Measurements, datasets and preliminary results from the RxCADRE project

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Abstract

The availability of integrated, 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. To help fill this gap, the Prescribed Fire Combustion and Atmospheric Dynamics Research Experiment (RxCADRE) project provided an opportunity to collect multi-scale data before, during, and after the same prescribed burns, share data among scientists, and place the datasets in a globally accessible data archive. The RxCADRE project team collected fuel and fire data on seven operational prescribed fires in 2008 and 2011 in longleaf pine ecosystems in Florida and Georgia. In 2012, the Joint Fire Science Program sponsored a continuation and expansion of this effort to include six small replicate and three operational prescribed burn blocks in grass, shrub, and forested ecosystems in Florida. During 2013 and 2014, data were quality assured, reduced, analyzed and formatted for placement in the archive. This overview of this special issue on the RxCADRE project summarizes nine companion papers on the data collection and preliminary results from six discipline areas of research. The goal is to provide a better understanding of the RxCADRE project and the datasets produced.

Summary

The Prescribed Fire Combustion and Atmospheric Dynamics Research Experiment (RxCADRE) project provides integrated, quality-assured fuel, atmospheric, fire behavior, energy, smoke, and fire effects dataset to evaluate fire models and test theory. In a series of nine articles we discuss data collection and preliminary results for each dataset.

Background

The availability of integrated, quality-assured fuel, atmospheric, fire behavior, energy, smoke, and effects data are limited and hinders our ability to evaluate fire models and tackle fundamental fire science questions (Cruz and Alexander 2010; Alexander and Cruz 2012). 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—pooled their operational and in-kind resources and collaboratively instrumented and collected 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 (Fig. 1). This effort was termed the Prescribed Fire Combustion and Atmospheric Dynamics Research Experiment (RxCADRE). This project encouraged participating fire 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 between 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 and three operational prescribed burn blocks in longleaf pine ecosystems on Eglin Air Force Base in northern Florida (JFSP 2012) (Fig. 1). The extra support funded data collection for RxCADRE 2012; data reduction and product preparation from the 2008, 2011 and 2012 RxCADRE project datasets; design of a data management system; and the transfer of the data into a permanent and public data archive. Nearly 30 scientists and technicians participated in the 2008 and 2011 efforts, and over 90 scientists and technicians participated in the 2012 project. Eglin Air Force Base was selected for the 2012 RxCADRE project because of its history of proven management support, availability of appropriate research sites, the high probability that experimental fires would occur, controlled air space for deployment of remotely piloted aircraft systems (RPAS) (also known as unmanned aircraft systems, (UAS)) along with manned aircraft and tethered balloons, and data acquisition and processing support.

The RxCADRE project organized its data collection around a thematic stepwise structure with six major research discipline areas (fuel, meteorology, fire behavior, radiative power and energy, emissions, and fire effects) and their associated variables (Fig. 2). The burn unit selection targeted simple grass, grass/shrub, and managed southern pine forest fuelbeds at both small (ca. 100 m^2) and prescription operational scales (ca. 1000 m^2). Each discipline employed a series of data collection techniques ranging from simple clipping and weighing fuel for biomass to mapping fire progression with both piloted and RPAS. Once collected, data were reviewed, reduced, analyzed, and linked to a descriptive set of metadata. Data were made available on a globally accessible archive maintained by the US Department of Agriculture, Forest Service Research (2014). Data are organized by discipline areas and have a table of contents with linkages to specific data locations.

In a series of nine articles in this issue, we discuss data collection and preliminary results and products organized by these six disciplines:

1. Pre- and postfire fuel characterization
2. Fire and atmospheric interactions
3. Fire behavior
4. Radiative power and energy
5. Emissions ground and aerial sampling
6. Fire behavior and effects

Although the majority of the papers discuss only the RxCADRE 2012 project, one paper presents data from 2008, 2011, and 2012 experiments (Ottmar *et al*. this issue) and one paper presents data from the 2011 and 2012 experiments (Hudak *et al.* this issue).

Pre- and postfire fuel characterization (Discipline 1)

Successful modeling of fire behavior, radiant energy, and fire effects such as soil heating, tree mortality, emissions, and plume rise depend on the characterization of the fuelbed components (e.g. trees, shrub, grass, woody debris, litter, and duff), and the amount and duration of the fires' consumption of each of these components. Techniques to describe and measure fuel and fuel consumption ranged from traditional destructive sampling to remotely sensed methods that can cover larger areas. Fuelbeds, and the consumption of the fuelbed components, are extremely complex and highly variable across the landscape (Keane *et al*. 2012); as the next generation wildland fire behavior models that simulate 3-dimensional fire propagation become operational (Linn *et al.* 2002; Mell *et al.* 2007), new methods and techniques are required to characterize fuel and fuel consumption (Ottmar 2014; Weise and Wright 2014). Further, pre-and postfire datasets are needed to evaluate models currently in use, develop new fire models, and test theory.

Ottmar *et al.* (this issue) offers a review of surface fuel data (loading, consumption, and moisture content) and postfire cover fractions of remaining fuel collected during the 2008, 2011, and 2012 RxCADRE field experiments in mixed herbaceous, shrub, and forest covered longleaf pine ecosystems in the southeastern United States. Rowell and Seielstad (*this issue*) describe methods for acquiring and processing high resolution terrestrial lidar data across 0.04-ha plots and 2-ha blocks of the mixed herbaceous and shrub fuel during the 2012 RxCADRE campaign, quantifying data accuracies and biases. Field sampling protocols were uniquely designed with a combination of clip plots and line-intersect inventory to provide the high resolution fuel information specifically requested by the terrestrial lidar scientists, and by fire modelers for software evaluation and modification. Plots were scanned by the terrestrial lidar and compared to measured results. The resultant fuel heights corresponded closely with field measurements of height. A translation of fuel height distributions to specific attributes will be necessary to maximize the utility of the data for fire modeling.

Fire and atmospheric interactions (Discipline 2)

The interactions between ambient fire weather conditions (e.g., wind speed, relative humidity, and temperature) and the propagation of fire is called *fire and atmospheric interactions* (Potter 2012). Most meteorological sampling for fire behavior prediction is collected at very coarse resolutions with standard weather stations often several kilometers apart (Horel and Dong 2010). As next-generation wildland fire behavior models emerge, there will be a need to better understand and predict fine-scale, near-surface weather conditions. Currently, FireFlux (Clements *et al*. 2007) data remains the standard for the fine-scale evaluation of coupled fire-weather models (Achtemeier 2013; Kochanski *et al*. 2013; Filippi *et al*. 2013). However, these do not include fire behavior measurements to compare with the fine-scale meteorology data collected. Clements *et al.* (this issue) describe fine-scale meteorological measurements during six small replicate block burns and 2 large operational block burns as part of the RxCADRE experiment in 2012. Preliminary results indicate that meteorological measurements captured the fire weather and fire-atmospheric interactions at the fire front in enough detail to define meteorological influences on fire propagation. The meteorological measurements provide another dataset to advance our understanding of the dynamics of fire-atmosphere interactions and fire behavior. Because the RxCADRE project also involved fire behavior measurements (Butler *et al.* this issue), future data analysis can merge meteorological and fire behavior data.

Fire behavior (Discipline 3)

The transfer of energy generated from the combustion of fuel drives wildland fire intensity and rate of spread (Anderson 1969). However, the quantification and variability of energy transport across time and space is a poorly documented element of wildland fire science. Studies have explored energy transport in wildfires for years both in the lab and in the field, but without datasets for the evaluation and testing of theory and models, the science of energy transfer and related fire intensity and rate of spread will stagnate and current fire behavior models in practice today will remain untested and evaluated.

Butler *et al.* (this issue) discusses data collection and analysis of time-resolved convective and radiative heat fluxes, air temperatures, vertical and horizontal velocities and flame emissive power from both small replicate and operational burn blocks burned during the 2012 RxCADRE experiment. The paper also correlates the measurements with fire, fuel, and environmental conditions. We intend for these measurements inform new understanding about the relative contribution of radiative and convective heating to overall energy budget during wildland fires under a variety of environmental and fuelbed conditions and to provide fire behavior data that can be integrated with other RxCADRE datasets from the same fire.

Fire radiative power and energy (Discipline 4)

Fire radiative power (FRP) from the burning of biomass during wildland fires directly relates to the combustion process and, if it can be adequately measured at a wide range of spatial extents and resolution, it may provide an important means to assess fire behavior, plume rise, and other wildland fire characteristics important to managing fire. Ground, airborne, and satellite-based sensors show great promise as methods for long-term monitoring of active fires, fuel consumption, and smoke production (Schroeder *et al*. 2013). The multi-scale FRP datasets provided by this project, along with time-integrated fire radiative energy (FRE) datasets that can be directly associated with fuel consumption, will provide some of the fundamental knowledge needed to evaluate models and measurement methods.

Dickinson *et al.* (this issue) describes four independent measurements of FRP over entire prescribed fires including (1) measurements from a boom-mounted, obliquely-oriented infrared camera; (2) measurements derived from a combination of data from RPAS-mounted infrared cameras and tower-mounted nadir radiometers; (3) measurements from the Wildfire Airborne Sensor Platform (WASP) imaging system mounted on a piloted, fixed-wing aircraft; and (4) measurements from the VIIRS and MODIS satellite-borne sensors. All measurement reported were from the RxCADRE 2012 experiments and demonstrated that these methods are feasible during experimental fire operations. A comparison of measurement methods reveals uncertainty and bias and the need to develop “gold standard” measurements (see Hudak *et al.* this issue). As well, a better understanding of measurement methods and the fundamentals of fire spectral radiation and flame front heat budgets are required to support future campaigns.

Hudak *et al.* (this issue) integrated repeated FRP measures to estimate FRE from several ground-based sensors and WASP datasets collected in the RxCADRE 2011 and 2012 campaigns. These FRE measures are then compared to surface fuel loads predicted from airborne lidar across 2011 and 2012 burn blocks, both forested and non-forested. The paper provides a basic interpretation of these datasets and discusses issues of aggregation, scale and sampling bias.

Remote Control Aircraft Systems (Disciplines 3 and 4)

RPAS are expected to provide timely infrared, visible, and other passive imagery in support of both wildand fire operations and research. However, RPAS have received limited testing and demonstration as to their capabilities (Hinkley and Zajkowski 2011). Zajkowski *et al.* (this issue) describe the RPAS and sensors deployed on them during this project. The RxCADRE experiment successfully demonstrated the use of the RPAS as an operational support tool. The RPAS flew over 50 sorties during missions involving multiple unmanned and manned aircraft and provided real time situational awareness to Incident Command staff. Time aloft, size, and required operations infrastructure ranged from the rapidly-deployable, short duration quadcopter (Aeryon Scout) to fixed-wing aircraft of moderate duration (G2R) and long-duration Scan Eagle. Research-related data from the RPAS are used in Dickinson *et al.* (this issue) and show promise for other, future research application. Development of small infrared sensors deployable on small RPAS that provide more quantitative data during wildland fire imaging are essential for research application. As well, orthorectification challenges limit current utility of RPAS data.

Emissions ground and aerial (Discipline 5)

In many regions around the world, fire is an essential ecological process, emitting particulate and gaseous compounds (Strand *et al.* 2011; Aurell *et al.* 2013). Understanding the impact of these emissions and evaluating models to better predict smoke impacts on global climate and regional air quality requires quantifying biomass burning emissions. Strand *et al*. (this issue) presents ground, airplane and tethered aerostat time-resolved smoke measurements of CO_2, CO, CH_4, and particulate measurements of optical properties and photographic imaging on three large prescription fire operational burn blocks during the 2012 RxCADRE research campaigns. Distinctions were observed between aerial and ground-based measurements, with aerial measurements exhibiting smaller particle size distributions and particulate matter emission factors, likely due to particle settling. Black carbon emission factors were similar for both burns and were highest during the initial flaming phase. On average, the particles from the forest fire were less light absorbing than those from the grass fires due to the longer duration of smoldering combustion with the forest biomass. CO and CH_4 emission factors were over twice as high for the forest burn compared to the grass burn, corresponding with a lower modified combustion efficiency and greater smoldering combustion. This dataset was collected for use by all who require data to test theory, develop fire behavior models, and to evaluate smoke prediction models.

Fire behavior and effects (Discipline 6)

Total energy release and the duration of that release during wildland fire is fundamentally important for the understanding and predicting both first- and second-order biological and ecological effects. The energy release is inherently difficult to measure and has been limited to ocular estimates, point measurements, or relative indices of intensity (Kennard et al 2005). However, recent advances in infrared (IR) thermography have made it possible to measure the FPR across time and space (Maldague 2001; Meléndez *et al*. 2010).

O'Brien *et al*. (this issue) describe methods for capturing and analyzing spatially and temporally infrared temperature data during the 6 small, replicate burn blocks during the RxCADRE 2012 campaign. The infrared data are compared at both the fine (1-4 cm^2) and moderate (1 m^2) scales with specific analysis of fine-scale spatial heterogeneity of FRP and FRE release. The paper concludes that IR thermography offers an unprecedented opportunity to provide an effective means to link the combustion environment of wildland fires with both post fire processes and fire modeling efforts. The accurate spatial measurements of heat over time can connect fire energy to post fire processes such as soil heating, plant mortality, and tissue damage as well as providing valuable data on the combustion environment for plume dynamic models (Achtemeier 2013).

Conclusion

As fire models are being scrutinized for their predictive capabilities, and as the need to better understand fire and its effects increases, it is important to have available quality-assured datasets for use by scientists, managers and anyone with an interest in wildland fire. This was the main objective behind the RxCADRE project that has led to a series of fire and fuel datasets that can be used to test theory and evaluate fire models. It was also very evident that the RxCADRE concept was extremely efficient with many aspects of fire measured on the same experimental blocks, allowing synergy between the various disciplines. The papers presented in this special issue only touch the surface of the datasets and products that will become available over time and the analyses that synergize as a result of this project.

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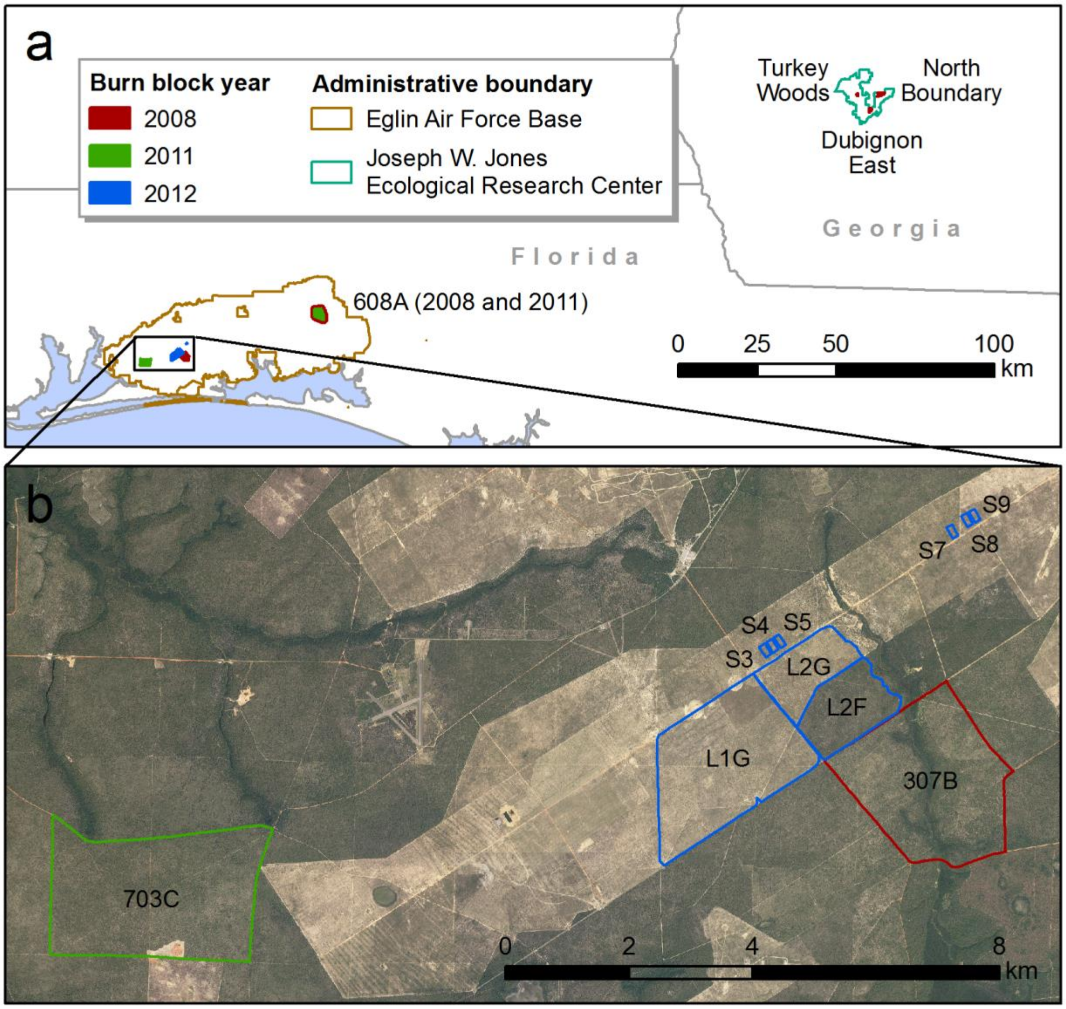

Fig. 1. (a) Location of the 16 RxCADRE experimental prescribed fires conducted in 2008, 2011 and 2012, and (b) small replicate and large operational burn blocks that were established for the 2012 RxCADRE research project located on the B70 bombing range at Eglin Air Force Base, Florida. Only large operational burn blocks were established for the RxCADRE research burns in 2008 and 2011.

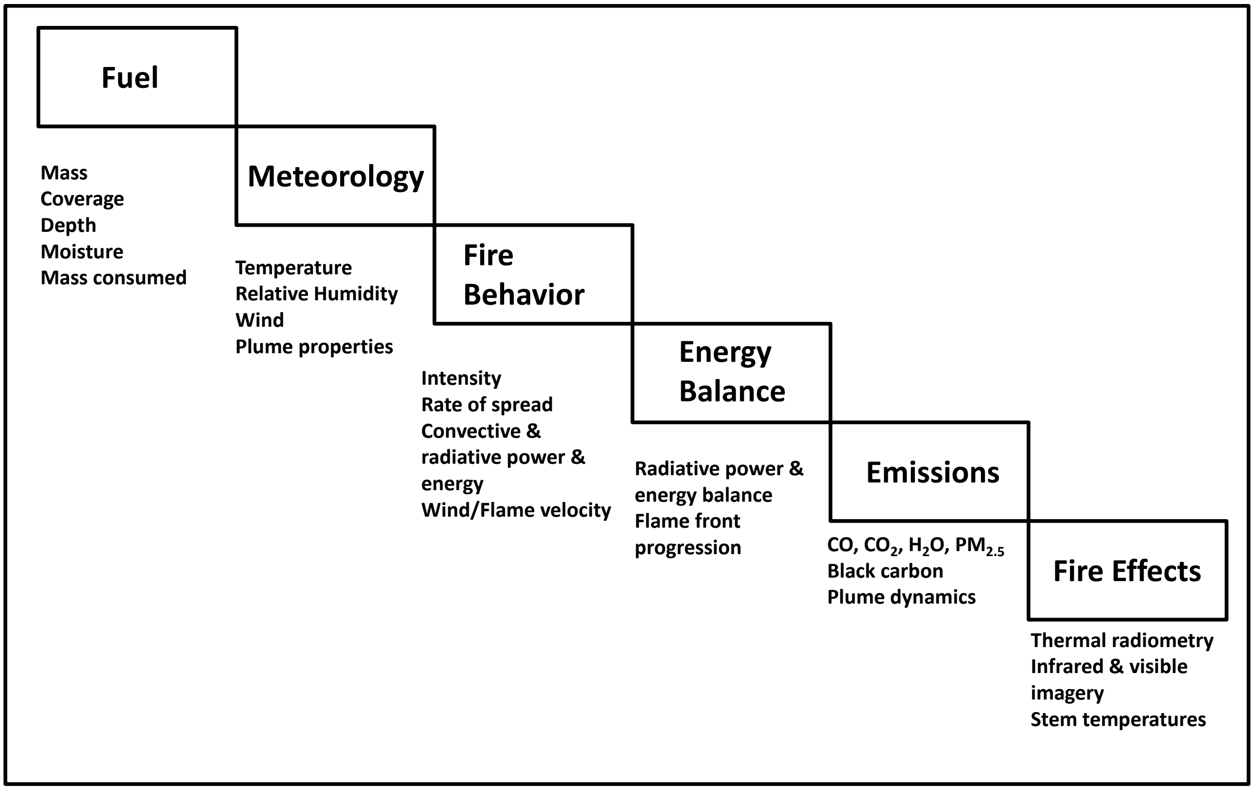

Fig. 2. Diagram of research disciplines and a partial list of associated variables to be measured for the RxCADRE project.