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Measurements, datasets and preliminary results from the RxCADRE project – 2008, 2011 and 2012

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Abstract. The lack of independent, quality-assured field data prevents scientists from effectively evaluating and advancing wildland fire models. To rectify this, scientists and technicians convened in the southeastern United States in 2008, 2011 and 2012 to collect wildland fire data in six integrated core science disciplines defined by the fire modelling community. These were fuels, meteorology, fire behaviour, energy, smoke emissions and fire effects. The campaign is known as the Prescribed Fire Combustion and Atmospheric Dynamics Research Experiment (RxCADRE) and sampled 14 forest and 14 non-forest sample units associated within 6 small replicate (<10 ha) and 10 large operational (between 10 and 1000 ha) prescribed fires. Precampaign planning included identifying hosting agencies receptive to research and the development of study, logistics and safety plans. Data were quality-assured, reduced, analysed and formatted and placed into a globally accessible repository maintained by the US Forest Service Research Data Archive. The success of the RxCADRE project led to the commencement of a follow-on larger multiagency project called the Fire and Smoke Model Evaluation Experiment (FASMEE). This overview summarises the RxCADRE project and nine companion papers that describe the data collection, analysis and important conclusions from the six science disciplines.

Additional keywords: fire behaviour, fire effects, fire model evaluation, fire weather, fuel, remote-piloted aircraft system, smoke.

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Background

The lack of independent, quality-assured data prevents scientists from effectively evaluating predictions and uncertainties in fire models used by land managers (Cruz and Alexander 2010; Alexander and Cruz 2013). To help fill this void, the Prescribed Fire Combustion and Atmospheric Dynamics Research Experiment (RxCADRE) was initiated to provide novel and critical measurement techniques and observational data necessary to evaluate, validate and advance fire and smoke modelling systems. The goal was to encourage scientists to integrate processes

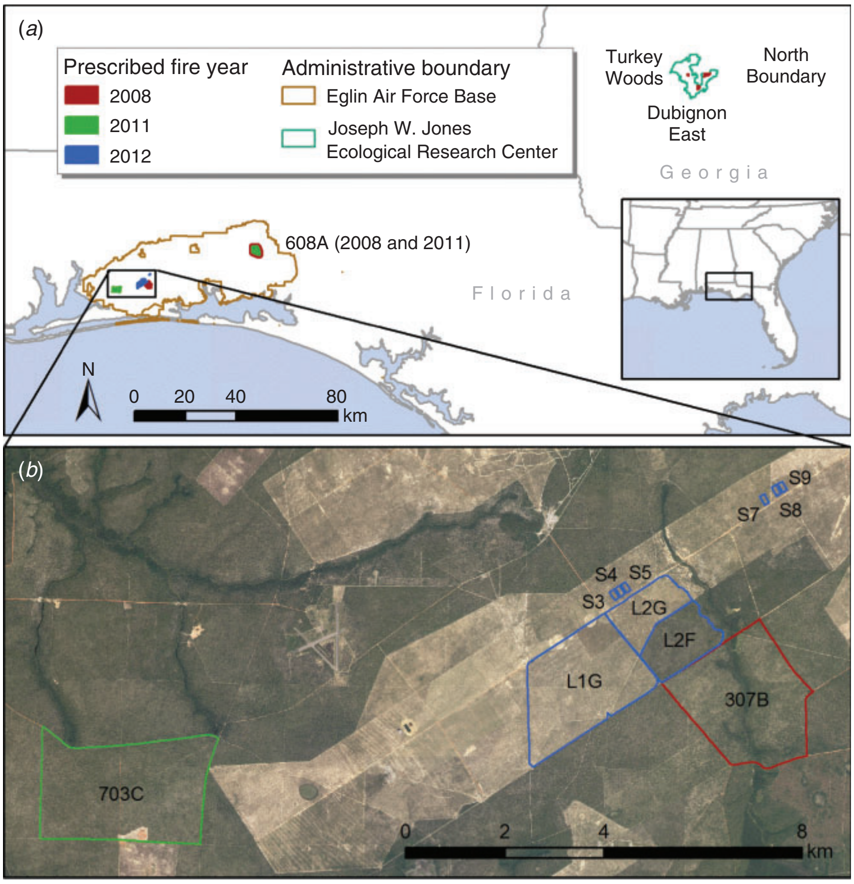

Fig. 1. (*a*) Location of the 16 RxCADRE experimental prescribed fires conducted in 2008, 2011 and 2012; (*b*) small replicate (S) and large operational (L) prescribed fires were selected for the 2012 RxCADRE research project located on the B70 bombing range at Eglin Air Force Base, Florida. Only large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

for collecting complementary research data across fire-related disciplines before, during and after the active burning periods of prescribed burns. Seven operational prescribed fires in longleaf pine (*Pinus palustris*) ecosystems were monitored in 2008 and 2011 at Eglin Air Force Base in north-west Florida and in 2008 at the Joseph W. Jones Ecological Research Center in south central Georgia (Fig. 1). In 2012, the Joint Fire Science Program (JFSP) validated and formalised this effort by funding a continuation and expansion of RxCADRE to include six small replicate and three large operational prescribed burns in longleaf pine ecosystems on Eglin Air Force Base (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 archive. Nearly 30 scientists, technicians and land managers participated in the 2008 and 2011 efforts and over 90 scientists, technicians and land managers participated in the 2012 project.

The 2008, 2011 and 2012 RxCADRE relied on hosting agencies receptive to research on prescribed burn sites that met the requirements of the study design (Fig. 2). The host agency provided logistic and coordination support. For example, Eglin Air Force Base was selected for the 2012 RxCADRE project because of its history of proven management support of fire science projects, availability of appropriate research sites, high probability that experimental fires would occur, data acquisition and processing support, and controlled air space for deployment of remotely piloted aircraft systems (RPAS, often referred to as drones), manned aircraft and tethered balloons.

RxCADRE organised its data collection around six core research discipline areas and their associated variables (fuel, meteorology, fire behaviour, energy, smoke emissions and fire effects) as defined by the fire modelling community (Fig. 2). Additional precampaign planning included the development of one study plan for each science discipline with a process diagram on how the data collected would be integrated between disciplines, an incident action plan that included logistics, safety and communications, and a data management plan. Because all associated variables for each discipline were measured on the same experimental burns, there was a synergy developed between the disciplines as all data were shared among scientists.

The burn unit selection targeted simple grass, grass-shrub and frequently burned southern pine forest fuel beds at both small replicate (~100 m^2) and large operational scales (~10–1000 ha) in 2012 and only large operational scales (~50–1200 ha) in 2008

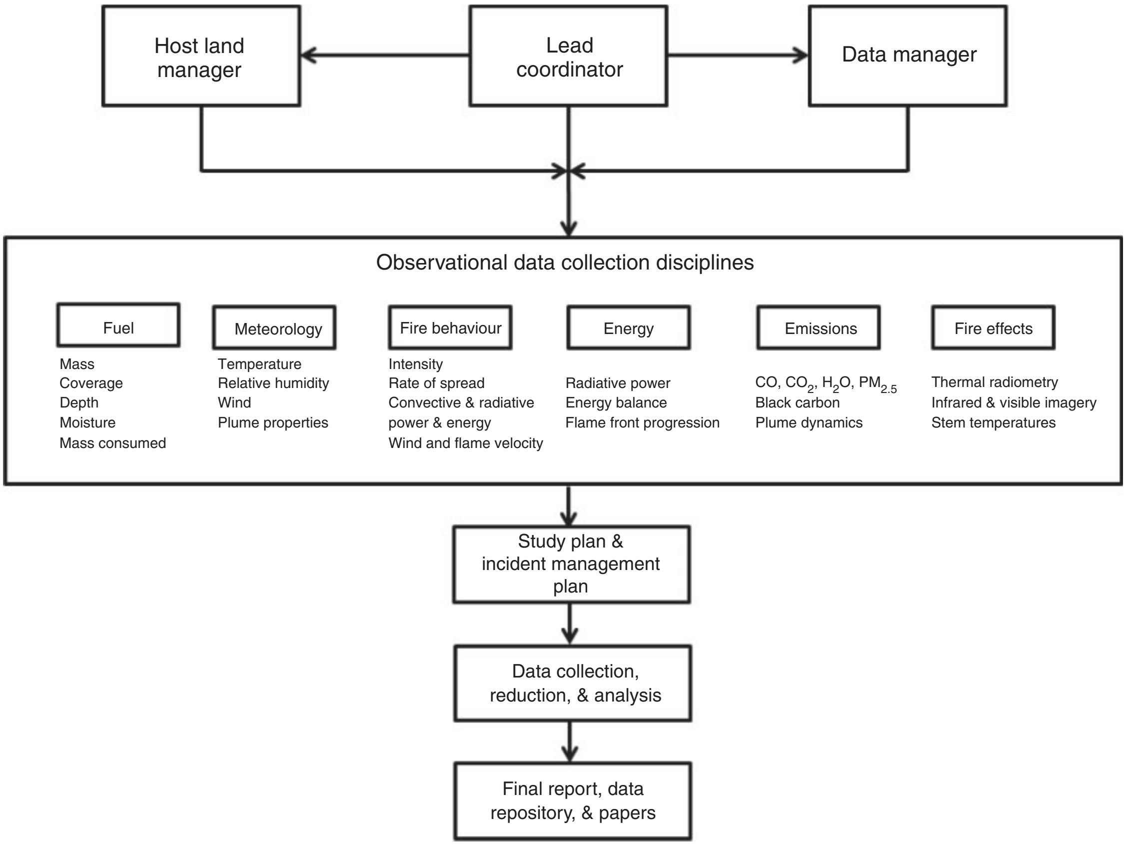

Fig. 2. Process diagram with research disciplines and a partial list of associated variables measured for the RxCADRE project.

Table 1. RxCADRE 2008, 2011, and 2012 research burn information including location (Eglin Air Force Base (EAFB) or Joseph W. Jones Ecological Research Center (JJERC)), burn date, cover type (forest or non-forest) and size

Prescribed burn ID	Location	Burn date	Cover type	Size (ha)
2008_608A	EAFB	1 Mar 2008	Forest	828
2008_307B	EAFB	2 Mar 2008	Forest	546
2008_TurkeyWoods	JJERC	3 Mar 2008	Forest	38
2008_NorthBoundary	JJERC	5 Mar 2008	Forest	178
2008_DubignonEast	JJERC	6 Mar 2008	Forest	76
2011_703	EAFB	6 Feb 2011	Forest	668
2011_608A	EAFB	9 Feb 2011	Forest	828
2012_S3	EAFB	1 Nov 2012	Non-forest	2
2012_S4	EAFB	1 Nov 2012	Non-forest	2
2012_S5	EAFB	1 Nov 2012	Non-forest	2
2012_L1G	EAFB	4 Nov 2012	Non-forest	454
2012_S7	EAFB	7 Nov 2012	Non-forest	2
2012_S8	EAFB	7 Nov 2012	Non-forest	2
2012_S9	EAFB	7 Nov 2012	Non-forest	2
2012_L2G	EAFB	10 Nov 2012	Non-forest	127
2012_L2F	EAFB	11 Nov 2012	Forest	151

and 2011. Fuels, meteorology, fire behaviour, energy and fire effects data were collected at both scales whereas the smoke emissions data were collected only at the large operational scale. Each discipline employed a series of both standard and experimental data collection techniques ranging from simple clipping and weighing fuel for biomass to ground-based LiDAR fuel characterisation and mapping fire progression with both piloted aircraft systems and RPAS.

Once collected, data were reviewed, reduced, analysed and linked to a descriptive set of metadata. An internal centralised data storage facility available to participants was designed to accommodate all data from 2008, 2011 and 2012 RxCADRE campaigns. The data and metadata were then made available on a globally accessible archive maintained by the US Department of Agriculture Forest Service Research (2014); http://www.fs.usda.gov/rds/archive/, accessed 9 November 2015). Data are organised by discipline areas and have a table of contents with linkages to specific data locations.

This overview for the RxCADRE special issue discusses the overall project and the data collection, preliminary results and conclusions from nine companion papers organised by the six core science disciplines.

Study area and experimental design

Six small replicate and 10 large operational prescribed fires were sampled at the Joseph W. Jones Ecological Research Center (JJERC) and Eglin Air Force Base (Eglin AFB) in the south-eastern USA in 2008, 2011 and 2012 (Fig. 1, Table 1). The 16 prescribed fires ranged in size from 2 to 828 ha. Within each of the three large operational burns in 2012, three highly instrumented plots (HIPs) were established that were 0.04 ha in size.

Fig. 3. (*a*) Forest, and (*b*) non-forest burn areas of the RxCADRE project.

The JJERC is located in the Lower Coastal Plain and Flatwood Province of southwestern Georgia and characterised as humid subtropical, with a mean annual precipitation of 131 cm distributed evenly throughout the year and mean daily temperatures ranging from 21 to 34°C in summer and from 5 to 17°C in winter (Goebel *et al.* 1997). The longleaf pine (*Pinus palustris*)–wiregrass (*Aristida stricta*) ecosystems have been maintained using regular understorey prescribed burning (average return interval of 3 to 4 years) since the 1930s (Hendricks *et al.* 2002). Eglin AFB, in the panhandle of western Florida, is characterised by large areas of xeric longleaf pine sand-hill forest and grass and grass–shrub-dominated military training areas kept in a tree-free state. The climate is subtropical, with warm, humid summers and mild winters. Mean annual temperature is 19.8°C, with a mean annual precipitation of 158 cm, most of which falls from June through September (Overing *et al.* 1995).

All of the 2008 and 2011 prescribed burns at both locations were forested (Table 1). Longleaf pine dominated the overstorey, with turkey oak (*Quercus laevis*) or saw palmetto (*Serenoa repens*) occurring in an understorey matrix of wiregrass or other grasses (Fig. 3*a*). Of the nine prescribed burns conducted in 2012, one was in a longleaf pine forest and the eight remaining burns were non-forest with a mix of grass and shrubs, predominantly turkey oak (Fig. 3*b*). All prescribed burns had been treated with fire every 1 to 4 years to meet several management objectives. The 10 large operational burns were ignited by land-management personnel with drip torches either while walking or driving an all-terrain vehicle (2012 and 2008) or by a helicopter with incendiary spheres (2008 and 2011) and typically burned using a strip heading or flanking fire. The six replicate burns were hand-ignited with a single strip of fire using a drip torch producing a single head fire. All burns followed established prescription criteria for meeting land-management objectives; no burning occurred under extremely dry or wet conditions. Prescription weather parameters included 10-h fuel moisture between 4 and 20%, 1000-h fuel moisture between 15 and 40% and wind <8.9 m s^{-1}.

All science discipline teams established ground plots and instrumentation on the perimeter or within each research burn sample unit. Piloted aircraft, RPAS and an aerostat balloon system flew over each research burn or near the perimeter to capture visible and infrared imagery, scan with LiDAR or sample emissions. More detailed information on experimental set-up can be obtained from individual papers in the special issue.

Fuels (Discipline 1)

Successful modelling of fire behaviour, radiant energy and fire effects such as soil heating, tree mortality, emissions and plume rise depends on the characterisation of the fuel-bed 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. Fuel beds, and the consumption of the fuel-bed components, are extremely complex and highly variable across the landscape (Keane *et al.* 2012). As the next-generation wildland fire behaviour models that simulate three-dimensional fire propagation become operational (Linn *et al.* 2002; Mell *et al.* 2007), new methods and techniques are required to characterise fuel and fuel consumption (Ottmar 2014; Weise and Wright 2014). Further, pre- and post-fire datasets are needed to evaluate models currently in use, develop new fire models and test theory.

Ottmar *et al.* (2015) offer a review of surface fuel data (loading, consumption and moisture content) and post-fire cover fractions of remaining fuel collected in the southeastern United States on 14 forest and 14 non-forest sample units within 6 small replicate and 10 large operational prescribed fires conducted for the RxCADRE project during 2008, 2011 and 2012. The sample units were in mixed herbaceous, shrub and forested longleaf pine ecosystems. 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 (Rowell *et al.* 2015) and fire modellers for fire model evaluation and modification. Twenty-five pre-fire and 25 post-fire fuel plots were alternately situated at 10-m intervals around each small replicate prescribed burn, 30 pre-fire and 30 post-fire fuel plots were alternately located at 50-m intervals along three approximately parallel transects on the large operational prescribed burns and 9 or 12 pre-fire and 9 or 12 post-fire clip plots were alternatively situated at 2.5-m intervals around the periphery of each 20×20-m HIP during the 2012 RxCADRE campaign (Ottmar *et al.* 2015; Figs 4, 5*a*). Fuel loading and fuel consumption averaged 6.8 and 4.1 Mg ha^{-1} respectively in the forested units and 3.0 and 2.2 Mg ha^{-1} in the non-forest units. Post-fire white ash cover ranged from 1 to 28%. Data were used to

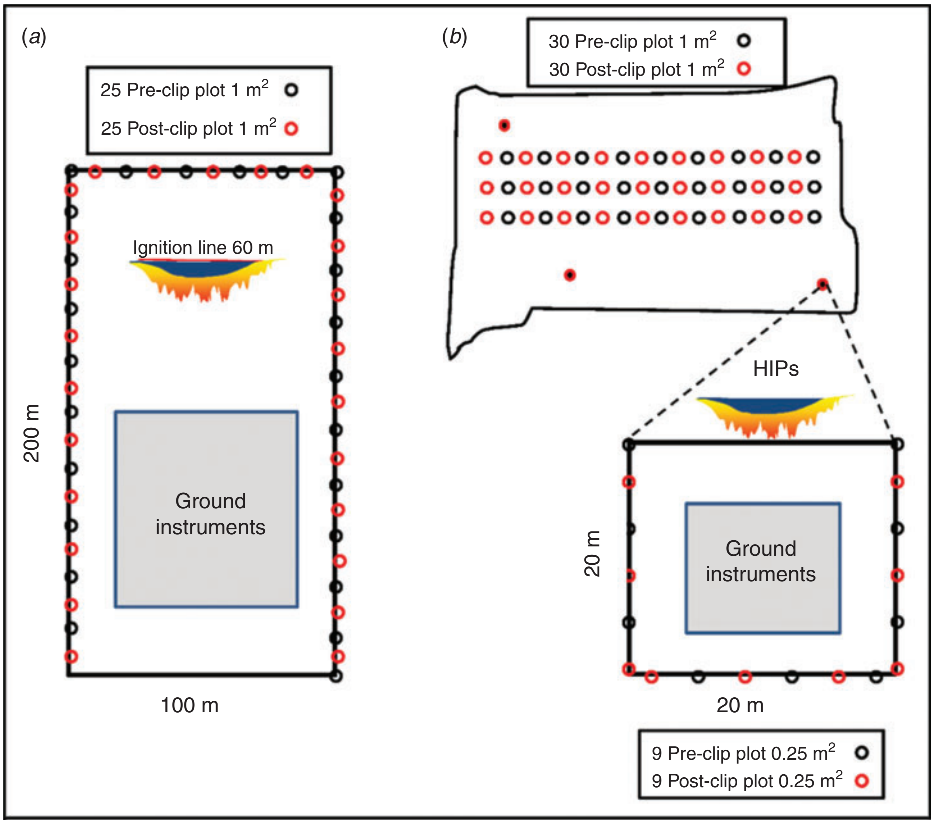

Fig. 4. Plot layout for (*a*) small replicate prescribed fires; and (*b*) large operational prescribed fires with sample units for the 2012 RxCADRE burns. Only large operational burns were established in the 2008 and 2011 research burns (HIP, highly instrumented plot).

evaluate two fuel consumption models, CONSUME and the First Order Fire Effects Model (FOFEM), and to develop regression equations predicting fuel consumption from white ash cover. CONSUME and FOFEM produced similar predictions of total fuel consumption and were comparable with measured. Simple linear models to predict pre-fire fuel loading and fuel consumption from post-fire white ash cover explained 46 and 59% of the variation respectively.

The emergence of next-generation wildland fire behaviour models that simulate fire propagation through three-dimensional lattices at fine scales requires new measurement approaches that distribute fuel realistically across the landscape and account for the often high variability. One such technique that shows promise is terrestrial laser (LiDAR) scans that are providing more accurate renderings of fuels in regards to spatial distribution of plant elements. Rowell *et al.* (2015) describe methods for acquiring and processing high-resolution terrestrial LiDAR data across six small replicate (2-ha) sample units of the mixed herbaceous and shrub fuels during the 2012 RxCADRE campaign. Fuel beds were scanned obliquely from edges at a height of 20 m above the ground. Fuel height models were developed at 1- and 0.5-m resolutions and compared with field measurements (Ottmar *et al.* 2015). The study produced a single large dataset suitable for validation of fire behaviour models and reported accuracies associated with the spatial fidelity. The resultant fuel heights corresponded closely with field measurements of height and are spatially accurate. These measurements represent a first step towards spatially explicit and continuous fuels data for advancement of fire behaviour modelling and many other types of models.

Meteorology (Discipline 2)

The evaluation of current and the emergence of new wildland fire models require fine-scale, near-surface weather datasets. Clements *et al.* (2015) describe the coupling of fine-scale velocity data obtained from a scanning Doppler LiDAR with airborne fire perimeter and fire radiative power measurements, allowing new observations to be made on the spatial variability of fire-induced flow during six small replicate block burns and two large operational block burns as part of the RxCADRE experiment in 2012 (Fig. 5*b*). Results indicate that even low-intensity prescribed fires cause fire–atmosphere coupling and can induce coherent flow features including upwind acceleration of the wind into and through the flame front. These findings also suggest that even low-intensity prescribed fire can be dominated by fire–atmosphere interactions rather than the ambient wind. This effort provided the rare opportunity to simultaneously monitor fire weather and micrometeorology with fine-scale fuels and fire behaviour sampling during multiple, low-intensity prescribed fires. This will allow scientists and modellers to better understand how fire–atmosphere coupling affects fire behaviour.

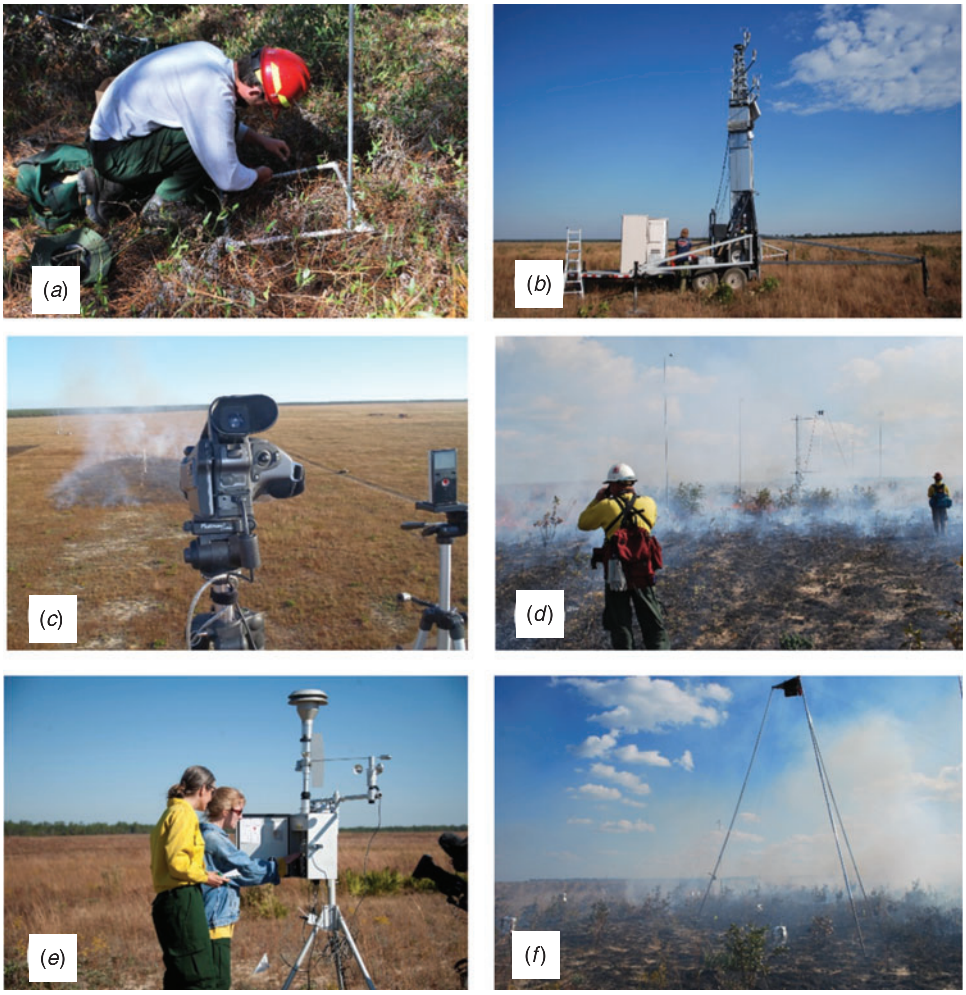

Fig. 5. RxCADRE disciplines including (*a*) fuel, (*b*) meteorology, (*c*) fire behaviour, (*d*) energy, (*e*) smoke emissions and (*f*) fire effects.

Fire behaviour (Discipline 3)

Transfer of energy generated from the combustion of live and dead vegetation drives wildland fire intensity and rate of spread (Anderson 1969). However, the quantification of energy transport across time and through space is a poorly documented element of wildland fire science. Butler *et al.* (2015) present 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 large operational prescribed fires ignited in grass and forest fuel bed types during the 2012 RxCADRE experiment (Fig. 5*c*). The paper also correlates the measurements with fire, fuel and environmental conditions. Measurements of peak radiant and total energy incident on the sensors during flame presence reached 18.8 and 36.7 kW m^{-2} respectively. Calculated fire radiative energy varied from 7 to 162 kJ m^{-2} and fire total energy ranged from 3 to 261 kJ m^{-2}. Measurement of flame emissive power peaked at 95 kW m^{-2} while the average horizontal flow reached 8.8 m s^{-1}. The measurements collected can be used to develop a new understanding about the relative contribution of radiative and convective heating to overall energy transport under a variety of environmental and fuel bed conditions and can provide fire behaviour data that can be integrated with other RxCADRE datasets from the same fires.

Energy (Discipline 4)

Radiation generated 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, may provide an important means to assess fire behaviour, plume rise and other wildland fire characteristics important to managing fire. Ground, airborne and space-borne sensors show great promise as methods for monitoring fire radiative power (FRP) of active wildland fires, fuel consumption and smoke production (Schroeder *et al.* 2014). The multiscale radiation datasets, along with time-integrated fire radiative energy (FRE) datasets that can be directly associated with fuel consumption, will provide the fundamental knowledge needed to evaluate models and measurement methods.

Dickinson *et al.* (2015) describe and compared several independent measurements of FRP for the RxCADRE 2012 small replicate (2 ha) and large operational (>100 ha) research burns (Fig. 5*d*). For the small replicate prescribed fires, FRP estimated from a boom-mounted, obliquely oriented infrared camera was compared with FRP derived from combined data from tower-mounted radiometers and RPAS. For the large research burns, satellite FRP measurements from Moderate-Resolution Imaging Spectroradiometer (MODIS) and Visible Infrared Imaging Radiometer Suite (VIIRS) sensors were compared with near-coincident FRP measurements derived from a long-wave infrared (LWIR) imaging system aboard a piloted aircraft. It was discovered that small RPAS have some utility for characterising flame-front development in small prescribed fires but their use will remain limited until temperature ranges of infrared sensors and image orthorectification can be improved. Oblique cameras have merit in operational imaging of small fires or parts of large fires and could be coordinated with airborne imaging. It was evident from this work that a better understanding of wildland fire spectral radiation and the development of measurement devices and calibration processes are needed for all ground, airborne and satellite sensors used in this study.

Hudak *et al.* (2015) present field and remotely sensed measures of pre-fire fuel loads, consumption, fire radiative energy density (FRED) and fire radiative power flux density (FRFD), from which FRED is integrated, across forested and non-forested burn experiments during the RxCADRE 2011 and 2012 campaigns. Fuel consumption predicted from FRED derived from both airborne LWIR imagery and ground sensors approaches a linear relationship with observed fuel consumption. Future research would include spatially explicit improvements for mapping these variables, which could serve as useful inputs into fire behaviour models.

RPAS are expected to provide timely infrared, visible and other passive imagery in support of both wildland fire operations and research. However, RPAS have received limited testing and demonstration as to their capabilities (Hinkley and Zajkowski 2011). Zajkowski *et al.* (2015) describe the RPAS that were successfully deployed during the RxCADRE 2012 campaign with and without manned aircraft in the air profile. RPAS deployed ranged both in time aloft and in size from the Aeryon Scout quadcopter (Aeryon Labs Inc., Waterloo, ON) to the fixed-wing G2R ScanEagle (Insitu Inc., Bingen, WA). RPAS measurements included visible and LWIR imagery, black carbon, air temperature, relative humidity and three-dimensional wind speed and direction. The RxCADRE 2012 campaign successfully demonstrated the use of RPAS as an operational support tool, flying over 50 missions, with no safety mishaps or loss of RPAS. Frequency management is a critical element for RPAS operations, while secure, reliable command and control and data links are critical for safe operations and data dissemination. Although each RPAS platform met all research and operations objectives, the Scout showed significant promise for tactical deployment.

Research-related data from the RPAS are used in Dickinson *et al.* (2015) and show promise for other, future research applications. Development of small infrared sensors deployable on small RPAS that provide additional quantitative data during wildland fire imaging are essential for research applications. Although real-time orthorectification tools employed on these research burns meet operational needs, additional processing is required for the utilisation of RPAS data at this scale.

Smoke emissions (Discipline 5)

Fire emits particulate and gaseous compounds that cause air quality and visibility impacts and can affect climate (Aurell *et al.* 2011; Strand *et al.* 2011). Understanding the impact of these emissions and evaluating models to better predict smoke impacts on regional air quality and global climate require quantifying emissions from wildland fire. Strand *et al.* (2015) present ground, airplane and tethered-aerostat time-resolved smoke measurements of carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), particulate matter (PM), and optical properties on non-forest grass and shrub and forest understorey operational prescribed fires during the 2012 RxCADRE research campaigns (Fig. 5*e*). Differences were observed between aerial and ground-based measurements, with aerial measurements exhibiting smaller particle size distributions and particulate matter emission factors, likely owing to fuel-bed type and particle settling. Black carbon emission factors were similar for both the non-forest grass and shrub and forest 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 and shrub non-forest burns owing to the longer duration of smouldering combustion with the forest biomass. Carbon monoxide and CH_4 emission factors were over twice as high for the forest burn compared with the grass and shrub non-forest burn, corresponding with a lower modified combustion efficiency and greater smouldering combustion. This indicates that composition and characteristic mosaic of the finer fuels need to be considered rather than just general fuel conditions.

Fire effects (Discipline 6)

Wildland fire radiant energy can be measured at wide spatial extents and at high temporal and spatial resolutions. These measurements are critical for making inferences about fire effects and useful for examining patterns of fire spread. O'Brien *et al.* (2015) describe methods for capturing and analysing LWIR imagery both spatially and temporally during the 2012 RxCADRE project and examine the utility of these data in investigating fire effects and fire behaviour (Fig. 5*f*). The LWIR data were compared at a range of spatial and temporal scales (1 cm^2 to 1 m^2; 0.12 to 1 Hz) using both nadir and oblique measurements. There was concurrence between the measurements, although the oblique view estimates of FRP were consistently higher than the nadir view estimates. 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 modelling 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 scrutinised for their predictive capabilities, and as the need to better understand fire processes increases, it is important to have available quality-assured datasets for use by scientists and wildland fire managers.

This was the main justification behind the RxCADRE project that has led to a series of fuel, meteorology, fire behaviour, energy, smoke emissions and fire effects datasets that can be used to test theory and evaluate fire models. For example, the pre-fire and post-fire fuel dataset was used to evaluate two fuel consumption models, CONSUME and FOFEM (Ottmar *et al.* 2015).

This project required new and creative measurement techniques to be developed and deployed with more conventional methods, thus testing opportunities for improved data collection procedures. Although conducting large research campaigns on actively burning fires is a high-risk proposition because of safety concerns, logistical challenges, limited burning opportunities, costs, science-interest conflicts and data-sharing concerns, each one of these challenges was minimised through a detailed planning process. Precampaign planning including recruiting for a hosting agency receptive to research, and the development of study, logistics, safety and data management plans enabled the RxCADRE project to become one of the largest and most efficient research efforts undertaken in the United States, with multinational participation and more than 90 scientists, research staff and land managers capturing critical information in the field. Also unique to this effort was the rapid processing and access of all data acquired, ranging from the combustion of fuels to fire behaviour, to energy release and the resulting smoke and fire effects to all interested scientists and individuals. Many aspects of the fire were measured on the same experimental prescribed fires, allowing integration among the science disciplines, furthering the efficiency of RxCADRE. Because of the success of RxCADRE, the larger, more complex and progressive Fire and Smoke Model Evaluation Experiment (FASMEE) project has commenced, with several cooperating agencies to continue the advancement of measurement techniques and observational data to further evaluate, validate and advance fire and smoke modelling systems. Much of the knowledge gained and lessons learned from RxCADRE will assist in planning the FASMEE project. The papers presented in this special issue only scratch the surface of the datasets and products that will become available over time and the integrated analyses that will occur as a result of this project.

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