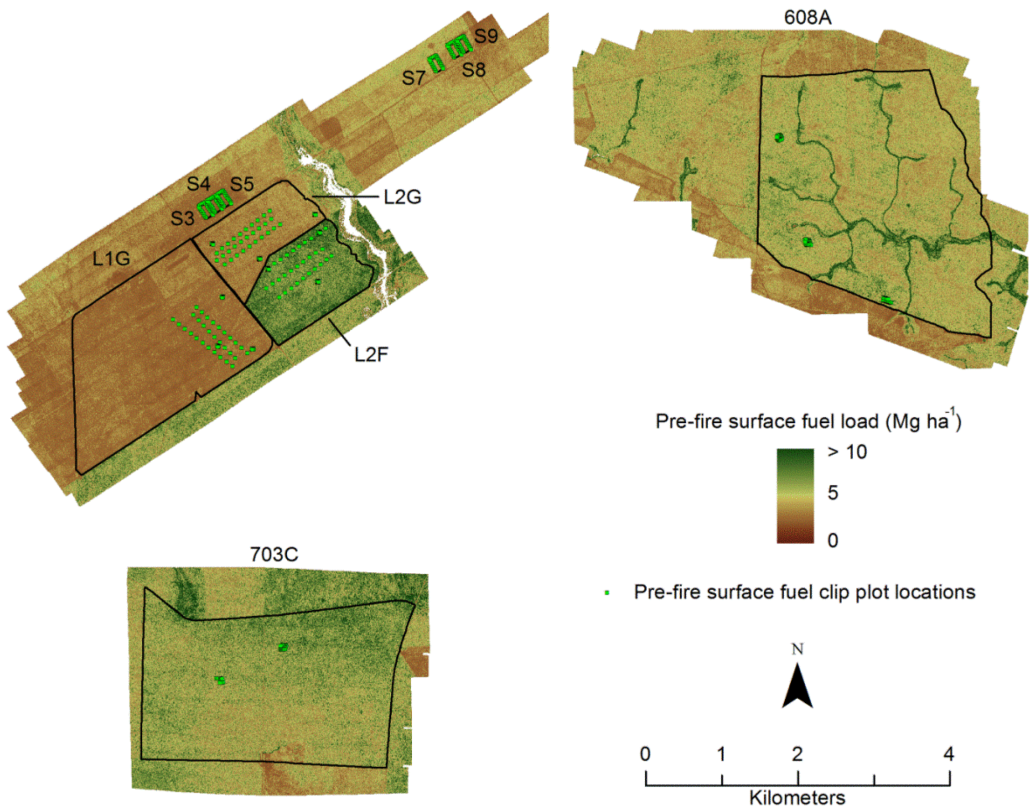

Figure 12. Prefire surface fuels predicted across the extent of the 2011 and 2012 lidar collections. Correction for overstory canopy occlusion in the forested areas has been applied.

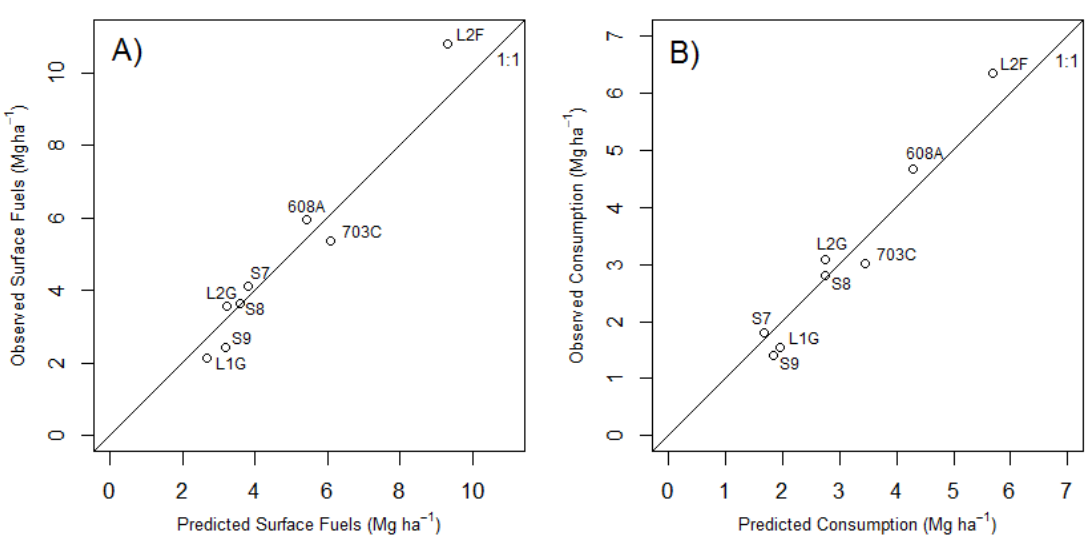

Figure 13. Burn block-level comparisons between predicted and observed (a) surface fuels and (b) consumption. Correction for overstory canopy occlusion in the forested blocks has been applied to predictions in both graphs.

Meteorology

The RxCADRE campaign represents a major effort in the simultaneous monitoring of fire weather and micrometeorology, with fine-scale fuels and fire behavior sampling during multiple low-intensity prescribed fire experiments. The experimental design was aimed at exploiting a high-spatial resolution network of instrumentation to measure the small-scale meteorology within and around each burn block. Fire weather conditions were favorable for conducting each experiment with favorable ambient wind speed and direction, temperature and humidity, and dispersion characteristics.

The experimental array consisted of a suite of cup-and-vane anemometers that lined each burn block perimeter, and an in situ micrometeorological tower that measured fire-induced circulations, sensible heat flux, and turbulence statistics associated with the fire front. Additionally, vertical wind profiles were obtained by a Doppler sonic detection and ranging instrument (SoDAR) placed upwind of each burn block, and by a scanning Doppler lidar, which also measured horizontal winds spatially across each burn block and provided measurements of plume height. Upper-air radiosonde soundings just before ignition and after burning was complete were made for each burn. The CSU-MAPS mobile 32-m meteorological tower was deployed during each experiment to measure profiles of wind speed and direction, temperature and relative humidity, and turbulence statistics.

Preliminary results show that the meteorological measurement campaign during RxCADRE was successful in capturing both fire weather conditions that influenced the experiments and local fire-atmosphere interactions at the fire front. The Doppler lidar provided a high-resolution and large areal coverage of radial velocities across each burn block. Fire-induced circulations were observed to occur during the L2G burn where strip head fires created a merged plume. A region of decreased radial velocities and reversed flow was observed to occur downwind of the plume and was most likely associated with the development of a convergence zone forming in response to instabilities associated with the fire front. The convergence zone was not observed during the S5 burn block most likely due to the smaller size of the fire line and overall lower-intensity of the fire.

Turbulence sensible heat fluxes measured during the fire front passage varied between 5 and 35 kw m^{-2} and compare well with measurements made by the passive heat flux radiometers, ~ 20 kW m^{-2}. Turbulent kinetic energy ranged from ~1 $m^2 s^{-2}$ for ambient conditions and up to 5 $m^2 s^{-2}$ during the fire. These measured values indicate that the S5 and L2G fires were very low in intensity as compared to other grass fires and or forest fires.

Fire behavior

Observations and metrics of flame size, fire spread rate and fire intensity suggest low intensity fire for both burns. Even though units were selected for the uniformity of vegetation type, loading and distribution, there remained significant spatial variability in these values. The variability was indicated in the observations of fire spread and intensity. For example, in L2G HIP1 head fire was indicated for the four sensors nearest the ignition line, but flanking fire for the remaining three sensors. Observations in L2G HIP2 suggest lower intensity fire at the FBP closest to the ignition line, but generally head fire at all other sensors, while L2G HIP3 seems to have burned with lower intensity and more sporadic fire behavior than the other two HIPs in the unit. Flame geometry and rate of spread varied significantly across sensor locations indicating the importance of using multiple sensors to capture the range of variability.

The RxCADRE 2012 campaign successfully demonstrated the use of RPAS as an operations-support tool. The RPAS flew over 50 sorties and provided real-time situational awareness to incident staff without major mishap. The Scout showed the most promise for tactical deployments from remote locations near incidents, but each RPAS platform met objectives for the research and operations purposes for which it was deployed.

Radiative power and energy

It was demonstrated that obtaining FRP from coincident radiometer, oblique infrared, airborne infrared (both from piloted and remotely-piloted aircraft), and satellite sensor measurements is feasible during experimental prescribed fire operations. For example, Table 3 shows the close temporal coincidence between measurements of fire radiated power from two satellites and one aircraft. However, comparisons highlight measurement bias and uncertainty and suggest that we as yet have no “gold standard” fire radiated power measurement (Fig. 14). We found that small RPAS have some utility for characterizing flame front development (Fig. 15) but their use will remain severely limited without small, lightweight, and quantitative infrared sensors and better 3D position data for image georectification. Improving confidence in the use of infrared data to estimate FRP requires a better fundamental understanding fire spectral radiation and its incorporation into measurement processes. The wide array of measurements conducted during RxCADRE 2012 provides opportunities for synthesis that have not been possible heretofore.

Calibrated fire radiative power flux density (FRFD) image time series generated from the WASP imagery were integrated over time to estimate fire radiative energy density (FRED) observed in the 2011 and 2012 large burn blocks over the duration of the burns. These images show apparent firelines which are an artifact of the WASP imagery undersampling the fire progression in both time and space (Fig. 16). In other words, the blue areas in fig. 16 represent not the absence of fuels, but the absence of FRFD observations.

Fire radiative energy was shown to be linearly related to fuel consumption in small scale experiments and the relationship was shown to approach linearity at the landscape level of prescribed fires after simple corrections were applied to compensate for temporal and spatial undersampling by the WASP sensor, as well as canopy occlusion in the case of the forested burn blocks in 2011 and 2012 (Fig. 17).

Table 3. Fire radiative power (FRP) estimated from airborne long-wave infrared (LWIR) thermography data from the wildfire airborne sensor program (WASP) system and near-coincident (a) moderate-resolution imaging spectroradiometer (MODIS) data and (b) VIIRS data. The timing of each measurement is provided along with differences in timing and FRP between airborne and spaceborne sensors. The MODIS FRP value is the average of FRP estimated from pixel and cluster methods. An estimate of cloud cover from WASP imagery is available for L1G satellite overpasses. The piloted aircraft was lower than the cloud deck during L2F so no estimate of cloud cover was made.

a. MODIS

	FRP (MW)			Cloud	Time (UTC)		
Fire	WASP	MODIS	Diff		WASP	MODIS	Diff (s)
L1G	148	111	37	Yes (5%)	19:19:47	19:18:58	49
L2G	111	167	-55	No	18:42:26	18:42:01	25
L2F	119	199	-80	No	19:25:56	19:25:05	51
		Mean (SD)	-33 (62)				

b. VIIRS

	FRP (MW)			**Cloud**	**Time (UTC)**		
Fire	**WASP**	**VIIRS**	**Diff**		**WASP**	**VIIRS**	**Diff (s)**
L1G	414	158	256	Yes (2%)	18:59:24	18:59:54	30
L2G	152	151	1	No	18:49:08	18:47:22	106
L2F	487	237	250	Yes	18:29:47	18:28:34	73
		Mean (SD)	169 (146)				

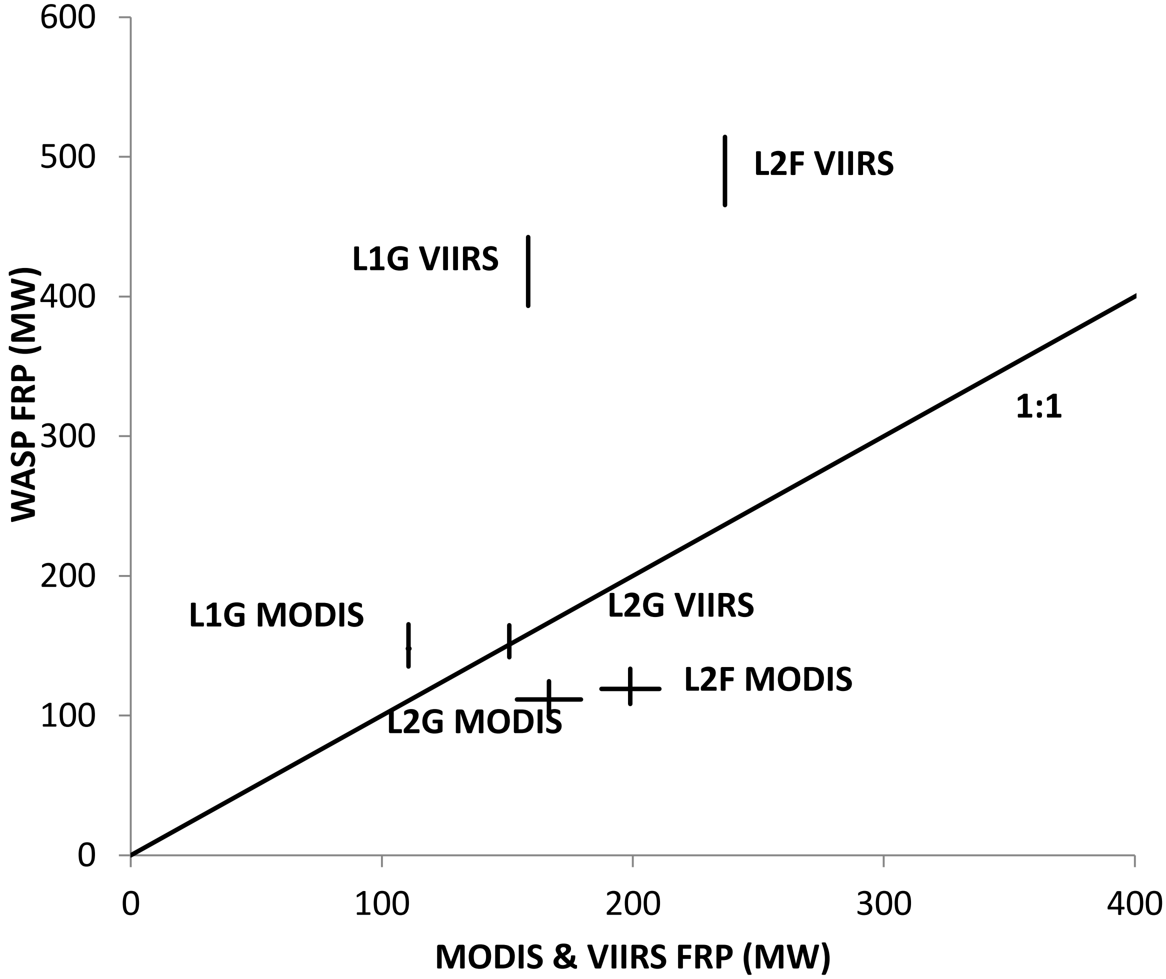

Figure 14. Comparisons of MODIS and VIIRS (satellite) estimates of fire radiative power with the estimate from WASP LWIR data that is closest to it in timing. The 1:1 reference line is provided. The range in MODIS measurements from two methods (where applicable) is shown along the x-axis. The 95% confidence interval in WASP measurements resulting from variation in estimates of background FRFD is shown on the y-axis. All measurements corrected for atmospheric absorption.

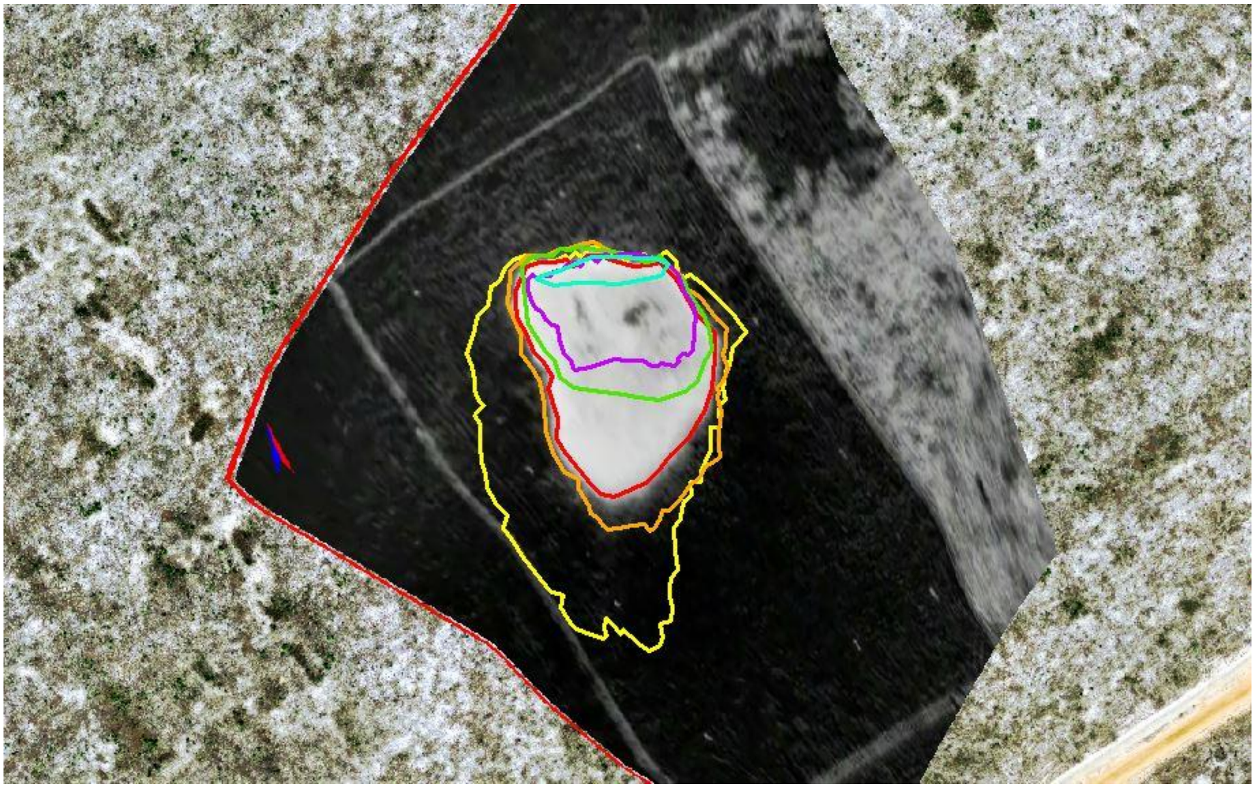

Figure 15. RPAS LWIR image from the FLIR Tau 640x480 camera at 18:15:40 UTC for fire in burn block S5 overlain with successive perimeters and underlain by a high-resolution orthophoto. Surveyed hot targets are visible in the infrared image with white being relatively hot and black being cool. Note evidence of prior burnout along the eastern perimeter. The G2R captured images used to extract perimeters from a southerly perspective at 600 ft AGL. Shown are successive perimeters drawn from infrared images at 18:10:28 (teal), 18:13:05 (purple), 18:13:30 (green), 18:15:40 (red), 18:17:59 (orange), and 18:22:49 (yellow).

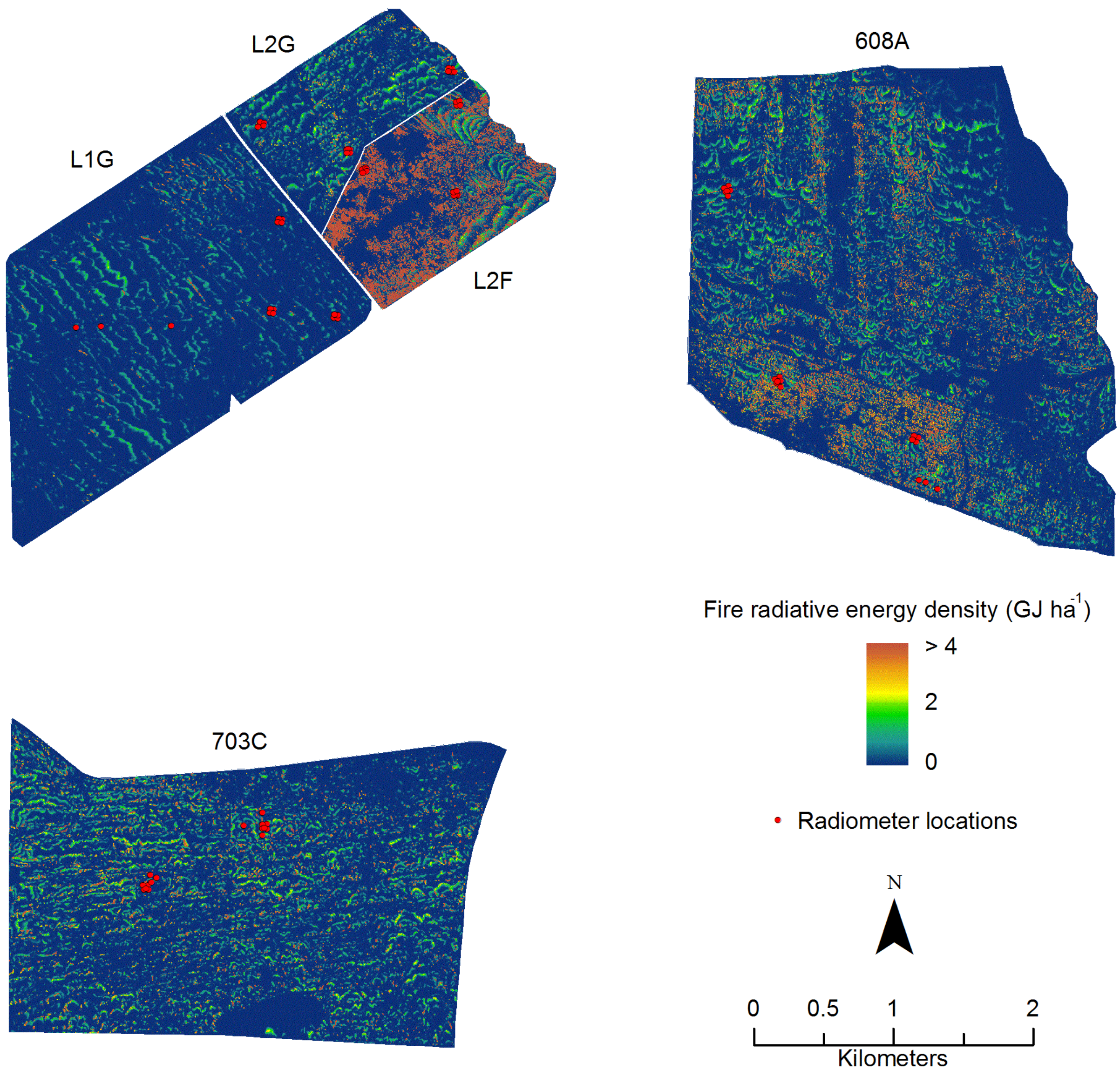

Figure 16. FRED estimated from WASP LWIR-derived FRFD image time series collected across the extent of the 2011 and 2012 large burn blocks. Correction for overstory canopy occlusion in the forested blocks has been applied.

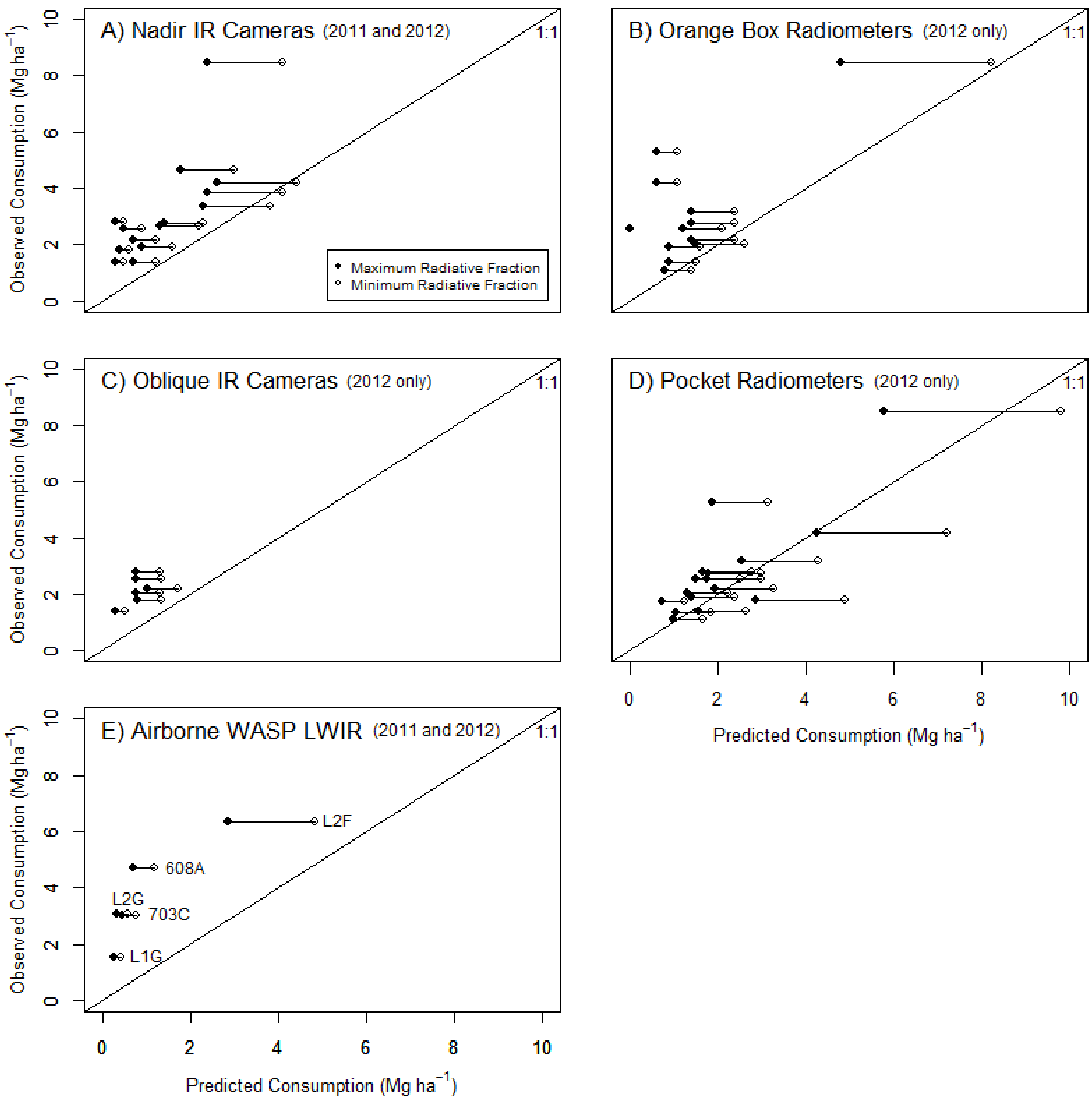

Figure 17. Validation of fuel consumption predicted following Reid and Robertson (2012) with FRED integrated from LWIR measures collected using five different sensor types: (**A**) tripod-mounted, nadir-viewing IR cameras (n = 14); (**B**) orange box radiometers (n = 12**); (C**) boom-mounted, oblique-viewing IR cameras (n = 6); (**D**) pocket radiometers (n = 60, aggregated to n = 16 sample units); and (**E**) airborne WASP LWIR imagery (n = 5), with all bias corrections applied. Horizontal line segments show expected ranges in predicted consumption based on estimated maximum or minimum radiative fraction (Kremens et al. 2012), indicated respectively at the lower and upper ends of each segment. Observed consumption is derived from clip plot biomass samples.

Emissions

Electronic beta attenuation monitor (EBAM) data have not been analyzed in any detail. Five-minute average PM2.5 concentrations clearly indicate the smoke distribution in space and time, including overnight smoldering effects. Similarly, photography has not been analyzed in more than a cursory way. The key findings here are that, to be useful, cameras must be sited with great care; in addition to wind direction and fire geometry, sun angle and ignition-time determine whether smoke is visible. Sun angle and relatively thin smoke from the grass burns appear to limit the value of much of the photography.

All three fires (L1G, L2G, and L2F) were sampled from ignition until smoke produced by the smoldering fire was no longer lofted high enough to be sampled by the aircraft (~160 m AGL). The fire-average modified combustion efficiency (MCE) and emission factors for the grass-dominated units (L1G and L2G) were in close agreement with differences of < 1% for MCE and EFCO2, and approximately 3% and 11% for EFCO and EFCH4, respectively (Table 4). The forested unit burned with a significantly lower MCE and had EFCO and EFCH4 that were 2 and 2.6 times the grass unit averages, respectively (Table 4).

During the L2F fire, EFCH4, and to lesser extent MCE, varied with the estimated time of emissions, with EFCH4 increasing over the course of the fire while MCE decreased. This behavior is consistent with a greater contribution from smoldering combustion during the later stages of the fire. However, the different temporal patterns in MCE and EFCH4 suggest they relate differently to fuel components and the combustion process. There was no correlation of EFCH4 (or MCE) with altitude or distance from the source indicating that the trend was not an artifact of the smoke sampling pattern nor of the length of time the smoke was in the atmosphere before sampling. For the L2F fire a linear least square regression of EFCH4 vs. MCE yielded the fit: $y = 54.4 – 55.3x$ ($R2 = 0.42$). There was not a significant correlation between EFCH4 and MCE for either the L1G or the L2G fire.

Table 4. Aircraft based measurements of fire-average modified combustion efficiency (MCE) and emission factors (EF) (±1 standard deviation)

Burn block	Number of samples	Fire-average modified combustion efficiency (MCE)	Emission factor for carbon dioxide ($EFCO_2$) ($g\ kg^{-1}$)	Emission factor for carbon monoxide (EFCO) ($g\ kg^{-1}$)	Emission factor for methane ($EFCH_4$) ($g\ kg^{-1}$)
L1G	30[a]	0.950±0.016	1738±29	58.4±18.9	1.75±0.96
L2G	10[b]	0.953±0.005	1743±8	55.0±5.4	1.57±0.48
L2F	30	0.906±0.019	1651±37	108.4±21.4	4.32±1.58

[a]$EFCH_4$ is based on 21 samples. [b]$EFCH_4$ is based on 7 samples

Fire effects

Long-wave infrared thermography (LWIR) imagery offers an opportunity to effectively link the combustion environment with postfire processes, remote sensing at larger scales, and wildland fire modeling efforts. A comparison of LWIR and visual imagery shows that LWIR imagery captures a broader range of combustion environments (both smoldering and flaming phases) whereas only the flaming phase of combustion was apparent in the visual images (Fig. 9). Both the nadir and oblique (rectified) LWIR imagery illustrated fluctuations in FRP influenced by fuels and changing wind patterns at the flaming front at both fine and moderate scales. These data reflect the heterogeneity of FRP that was released from these surface fires. This was shown in the nadir LWIR imagery, where detailed fire line intensity was highly variable within a small area (about 16 m^2). This also was evident in the oblique LWIR imagery, where fireline geometry and shifting wind patterns influenced fireline depth (e.g., backing vs. flanking fire) and total FRED across the burn block (Fig. 18). As the fireline depth was often within 2 m, the nadir LWIR camera was able to record FRP of the true flaming front, without the signal attenuation that may be caused by blending burning and non-burning areas within pixels at coarser scales. The accurate two-dimensional spatial measurements of surface radiative energy release over time can connect fire to such processes as soil heating, plant mortality, and tissue damage and also provide valuable data on fire spread and radiant energy fluxes useful for refining fire spread and smoke dynamics models.

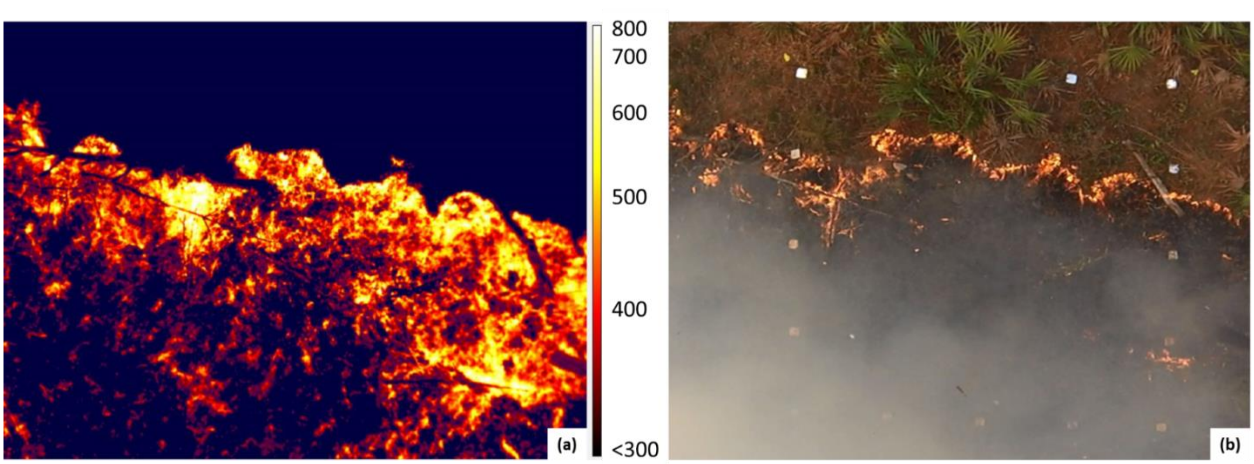

Figure 18. (a) Snapshot of nadir LWIR imagery versus (**b**) a color digital photograph of a surface fire (L2F HIP 3). Note the transparency of smoke in the LWIR imagery and the detection of thermal signatures of both flaming and smoldering combustion. The metal targets (in b) are used for post-processing and are positioned 1 m apart around the small highly-instrumented plot (SHIP) perimeter. Color legend for the LWIR image is in °C.

Data management

The RxCADRE is composed of multidisciplinary and geographically distributed teams, generating widely varied data including spreadsheets, meteorological files, infrared imagery, lidar, images, video and photographs. We first found it was important to have two temporary data repositories. The first repository allowed scientists to upload data immediately during the field campaign for safe storage and for other scientist to review and assist in planning for the remaining field campaign. The second data repository was used to upload reduced and quality-assured data for use by scientists and as a storage facility as scientists were checking their data. Once the data was thoroughly checked, it was flagged for transfer to the Forest Service Research Data Archive.

The Forest Service Research Data Archive is a critical resource for storing and providing access to the RxCADRE datasets. The archivist reviews the RxCADRE datasets by discipline area and communicates directly with the lead scientists to provide the necessary (1) identification information, (2) data quality information, (3) entity and attribute information , (4) distribution information, and (5) meta-reference information. The archivists were extremely helpful and worked closely with the scientists to make sure their needs were met and discussed with them when the data should go “live”. All scientists were extremely pleased with the cooperation and support given by the Forest Service Research Data archivists.

Although the datasets are just beginning to be published as archived data sets, 5 scientists have contacted the RxCADRE members and have acquired datasets for use in evaluating and modifying models. Table 5 lists those scientists.

Table 5. Scientist that are currently using the RxCADRE data for evaluation and modification of models.

Scientist	Location	Purpose
Rod Linn	Los Alamos	Simulations with both FIRETEC and to use in the development of newer more computationally lean models.
Scott Goodrick	Northern Research Station	Smoke and fire model improvement and development.
Gary Achtemeier	Southern Research Station (retired)	Improvement and further development of Rabbit Rules
Ruddy Mell	Pacific Northwest Research Station	Improvement and further development of WFDS
Michael Gollner	University of Maryland	Improvement and further development of WIFIRE

IV. Science and Management Implications by Discipline

RxCADRE proved that it is possible to bring many scientists together too successfully and efficiently complete several large research campaigns. Furthermore, the project provided quality assured datasets for development and evaluation of fire models. Implementation of the project and preliminary analysis of the data has led to important science and management implications and support for 16 undergraduates, graduate, PhD, and non-degree students (see Appendix V). As the data is analyzed further, additional implications will come forth.

Fuels

- Fuel loading and fuel consumption data reported here have not been used to develop fire models and can therefore be used as an independent dataset for evaluating such models.
- Post-fire white ash is an effective indicator of surface fuel consumption and, provided it can be quickly measured postfire (before it dissipates), may be a method that can be used in the future to reduce the time and cost of measuring fuel consumption.
- Fine surface fuel loads can be predicted from airborne lidar metrics, even beneath longleaf pine forest canopies.
- Fuel consumption can be predicted from fire radiative power flux (FRFD) measured from airborne long-wave infrared (LWIR) imagery and ground validation sensors.
- Robust terrestrial lidar scan (TLS) data collection and processing methods were developed to produce high fidelity 3-dimensional fuel structure data.
- The geometric consistency of TLS datasets is very high and there is little evidence for spatial bias.
- TLS fuel height data corresponded closely with field measurements of height and provide spatially explicit representations of fuel heights across burn units not attainable with field sampling.

Meteorology

- The RxCADRE campaign provides researchers a dataset with which to study atmospheric turbulent structures and fluxes associated with different fuel types, and provides a basis to further our understanding of the dynamics of fire-atmosphere interactions.
- Turbulent, sensible heat fluxes indicated the grass fires of the 2012 RxCADRE were of very low intensity as compared to other grass fires.

- Doppler lidar measurements of the plume show a weakening of wind velocity sometimes occurs immediately downwind of the plume. This decrease in velocity is associated with a convergence zone that develops in response to plume heating.

- The scanning Doppler lidar was able to track plume location near the surface and could potentially be used for fire front tracking.

Fire behavior

- The measurement of energy and mass transport is difficult and is associated with increased measurement uncertainty due to the fluctuating nature of the wildland fire environment.

- These data are part of the larger RxCADRE dataset, and build on what has historically been a limited dataset of similar measurements.

- These data are at the low end of fire intensity and represent an important first step in the building of a comprehensive dataset and will support evaluation and development of fire behavior, effects, and emissions models.

- These data are integral to a better understanding of the contributions of radiative and convective heating to energy transport.

- These observations suggest that convective heating is the major driver of ignition and that the convective events are sufficient to lead to ignition of the irradiated vegetation.

- The Scout showed the most promise for tactical deployments from remote locations, but all RPAS platforms met objectives for the research and operations.

Radiative power and energy

- Fire radiative power can be measured from coincident radiometer, oblique infrared, airborne infrared (both from piloted and remotely-piloted aircraft), and satellite sensors.

- Remotely-piloted aircraft systems (RPAS) have some utility for characterizing flame front development but their use will remain severely limited without small, lightweight, and quantitative infrared sensors and better 3-dimensional position data for image georectification.

- Better fundamental understanding of fire spectral radiation and its incorporation into measurement processes is needed.

- The wide array of measurements collected during RxCADRE 2012 provides opportunities for synthesis that have not been possible heretofore.
- Fire radiative energy is linearly related to fuel consumption in small-scale experiments and was shown to approach linearity at the landscape level of prescribed fires, after correcting for under-sampling biases.
- Airborne measurements of fire radiation provide a means of comparing ecosystems and ignition strategies relative to smoke plume dynamics and reveal large differences among burns.

Emissions

- The grass-dominated units burned with high modified combustion efficiency (MCE) and low EFCO and $EFCH_4$ in contrast to the forested unit.
- The RxCADRE fires, dominated by fine fuel consumption, burned with significantly different MCE and produced different emission factors than is reported in the literature, suggesting that the composition and characteristics of fine fuels (grass and forbs vs. litter and woody debris) may be an important factor influencing emissions.
- Findings suggest that MCE is a reliable predictor of $EFCH4_4$ for understory prescribed burns in the Southeast.
- The downwind smoke concentration fields (CO and CH_4) measured from the aircraft provides a dataset that can be used to evaluate smoke dispersion models.
- The CO and CH_4 concentrations may be employed in a model-data assimilation framework to quantify the emission intensities of the fires.

Fire effects

- Long-wave infrared (LWIR) imagery offers an opportunity to effectively link the combustion environment with postfire processes, remote sensing at larger scales, and wildland fire modeling efforts.
- Accurate two-dimensional spatial measurements of surface radiative energy release over time can connect fire to such processes as soil heating, plant mortality, and tissue damage and also provide valuable data on fire spread and radiant energy fluxes useful for refining fire spread and smoke dynamics models.

Data management

- Providing access to the storage via a common, platform-neutral, robust and secure data transfer mechanism (SFTP) proved the most expeditious and intuitive way to share files. It was also the most reliable way to transfer large files. It is recommended that this level of access always be provided even though it does not serve the longer term goal of ensuring that the data are transferred to the archive.

- The solution chosen did a good job of collecting datasets in one place without interposing a third party between the scientists and the archivists. Repeating this strategy on future large, distributed projects is recommended.

- Provided a more dynamic and informal data management solution, allowing either structured or free-form keywording, ad-hoc annotations providing context to the data, discussions by project members, and better control over data sharing. This encouraged data to be captured earlier (before being finalized and packaged for delivery to the archive). This is also a valuable function which should be considered by future teams.

- Leveraged infrastructure for user accounts, where Forest Service users can use their "normal" passwords. Separate accounts must be for all others, but their passwords on all the websites and the file server are the same). This was popular with the users. Making it easy for other projects to do this as well is recommended.

- Geonetwork Opensource is a good solution for a geographically distributed team's metadata editing needs, but a poor choice for storing and managing the datasets themselves. Over the course of this project, new releases of this software (to which we did not upgrade for consistency's sake) are purported to improve this situation.

    - Recommendation alternative #1 (workaround): Future projects either should not try to attach datasets to metadata at all, or carefully evaluate the new version's data management characteristics on datasets relevant to them.

    - Recommendation alternative #2 (fix): As this is an open source project, JFSP could fund improvements targeted to improving data management in Geonetwork Opensource, outside of any science-related activity. This would eliminate the need for recommendation alternative #1.

- Using Geonetwork Opensource streamlined the dataset submission workflow by providing a "Ready to Submit" area. Scientists added their metadata to this area when they felt ready, and the archivists had a single place to check for new metadata. This allowed the archivists to review many individual submissions and provide preliminary, general feedback applicable to the datasets. It is recommended that future projects include a means of streamlining the data submission workflow at the end of the project.

- Two data products generated during this project may have enduring value:

    a. Because the Forest Service Research Data Archive requires datasets to have keywords drawn from the Forest Service Research and Development taxonomy, we converted the taxonomy to Simple Knowledge Organization System (SKOS) format, which Geonetwork Opensource (and others) can read.

    b. A template for ISO19115 metadata was generated. This template gives users a good starting point for creating metadata to submit to the Forest Service Research Data Archive. This template is in XML and can be used by any software which understands ISO 19115 metadata.

V. Relationship to Other Recent Findings and Ongoing Work

The availability of integrated and quality-assured fuel, atmospheric, fire behavior, energy, smoke, and fire effects data are limited, reducing our ability to evaluate fire models and tackle fundamental fire science questions. Consequently, there are not many recent findings or ongoing work to relate to.

There have been several large fire experiments in the past 20 years. The International Crown Fire Experiment was a series of 18 experimental crown fires that were conducted in the Northwest Territories of Canada between 1995 and 2001 (Stocks et al. 2004). It provided data and insights into the characteristics of crowning wildland fire that were used to improve physical modeling of high intensity forest fires. The Frostfire project (Hinzeman et al. 2002, Ottmar and Sandberg 2003) was the first experimental burn of a watershed and one of the most thoroughly documented prescribed fires. This experiment provided insights into fuel consumption, fire behavior, and emissions to be used in improving existing fire models. Both studies were limited to boreal forest ecosystems and did not specifically direct data collection for evaluating fire models.

In 2008, the Strategic Environmental Research and Development Program (SERDP) began a program to characterize the fuels, smoke chemistry and transport associated with prescribed burning on Department of Defense bases in the United States. Three projects have been completed. Although the specific objective of the study was not to provide data for fire model evaluation, it could be used as such if the appropriate input data was collected for individual model testing.

Fire-spread was measured and observed on 121 grass fires in Australia's Northern Territory (Cheney et al. 1993). Although the data has been used extensively to modify fire behavior models to better represent fire spread in a simple fuelbed, it cannot be used to validate those models.

Currently, there are several scientists actively engaged in using the RxCADRE data sets in evaluating and modifying fire models (Table 5). Rod Linn of Los Alamos is actively exploiting RxCADRE data for simulations with both FIRETEC and to use in the development of newer more computationally lean models. Scott Goodrick (Northern Research Station) and Gary Achtemeier (Southern Research Station, retired) are both using RxCADRE data for smoke and fire model improvement and development. Achtemeier is improving Rabbit Rules and increasing its flexibility by using the data to investigate scaling in the model. Ruddy Mell is using the data for evaluating the Wildland Urban-interface Dynamics Simulator (WFDS). Michael Gollner, University of Maryland is requesting the RxCADRE data for evaluating WIFIRE that assimilates fire spread in grassland fuelbeds. Finally, we expect many more request s as the datasets are published in the US Forest Service National Archive and with the publication of the RxCADRE special issue of the International Journal of Wildland Fire.

VI. Future Needs by Discipline

The RxCADRE datasets captured fire data from relatively simple fuelbeds that included nonforest grass, grass/forb/shrub, and managed forest fuelbeds that are regularly treated with prescribed fire. Although this research effort was a major step in providing datasets for use in evaluating models, additional datasets are needed to cover a larger range of fuel and environmental conditions. Furthermore, analysis of this RxCADRE dataset has just begun and much more information can be gleaned in years to follow. This section will describe future work needs by discipline areas used in the RxCADRE and data management.

Fuels

The RxCADRE project was designed, in part, to accommodate fire behavior models. Replicate burn blocks of simple fuelbed types were targeted. The next series of experiments needs to target larger units, more complex fuelbeds with greater spatial variability, heavier fuel loads, and higher intensity fires for better assessing smoke models and fire behavior modeling. Although we used a standard sampling protocol of destructive sample plots and the planar-intersect inventory, more plots and longer transects should be considered, where needed, to reduce the error associated with fuel variability. In fuelbeds with heavier loadings, ash measurements should take into account for total ash and not just the cover of ash. In addition, continued investigation of fuel loading and height distribution from terrestrial laser scans of fuelbeds is needed. The canopy-top metric (maximum height) defines the volume occupied by fuel. Canopy top alone does not address how much fuel resides in the volume, where it is concentrated, or what its characteristics are. However, it is anticipated that the height of maximum amplitude, inflection points, or central tendency metrics will address the question of where biomass is concentrated in the vertical domain. A big unknown is how much fuel exists in a given cell. Fuel loading will need to be modeled from height distributions or fuel types and will have to be classified so that fuel characteristics can be inferred from field measurements. In the meantime, we need to investigate fire model sensitivity to fuels variability to determine how accurate the fuels data need to be. Finally, research to explore the integration of plot-scale fuel measures from terrestrial lidar and stand- to landscape-scale measures from airborne lidar is needed, to improve the local accuracy of lidar-derived surface fuel maps.

Meteorology

To better understand the role fire-atmosphere interactions have on fire behavior and plume dynamics, highe- resolution vertical profiles of winds both inside the smoke column and ambient are needed. This can be done with triple Doppler lidar scanning allowing for a virtual tower-like profile of three-dimensional winds at high temporal resolution. Besides the virtual tower, dual-Doppler lidar scans provide horizontal winds across the burn area. While a single Doppler lidar provided measurements that allowed new insights into plume structures and fire-induced circulations, these measurements were limited in temporal and spatial scales. In addition, triple-lidar studies of plumes will provide highly accurate and real-time observations of plume rise that cannot be sampled accurately otherwise.

Another need involving the micrometeorology of the fire front is the use of in situ fast-gas flux analyzers on towers to directly measure the fluxes of greenhouse gases and other combustion gases (CO_2, H_2O, CH_4, CO). Measurements of this sort will provide a new bound on fresh emissions that can be coupled to aircraft and downwind measurements.

Fire behavior

In the field campaign, several aspects of sensor setup and experiment methods could be improved including: (a) the need for distance and height metrics in camera field-of-view, measurement and recording of the height of the sensors relative to the vegetation height, (b) the utility of overhead infrared imagery in developing continuous fire rate of spread information,(c) the need for additional measurements and analysis of flame temperature data from very fine wire thermocouples, and (d) the need for additional measurements at high sampling rates to further characterize the temporal properties of the energy release from the flames. Further analysis of the data is also needed.

Additional missions with remotely-piloted aircraft systems (RPAS) on prescribed fires and wildfires will provide the necessary experience and data to support a greater role for RPAS in research and operations support. However, improved methods for orthrectifying imagery and for generating quantitative fire radiation measurements from sensors is required. Without better methods for orthorectifying imagery, small RPAS will have limited use in quantifying fire progression. Until higher-quality sensors are developed for small RPAS, it may be necessary to use larger RPAS to provide the "staring" (continuous) and quantitative imagery that is so valuable for research. Collaboration with NASA and other agencies may be required to meet data requirements.

Radiative power and energy

Comparisons among sensors and platforms show that measuring fire radiation remotely is still associated with a lot of uncertainty. Efforts underway to develop a better understanding of fire radiant emissions and to design small sensors for which measurement accuracy and precision are better known will support future campaigns. As well, fuel consumption measured in RxCADRE provided a standard by which fire radiation measurements could be evaluated. Fuel consumption is not a perfect standard, requiring the time integration of fire radiation measurements (to provide fire radiated energy) and assumptions about radiated fraction and fuel heats of combustion. However, though imperfect, future studies should involve more extensive estimates of fuel consumption such as those that will emerge from RxCADRE fuel consumption and lidar measurements. Also, studies are needed that will estimate radiated fractions (the fraction of total heat generated that is dissipated by radiation) and effective heats of combustion (analogous to combustion efficiency measured in plumes). Continued analysis of RxCADRE data, building on the analyses in the International Journal of Wildland Fire special issue will put us on a better footing for future campaigns.

Methods to interpolate between hot pixel observations in fire radiative power (FRP) images are needed to overcome undersampling problems with LWIR imagery collected from fixed-wing aircraft. An experiment to collect continuous, landscape-level FRP imagery from a near-stationary helicopter or tethered balloon platform could help as a form of validation. Further technological improvements are needed to achieve comparable time series imagery from RPAS platforms, but the rate at which RPAS remote sensing capabilities are improving leaves much room for optimism. Unmanned platforms have obvious applicability for wildfire monitoring, especially in steep, remote, or otherwise inaccessible terrain, although it remains advisable to show proof of concepts in flat terrain and more manageable burning conditions.

Emissions

The smoke data collected can be used in transport and dispersion modeling and, when combined with the fuels and behavior data, may allow consumption model validation. Data on transient behavior of the plume near the fire, which influences the vertical smoke distribution and subsequently long-range transport, was severely limited by burn constraints. Efforts to merge so many disciplines and the constraints each placed, as well as the normal burn prescription and the effort to get data usable for fine-scale modeling precluded collecting transient plume data that would otherwise have been possible. Future work, if focusing on emissions and smoke processes, should limit the prospect of other concerns becoming obstacles to these types of observations. Keeping terrain and fuels simple, with large and long-lasting burns, would also be essential.

It would also be valuable to collect data on secondary chemical processes, which affect smoke properties further downwind. These properties more accurately represent the potential smoke effects on human populations not in the immediate vicinity of the fire. Again, large, long-lasting burns would be necessary to collect these measurements.

Fire effects

Even though fire effects research was ancillary to the focus of this RxCADRE, we were able to develop new techniques useful for fire effects research. We need to apply these techniques in research on mechanisms driving both mortality and recruitment in vegetation following fire. For example, the links between within fire fine scale spatial heterogeneity of fire energy release and fire effects has not been well developed in ecosystems other than southern pines. Opportunities for testing new theories on the role of fire in community assembly and forest dynamics would benefit from testing in other ecosystems/fire regimes.

Data management

Continued support of a national archive and staff for uploading and archiving datasets is important. The staff also needs to provide consistency and over site on all data and metadata that comes to the site. Finally, improved technology for transferring data is required as our datasets becoming much larger and complex.

VII. Lessons Learned

RxCADRE

Conducting large research campaigns on actively burning fires is a high risk proposition because of safety concerns, logistical challenges, costs, science interest conflicts, and data sharing concerns (Lentile et al. 2007a,b; Macholz et al. 2010a,b). Each one of these challenges needs to be minimized or eliminated to increase the chance of a successful research campaign.

Safety must be considered throughout the planning process and cannot be compromised in the effort to meet research objectives. 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 be in communication at all times and no research burn was conducted until all personnel were identified and located before ignition.

There are several logistical challenges to overcome in implementation of a large research project including but not limited to (1) a harsh fire environment, (2) potentially poor access and extremely rugged terrain, (3), the 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 needed to be designed to tolerate the fire temperature and heat duration. All-terrain vehicles were used to access to the research sites. Additional data collection sites were required 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 the air space to allow for deployment of remotely piloted aircraft systems, and data acquisition and processing ability. Finally, due to weather and the burning record of Jackson Guard, there was > 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 researchers in each discipline had skills that could often be used across disciplines, enabling the research data collection to be more efficient.

Scientists often have varying interests that may conflict with the overall objective of a large fire project. This conflict may originate with the scientist or the funding agency. It is important to understand the motivation of each lead scientist and make sure there is common ground between individual objectives and project goals. It is best to have a ground-up approach.

Sharing data is a concern, especially before the information is published. A discussion and conformation with all scientists before the field data collection begins is critical so that all parties involved understand the rules. It is best to have an agreement where all data will be shared among scientists involved with the project to assist in making the correct inferences and conclusions.

Finally, “if you build it they will come”. The organization and support of this project provided the opportunity for many other scientists and agencies to participate in this unique research effort. For example, science teams from EPA, NASA, and Georgia Institute of Technology used the RxCADRE to collect data and use data collected from other scientists to advance their research effort in moving the knowledge of fire science forward.

Data management

We discussed the archival process with the US Forest Service. The things we planned for that worked well for data management include:

- Providing an online location to see all of the data products and access them at any time. This facilitated data sharing among team members and data users (in this case, the modelers for whom the data were collected), provided a common web-based method of entering metadata and expedited the final transfer to the archive. In addition, the central storage acted as an off-site backup for scientists who may not otherwise have bothered.
- Ability to download the data directly from the site (as opposed to receiving a ton of emails/downloads).
- The use of an FTP site when there were many files or the files were large in size.

Things that could be improved include:

- Access to the metadata needs to be improved. We had a hard time accessing the XML file, and for many we just retyped the info into Metavist.
- The main sections of the metadata were typically completed, but the more complicated sections usually were left blank. We might need to work more with scientists early on to help them better understand what goes into those sections.

- Determining how to group the data products after submission made it slightly confusing for our interns, perhaps we could determine ahead of time what a "product" will contain and upload them in that format. (In other words, sometimes we combined 6 of the individual entries on the site into 1 data product). However, that being said … sometime researchers may not know how they want to combine or break up datasets into products until the later in the process, so this may not be something we need to change. But providing more info to the scientists early might help.
- Not all of the download links behaved the same, which was likely a result of the scientists uploading them differently. We were able to access all of them, but it took some playing around or emails to access the files.

VIII. Next Steps

RxCADRE

The RxCADRE project was one of the largest and most efficient fire research campaigns ever undertaken, and provided a quality-assured fuel atmospheric, fire behavior, energy, smoke, and fire effects dataset for evaluation and modification of fire models. These datasets will provide a unique opportunity to advance the science of fire modeling. However, there are several "next steps" to move the science even further ahead.

The datasets are very unique in that they capture the critical information from the combustion of to fire behavior to energy release and resultant fire effects and smoke. However, funding of this research effort targeted the collection and management of the data. The next step should include a thorough analysis of these datasets to unlock all the information that these datasets could provide. Secondly, the measurements collected from these field campaigns targeted relatively simple fuels and flat terrain and are insufficient to fully characterize fires that occur in heavy, complex fuels and steep terrain. Another research effort targeting heavier fuels in more complex terrain is necessary. Finally, a critical sensitivity analysis on fire models targeted for evaluation is needed before another campaign is begun. 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 and scales.

Data management

The next step for Forest Service Research and Development is to improve connectivity between our major research centers and external universities, serendipitously increasing the number of potential hosts for large central datasets. The RxCADRE project was the flagship user of the prototype Internet 2 connection at Missoula. As such, we were far better connected to our educational partners than to peer individuals or units within the FS. Evidence of this is reflected in the fact that the only groups finding it necessary to send data by mailing disks were Forest Service units—other partners were able to exploit the high-bandwidth infrastructure provided by the Internet 2 pilot.

Connectivity to Internet 2 is now an activity which is being embraced at the USDA level, as a partnership between the Forest Service, Agricultural Research Service (ARS), and the Animal and Plant Health Inspect Service (APHIS). Equally important is the institutional recognition that Internet 2 is not a government network, making it more research-friendly. With this freedom comes the fact that the burden for administrating connectivity and use lies completely on the scientist at this point. In addition to bringing new sites online, the next data management step should include a rigorous and intensive look at which administrative tasks can be delegated away from the scientists without turning our I2 environment into yet another network we're not allowed to use.

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XI. Timeline

This is a simple list of critical milestones met during the project. Further information on deliverables is presented in Section XII.

September 2012: Annual progress report submitted to JFSP.

October 31-November 12, 2012: Field effort complete, manager workshop held.

December 2012: Fire ecology conference, Portland, OR., RxCADRE presentation.

January-February 2013: Several presentations to managers on RxCADRE.

February 2013: 4th Fire Behavior and Fuels Conference. RxCADRE special session, fifteen presentations, two proceeding papers and 1 extended abstract completed.

August 2013: Outside the reporting period progress report submitted to JFSP.

September 2013: JFSP Annual progress report submitted.

September 2013: Outline of final report prepared and submitted to RxCADRE scientists.

October 2013: International Smoke Symposium. Special session on State of Fire Behavior Models and their Application to Ecosystem and Smoke Management Issues. Five presentations from RxCADRE members and one proceeding paper summarizing the session.

January-February 2014: Several presentations to managers on RxCADRE

May 2014: Large fire conference. One presentation and one poster presented.

July 2014: Outside the reporting time period progress report submitted to JFSP.

September 2014 A majority of the datasets have been uploaded to the US Forest Service National Archive data center. Several datasets are published. Discussions between the archivists and the scientist to complete required fields are occurring on remaining datasets. Several datasets has been published.

September 2014. Ten draft papers for a special issue of the International Journal of Wildland Fire have been completed and submitted to the IJWF for a special issue.

September 2014. Final report submitted to JFSP.

XII: Deliverables Crosswalk Table

All deliverables (red) and several additional deliverables (blue) have been completed and are presented in the proceeding table.

Deliverable type	Description	Delivery dates
Fire behavior meetings	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.	**<u>June 2013</u>: Complete**. Two meetings and several conference calls and e-mail discussions including: September 2011. The PI and Co-PI met with fire behavior and other modelers in Boise to provide variables, scales, and fuelbed types for study. September 2012. Conference calls, a field trip to Eglin Air Force Base, and e-mail correspondence with models resulted in the selection of small replicate units in simple fuelbeds along with as well as several large operational burns to be selected for the 2012 campaign. Discussions also determined variables to collect and archival organization of the datasets. February 2013. Met with modelers during the 4th Fire Behavior and Fuels Conference and discussed data analysis and data repository structure required.
RxCADRE website	Establish RxCADRE website for informational exchange	**<u>September 2014</u>**: **Complete.** Forest Service Research Data Archive http://www.fs.usda.gov/rds/archive/ (in progress, see appendix V) **<u>April 2012</u>: Complete**. Two websites established including: http://firelab.org/project/rxcadre-project http://www.fs.fed.us/pnw/fera/research/rxcadre/index.shtml.
Special session at a major fire conference	Senior , co-PIs , and scientists will present preliminary results at a major Fire Conference in 2014	**<u>February 2013</u>: Complete.** February 2013: 4th Fire Behavior and Fuels Conference, Raleigh, North Carolina. RxCADRE special session with fifteen presentations by RxCADRE participants. 15 abstracts, 2 proceeding papers and 2 extended abstract (see Appendix II).

Deliverable type	**Description**	**Delivery dates**
Other conferences	Senior PIs , co-PIs , and scientists will present preliminary results at a major conferences	**September 2014: Complete.** Additional deliverables with presentations at 4 conferences and 1 symposium. **May 2014.** AFE/IAWF Conference on Large Wildfires, Missoula, MT. There were two presentations and one workshop. There were two published abstracts (see Appendix II) **May 2013.** Numerical Wildfire Conference, Corsica, Spain. 1 presentation. No publication. **October 2013:** International Smoke Symposium, Maryland. Special session on State of Fire Behavior Models and their Application to Ecosystem and Smoke Management Issues. There were five presentations from RxCADRE members. There was one proceeding paper (see Appendix II) **December 2013**. American Geophysical Union. 1 presented post and abstract (see Appendix II) **December 2012.** Portland meeting, 1 presentation on the RxCADRE progress, published abstract (see Appendix II)
Workshop and conference for managers	Program manager and senior and co-PIs will present findings to managers in the southern U.S.	**September 2014:** Complete with findings presented at 12 manager workshops, training venues, and conferences as noted below: Oct. 2012 Rx310, Eglin Air Force Base. Dec. 2012 BLM and USFS Region 6 Jan. 2013, 2014 RxCADRE, Region 6 Jan. 2013 RxCADRE, Region 1 Feb. 2013, 2014 RxCADRE, Region 4 Feb. 2013 RxCADRE, Region 9 Feb. 2013 RxCADRE, Region 9 March 2013 RxCADRE, Region 10 March 2013 RxCADRE Missoula lab webinar April 2013 RxCADRE, Joint Base Lewis-McChord June 2013 RxCADRE presentation to Sam Foster June 2013 RxCADRE, Fire Science Champions Network

Deliverable type	**Description**	**Delivery dates**
Final report	Summary description of findings to JFSP	**September 30, 2014.** Completed and submitted.
Documented datasets	Fully quality assured and documented datasets, posted on SEMIP and/or FRAMES	**September 30, 2014**. The majority of datasets collected by the RxCADRE have been submitted to the US Forest Service Research Data Archive (2014) for use in testing and evaluation of fuel, fire, and fire effects models. Five datasets are published at the time of this final report and are available for download. Sixty-five datasets are reconciled with the archivist and are awaiting official word for publication. Forty datasets have not been uploaded but will be by November 1. We expect all datasets will be available for download by December 31, 2014. However, several scientists may opt to wait on the official release (published) of the datasets until the IJWF special issue is published (Appendix IV).
Scientific papers	Manuscripts describing all primary findings; drafts to be ready for publication in journal special issue	**September 30, 2014.** Ten papers have been submitted to the International Journal of Wildland Fire to be published as a special issue. Guest editors are Colin Hardy and David Peterson and include: Ottmar et al., Ottmar et al., Rowell et al., Clements et al., Butler et al, Zajkowski et al., Dickinson et al. (with 2 ancillary publications), Hudak et al., Strand et al., O'Brien et al. (Appendix I)

Deliverable type	Description	Delivery dates
Other papers	Published manuscripts and abstracts describing primary findings and not part of the special issue	**<u>September 30, 2014</u>.** Thirty-four additional papers and abstracts associated with the RxCADRE have been published. These include: Aurell and Gullet (2013), Butler (2014), Cannon et al. (2014), Clements (2013), Dickinson et al. (2013), Frankman et al. (2013), Frankman et al. (2012), Gullett and Aurell (2013), Hiers (20130, Hiers et al.(2009), Hudak et al. (2013a), Hudak et al. (2013b), Hudak et al.(2013c), Hudak et al. (2013d), Hudak et al. (2013e), Jimenez et al. (abstract accepted), Loudermilk et al. (in press), Loudermilk et al. (2012), Loudermilk et al. (2009), Mell (2013), Nordgren (2013), O'Brien (2014), O'Brien (2013), Ottmar (2014), Ottmar (2013), Ottmar et al. (2013), Ottmar (2012), Potter, et al. (2013),), Prichard and Ottmar, (2014), Seielstad and Rowell (20130, Urbanski (2014), Urbanski (2013), Walker et al. (2013), Zajkowski et al. (2013) (See Appendix II)

Deliverable type	Description	Delivery dates
Other deliverables	News articles and video	**September 30, 2014:** Additional deliverables, videos, articles, and general news Discovery Channel—Canada: Daily Planet – Controlled Burn. http://watch.discoverychannel.ca/#clip918742 Pacific Northwest Research Station 2013 Science Accomplishments. (US Forest Service, 2014) http://www.fs.fed.us/pnw/pubs/2013-science-accomplishments.pdf RxCADRE Prescribe Fire, Eglin Air Force Base (U.S. Geological Survey 2014) http://uas.usgs.gov/eglinprescribeburn.shtml Capturing Fire: RxCADRE Takes Fire Measurements to Whole New Level (Joint Fire Science Program 2013) http://fireecology.org/docs/conferences/4IFEC/Abstracts/353.pdf Smoke Plume Research (Scion Research 2013) http://www.wrfa.org.nz/uploads/docs/Research/Rural%20fire%20research%20activities%20Oct%202012%20-%20Feb%202013.pdf Large Group of Researchers Hopes to Develop More Accurate Fire Models (Wildfire Today 2013) http://wildfiretoday.com/2013/11/15/large-group-of-researchers-hopes-to-develop-more-accurate-fire-models/ Aeryon Scout UAS Supports Critical Florida Wildfire Research (sUAS News 2013) http://www.aeryon.com/news/latest-news/pressreleases/541-uaf-scout-research.html Eglin's Controlled Burns Advance Fire Research (Eglin Air Force Base 2012) http://www.eglin.af.mil/news/story.asp?id=123326882 RxCADRE: A Novel Approach to Wildland Fire Research (Southern Fire Exchange 2012) http://www.southernfireexchange.org/newsletters/v2-1.pdf Fire on the Base (U.S. Forest Service, Southern Research Station 2012) http://www.srs.fs.usda.gov/compass/2012/04/10/fire-on-the-base-4/ All in the Name of Science: Unmanned Aircraft Battle Flames and Smoke during RxCADRE 2011 (Association of Unmanned Automated Vehicle Systems International 2011) http://rmgsc.cr.usgs.gov/uas/pdf/newsmedia/eglin/auvsi_0311UnmannedSystems_web.pdf RIT Scientists 'Feel the Burn' of Wildfire Research (Rochester Institute of Technology 2008) http://www.rit.edu/news/story.php?id=46092 Fire Measurements in the Southeastern United States (Landscape Center for Nation Center for Landscape Fire Analysis, University of Montana) http://www.rit.edu/news/story.php?id=46092

Appendices

Appendix I: Manuscripts Submitted to the International Journal of Wildland Fire for Publication as a Special Issue Entitled: “Measurements, Datasets and Preliminary Results from the RxCADRE Project”

Guest editors: Dr. David L. Peterson and Dr. Colin Hardy

Ottmar, R.D., Hiers, K.H., Clements, C.B., Butler, B., Dickinson, M.B., Potter, B., O’Brien, J.J., Hudak, A.T., Rowell, E.M., Zajkowski, T.J. (Submitted) Measurements, datasets and preliminary result from the RxCADRE project. Special Issue, International Journal of Wildland Fire.

Ottmar , R.D., Hudak, A.T., Wright, C.S., Vihnanek, R.E., Restaino, J.C. (Submitted) Pre- and postfire surface fuel and cover measurements—RxCADRE 2008, 2011, and 2012. Special Issue, International Journal of Wildland Fire.

Rowell, E.M., Seielstad, C.A., Ottmar, R.D. (Submitted) Development and validation of fuel height models for terrestrial lidar— RxCADRE 2012. Special Issue, International Journal of Wildland Fire.

Clements, C.B., Lareau, N., Seto, D., Contezac, J., Davis, B., Teske, C, Butler, B., Jimenez, D. (Submitted) Meteorological measurements and fire weather conditions-RxCADRE 2012. Special Issue, International Journal of Wildland Fire.

Hudak, A.T., Dickinson, M.B., Bright, B.C., Kremens, R.L., Loudermilk, L.E., O’Brien, J.J., Hornsby, B., Ottmar, R.D. (Submitted) Measurements relating fire radiative energy density and surface fuel consumption—RxCADRE 2011 and 2012. Special Issue, International Journal of Wildland Fire.

Butler, B., Teske, C., Jimenez, D., O’Brien, J., Sopko, P., Wold, C., Vosburgh, M., Hornsby, B., Loudermilk, E. (Submitted) Observations of fire intensity and fire spread rate—RxCADRE 2012. Special Issue, International Journal of Wildland Fire.

Dickinson, M.B., Hudak, A.T., Zajkowski, T., Loudermilk, L.E., Schroeder, W., Ellison, L., Kremens, R.L., Holley, W., Martinez, O., Paxton, A., Bright, B.C., O’Brien, J.J., Hornsby, B., Ichoku, C., Faulring, J., Gerace, A., Peterson, D., Mauseri, J. (Submitted) Ground, airborne, and satellite measurements of fire radiative power—RxCADRE 2012. Special Issue, International Journal of Wildland Fire.

Dickinson, M.B., Kremens, R.L. (Submitted) Accessory publication 1 to Dickinson et al. Calibration procedures for single-band WASP LWIR data-incorporating spectral sensor response and atmospheric transmission. Special Issue, International Journal of Wildland Fire.

Ellison, L., Ichoku, C. (Submitted) Accessory publication 2 to Dickinson et al. Alternative methods for estimating fire radiative power from MODIS observations when fire boundaries are known. Special Issue, International Journal of Wildland Fire.

Zajkowski, T.J., Dickinson, M.B., Hiers, K.J., Holley, W., Williams, B.W., Paxton, A., Martinez, O., Walker, G.w. (Submitted) Testing and use of remotely piloted aircraft systems—RxCADRE 2012. Special Issue, International Journal of Wildland Fire.

Strand, T., gullett, B., Urbanski, S., O'Neill, S.O., Potter, B., Aurell, J., Holder, A., Larkin, N, Moore, M., Rorig, M. (Submitted) Smoke and emissions measurements— RxCADRE 2012. Special Issue, International Journal of Wildland Fire.

O'Brien , J., Loudermilk, L.E., Hornsby, B., Hudak, A.T., Bright, B.C., Dickinson, M.B., Hiers, K.J., Ottmar, R.D. (Submitted) High resolution infrared thermography measurements for capturing fire behavior in wildland fires—RxCADRE 2012. Special Issue, International Journal of Wildland Fire.

Appendix II: Other Publications and Published Abstracts

Aurell J, Gullett B (2013). Emission factors from aerial and ground measurements of field and laboratory forest burns in the southeastern U.S.: PM2.5, black and brown carbon, VOC, and PCDD/PCDF. *Environmental Science & Technology* **47**.

Butler BW (2014) Wildland firefighter safety zones: a review of past science and summary of future needs. *International Journal of Wildland Fire* **23**, 295-308.

Butler B, Jimenez D (2013) Ground based measurements of energy release and air flow in experimental and operational prescribed fires in grass and long leaf pine woodlands. **Special session—** *International Association of Wildland Fire 4th Fire Behavior and Fuels Conference, Raleigh, North Carolina,* 18-22 Feb 2013. (oral presentation, published abstract).

Cannon JB, O'Brien JJ, Loudermilk EL, Dickinson MB, Peterson, CJ (2014)The influence of experimental wind disturbance on forest fuels and fire characteristics. *Forest Ecology and Management* **330**: 294-303.

Clements C (2013) meteorological measurements during the Prescribed Fire Combustion and Atmospheric Dynamics research Experiment (RxCADRE). **Special session—** *International Association of Wildland Fire 4th Fire Behavior and Fuels Conference, Raleigh, North Carolina,* 18-22 Feb 2013. (oral presentation, published abstract).

Dickinson M, Schroeder W, Kremens R, Ichoku C, Ellison L, Kahn R, Zajkowski T, O'Brien J, Hudak A, Holley B, Martinez O, Parton A. (2013) Linking ground, airborne, and satellite measurements of fire power. Special Session - "A data set for fire and smoke model development and evaluation—the RxCADRE project. *International Association of Wildland Fire 4th Fire Behavior and Fuels Conference, Raleigh, North Carolina*, 18-22 Feb 2013. (oral presentation, published abstract).

Frankman D, Webb BW, Butler BW, Jimenez D, Harrington M (2013) The effect of sampling rate on interpretation of the temporal characteristics of radiative and convective heating in wildland flames. *International Journal of Wildland Fire* **22**, 168-173.

Frankman, D, Webb, BW, Butler, BW, Jimenez, D, Forthofer, JM, Sopko, P, Shannon, KS, Hiers, JK, Ottmar, RD (2012) Measurements of convective and radiative heating in wildland fires. *International Journal of Wildland Fire* **22**, 157-167.

Gullett B, Aurell J. (2013) Aerial and ground measurements of emissions from prescribed and laboratory forest burns. **Special session—** *International Association of Wildland Fire 4th Fire Behavior and Fuels Conference, Raleigh, North Carolina,* 18-22 Feb 2013. (oral presentation, published abstract).

Hiers J. (2013) prescribed fire combustion and atmospheric dynamics research experiment overview. Special session— *International Association of Wildland Fire 4th Fire Behavior and Fuels Conference, Raleigh, North Carolina,* 18-22 Feb 2013. (oral presentation, published abstract).

Hiers JK, O'Brien JJ, Mitchell RJ, Grego JM, Loudermilk EL. 2009. The wildland fuel cell concept: an approach to characterize fine-scale variation in fuels and fire in frequently burned longleaf pine forests*. International Journal of Wildland Fire*. **18**: 315-325.

Hudak AT, Ottmar R, Vihnanek B, Brewer N. Smith AMS, Morgan R. (2013a) The relationship of postfire white ash cover to surface fuel consumption. *International Journal of Wildland Fire* **22**: 580-585. doi: 10.1071/WF12150.

Hudak, AT, Ottmar, RD, Vihnanek RE, Wright, CS. (2013b) Relationship of postfire ground cover to surface fuel loads and consumption in longleaf pine ecosystems. *Proceedings of the 4th Fire Behavior and Fuels Conference*, Raleigh, North Carolina, 6 p.

Hudak, A, Satterberg, K, Dickinson, M, Kremens, R, Bright,B, Loudermilk, L, O'Brien, J, Strand, E, Ottmar, R. (2013) Fire radiative power and fire radiative energy estimated from multi-temporal airborne WASP thermal infrared images of active fire at Eglin Air Force Base, Florida. *American Geophysical Union Fall Meeting, San Francisco, California*, 9-13 Dec 2013. (poster, published abstract).

Hudak, A, Ottmar, R, Wright, C, Vihnanek, B, Dickinson, M, Kremens, R, Strand, E, Satterberg, K, Smith, A. (2013) Relationships between prefire fuels, fire radiative energy, and postfire ash. Special Session - A data set for fire and smoke model development and evaluation—the RxCADRE project*. International Association of Wildland Fire 4th Fire Behavior and Fuels Conference, Raleigh, North Carolina,* 18-22 Feb 2013. (oral presentation, published abstract).

Hudak, A, Dickinson M, Kremens, R., Bright, B, Loudermilk, L, Hornsby, B, O'Brien, J, Ottmar, R, Satterberg, K, Strand, E. (2014) Landscape-level relationship of fire radiative energy density to surface fuel loads. AFE/IAWF Conference on Large Wildland Fires, Missoula, MT, 19-23 May 2014. (oral presentation, published abstract).

Jimenez, D, Butler, B, Teski, C. (Abstract accepted) **Wind Flow Characterization Associated with Fire Behavior Measurements. Proceeding presentation** VII International Conference on Forest Fire Research in Coimbra, Portugal November 14-20.

Loudermilk, E.L., Achtemeier, G.L., O'Brien, J.J., Hiers, J.K. (in press). High-resolution observations of combustion in heterogeneous surface fuels. International Journal of Wildland Fire.

Loudermilk, E.L., O'Brien, J.J., Mitchell, R.J., Cropper Jr., W.P., Hiers, J.K., Grunwald, S., Grego, J., Fernandez, J.C. (2012) Linking complex forest fuel structure and fire behavior at fine-scales. International Journal of Wildland Fire. 21: 882-893.

Loudermilk, EL, Hiers, JK, O'Brien, JJ, Mitchell, RJ, Singhania, A, Fernandez, JC, Cropper Jr., WP, Slatton, KC(2009). Ground-based LIDAR: a novel approach to quantify fine-scale fuelbed characteristics. International Journal of Wildland Fire. 18: 676-685.

Mell, W. (2013) New scientific investments and approaches to fire behavior. **Special session—** *International Association of Wildland Fire 4th Fire Behavior and Fuels Conference, Raleigh, North Carolina,* 18-22 Feb 2013. (oral presentation, published abstract).

Nordgren, B. (2013) Data management of the prescribed Fire Combustion Atmospheric Dynamics Research Experiment (RxCADRE). Special session— *International Association of*

Wildland Fire 4th Fire Behavior and Fuels Conference, Raleigh, North Carolina, 18-22 Feb 2013. (oral presentation, published abstract).

O'Brien, J. (2013) Fine scale spatially explicit fire measurements. **Special session—** *International Association of Wildland Fire 4th Fire Behavior and Fuels Conference, Raleigh, North Carolina,* 18-22 Feb 2013. (oral presentation, published abstract).

Ottmar RD (2014) Wildland fire emissions, carbon, and climate: modeling fuel consumption. *Forest Ecology and Management* **317**, 4–50. doi: 10.1016/j.foreco.2013.06.010

Ottmar, RD. (2013) Ground measurements of fuel and fuel consumption from the Experimental and operational prescribed fires at Eglin Air Force base, Florida. **Special session—** *International Association of Wildland Fire 4th Fire Behavior and Fuels Conference, Raleigh, North Carolina,* 18-22 Feb 2013. (oral presentation, published abstract).

Ottmar, RD, Vihnanek, RE, Wright, CS, Hudak, AT (2013) Ground measurements of fuel and fuel consumption from experimental and operational prescribed fires at Eglin Air Force Base, Florida. *Proceedings of the 4th Fire Behavior and Fuels Conference*, Raleigh, North Carolina, 8 p.

Ottmar, RD (2012) A data set for fire and smoke model development and evaluation—RxCADRE. The Association for Fire Ecology (AFE) 5th International Fire Ecology and Management Congress, Portland, Oregon, 3-7 Dec 2012. (oral presentation, published abstract).

Potter, B, Curcio, G, Strand, T, O'Neill, S, Moore, M, Rorig, M, Larkin, S, Krull, C. (2013) The RxCADRE project: ground based emission and plume dynamics measurements. **Special session—** *International Association of Wildland Fire 4th Fire Behavior and Fuels Conference, Raleigh, North Carolina,* 18-22 Feb 2013. (oral presentation, published abstract).

Prichard, S, Ottmar, R. (2014) State of Fire Behavior Models and their Application to Ecosystem and Smoke Management Issues. *Proceedings of the International Smoke Symposium,* Aldephi, Maryland, 54p.

Seielstad, C, Rowell, E. (2013) Ground LiDAR fuel measurments of the Prescribed Fire Combustion and Atmospheric Dynamics research Experiment (RxCADRE). **Special session—** *International Association of Wildland Fire 4th Fire Behavior and Fuels Conference, Raleigh, North Carolina,* 18-22 Feb 2013. (oral presentation, published abstract).

Urbanski, SP. (2014). RxCADRE 2012: Airborne measurements of smoke emission and dispersion from prescribed fires. Fort Collins, CO: Forest Service Research Data Archive. http://dx.doi.org/10.2737/RDS-2014-0015

Urbanski, S. (2013) Airborne measurements of smoke chemical composition, plume rise, and smoke dispersion from operational prescribed fires in Florida. **Special session—** *International Association of Wildland Fire 4th Fire Behavior and Fuels Conference, Raleigh, North Carolina,* 18-22 Feb 2013. (oral presentation, published abstract).

Walker, G, Cervensten, B, Cahill, C. (2013) merging unmanned aircraft collected aerial imagery to map the 2012 RxCADRE prescribed burn plots. **Special session—** *International Association of Wildland Fire 4th Fire Behavior and Fuels Conference, Raleigh, North Carolina,* 18-22 Feb 2013. (oral presentation, published abstract).

Zajkowski, T, Hiers, J, Paxton, A, Martinez, O, Holley, W, Dickinson, M. (2013). Supporting RxCADRE fire measurements with unmanned aircraft systems. **Special session—** *International Association of Wildland Fire 4th Fire Behavior and Fuels Conference, Raleigh, North Carolina,* 18-22 Feb 2013. (oral presentation, published abstract).

Appendix III: Other Deliverables

4th Fire Behavior and Fuels Conference, February 2013

A special session was held at the 4th Fire Behavior and Fuels Conference held in Raleigh, NC, February 17-22, 2013. Kevin Hiers and Roger Ottmar chaired the special session. The presentation resulted in two proceedings papers and an extended abstract being published. Presentations in order included:

- **Kevin Heirs (Session Co-Chair)**—RxCADRE overview
- **Bryce Nordgren—**Data management
- **Roger Ottmar (Session Chair)**—Fuel loading and fuel consumption measurements
- **Carl Seielstad—**Ground lidar fuel measurements
- **Andy Hudak—**Surface cover fraction measurements
- **Craig Clements**—Meteorological measurements
- **Matthew Dickinson—**Linking ground, airborne, and satellite measurements of fire power.
- **Bret Butler—**Surface fire behavior measurements
- **Joseph O'Brien—**Fire effect measurements
- **Greg Walker**—Measurements from the quad copter and G2R unmanned aerial systems
- **Tom Zajkowski**—Measurements from the Scout unmanned aerial system
- **William (Ruddy) Mell—**New approaches to fire behavior modeling
- **Brian Potter—**Emission and plume dynamic measurements
- **Shawn Urbanski—**Airborne smoke measurements
- **Brian Gullett**—Aerial and ground measurements of emissions

International Smoke Symposium, October 2013

A special session was held at the International Smoke Symposium, October 24, 2013 in Adelphi, MD entitled: "State of Fire Behavior Models and their Application to Ecosystem and Smoke Management Issues". Roger Ottmar and Kevin Hiers chaired the session and Susan Prichard captured a summary of each presentation and has drafted a manuscript to be published as a proceedings paper by the IJWF. Many of the RxCADRE scientists (italicized in this list) presented during this session. Titles of presentations and presenters include:

1. Overview of Funding Sources SERDP/ESTCP and JFSP and their research/demonstration priorities- John Hall and John Cissel
2. State of fuel characterization and consumption for wildland fire planning – Roger Ottmar/Carl Seielstad
3. State of smoke dispersion modeling for wildland fire planning – *Sim Larkin/Susan O'Neill*
4. Wildland fire smoke model validation needs – *Tim Brown/Craig Clements*
5. State of fire behavior modeling —*Mark Finney*
6. Future of coupled fire-atmospheric modeling – *Ruddy Mell/Rod Linn*
7. Micrometeorology links to combustion physics and smoke dispersion dynamics– *Craig Clements*/*Scott Goodrick*
8. State of fire modeling for ecosystem management-*Kevin Hiers*
9. Research and model validation gaps for understanding fire effects- *Matthew Dickinson/Joseph O'Brien*

International Smoke Symposium Proceedings Paper

Prichard, Susan, Ottmar, Roger. In press. State of fire behavior models and their application to ecosystem and smoke management issues. *Proceedings of the International Smoke Symposium.* Aldephi, MD: International Association of Wildland Fire. 54 p.

Numerical Wildfires 2013, Cargese, Corsica

(http://anridea.univ-corse.fr/cargese2013/)

1. Round Table: Experiments at large scale (Chair Craig Clements)
   - Instruments
   - available datasets

2. Wildland fire experiments at the field scale, *Craig Clements* (Invited)

Appendix IV: Data Archive

The majority of the 128 datasets and accompanying metadata have been uploaded to the Forest Service Research Data Archive. Several (5) datasets have been published and are available for download by managers, scientists and others. We expect all datasets will be available by December 31, 2014. However, several scientists may opt to wait on the official release (published) of the datasets until the IJWF special issue is published.

Scientist	Discipline	Dataset years	Datasets to be sent to national archive	Datasets awaiting comments from archivist	Dataset comments reconciled and back to archivist	Datasets published	Comments
Ottmar	Fuels	2008, 2011, 2012			5		Datasets ready for publication upon notification by archivist
Seielstad	Fuels-lidar	2011, 2012	30				Datasets scheduled to be uploaded to national archive by October 10
Clements	Meteorology	2012		2			Datasets transferred to national archive and waiting for comments from the archivist.
Butler	Fire behavior	2011, 2012	6	6			Datasets transferred to national archive and waiting for comments from the archivist.
Zajkowski	Remote piloted aircraft systems	2012	4				Datasets scheduled to be uploaded to national archive by October 10
Dickinson	Energy	2011, 2012		3			Datasets transferred to national archive and waiting for comments from the archivist.
Hudak	Fuels, Energy	2008, 2011, 2012			60		Datasets ready for publication upon notification by archivist
Potter	Smoke	2012		3			Datasets transferred to national archive and waiting for comments from the archivist.
Urbanski	Smoke	2012				5	Datasets published
O'Brien	Thermography /Effects	2011, 2012		4			Data transferred to national archive and waiting for comments from the archivist.
Total			40	18	65	5	

Appendix V: Undergraduate and Graduate Students

Scientist and discipline	Undergraduate	Masters	Doctorate	Non-degree
Ottmar (Fuels)	1	5	2	0
Clements (Met)	2	3	0	1
Butler (FB)	0	1	0	0
Dickinson (Energy)	0	0	0	0
Potter (Emissions)	0	0	0	0
O'Brien (FB and effects)	1	1	0	0
Total	**3**	**10**	**2**	**1**