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Intermediate-scale Fire Behavior Measurements in the Field: Bridging the Gap Between Laboratory Experiments and Management-scale Prescribed Fires

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Introduction

The dynamics of fire propagation through forest fuels are best characterized as a coupled fuel – fire – atmosphere system, where key interactions among processes at each scale become the basis for interpreting overall fire behavior across scales. While wildfires dominate the combustion of forest fuels in the western USA, prescribed fires are of greater significance in the eastern USA, where they are conducted primarily to reduce hazardous fuel loads and maintain desired ecological structure and functioning in forests (Agee and Skinner 2005, NIFC 2018). Much of our understanding of combustion processes, turbulence, and energy exchange during prescribed fires is derived from measurements made at two separate scales; small-scale laboratory experiments and large-scale operational prescribed fires. Integrating results across scales using physics-based fire behavior models has highlighted benefits and limitations of both approaches, and has revealed a number of uncertainties that remain to be resolved. At the small scale, burn-table experiments in the laboratory have quantified key processes controlling combustion and fire propagation across fuel beds under well-controlled conditions, and have demonstrated highly predictable relationships between fuel loading, fuel consumption, flame heights and peak heat-release rates (HRR)(Campbell-Lochrie *et al*. 2018). However, important questions such as how variation in ambient wind fields interact with forest structure to alter patterns of fire-induced turbulence, convective heat transfer, and ultimately rates of fire

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propagation cannot be addressed adequately at this scale. At a larger scale, tower-based measurements during low- and high-intensity prescribed fires have quantified ambient wind and fire-induced effects on turbulence and convective heat fluxes, and how these factors in turn affect overall fire behavior, fuel consumption and firebrand production (Heilman *et al*. 2017, 2019, Mueller *et al*. 2017). These efforts have characterized the magnitude of horizontal and vertical wind velocities, turbulent kinetic energy, and sweep - ejection dynamics associated with buoyant plumes in and above the forest canopy during planned fires, and have documented the occurrence of downdrafts and inflow of cooler air into the back of flame fronts during more intense fires but not during low-intensity fires. However, while measurements made during large-scale operational burns can be used to evaluate the overall performance of fire behavior models, they typically integrate so many complex processes that disentangling the underlying relationships is often difficult, limiting their utility. In addition, while these experiments have simultaneously quantified turbulence and heat fluxes in the fire environment, fuel consumption measurements have been relatively coarse scale, and a number of these large-scale experiments were limited by a lack of comprehensive fire behavior measurements (e.g., rates of spread, HRR, and flame residence times).

An important question in the prediction of fire behavior during prescribed fires becomes which relationships or phenomena occur consistently across scales? Alternatively, do "emergent behaviors" occur at larger scales that that may not occur or are undetected at smaller scales? For example, when and at what spatial scale do more intense fires initiate and enhance larger scale circulations, and how do they in turn affect fire behavior and the transport of firebrands? A second important issue revolves around our ability to synthesize and predict fire behavior during planned wildland fires. Despite the development of a number of physics-based fire behavior models (WFDS, FIRETEC), their use for simulating planned wildland fires has not been widely adopted. One limitation has been the availability of data to initialize, parametrize and evaluate these models across scales. As a first step in addressing these knowledge gaps, we have designed and implemented a series of intermediate-scale experiments to provide a better integration of small-scale laboratory flammability experiments and large-scale operational prescribed fires. We conducted these highly-instrumented experiments on 100 m^2 (10 m x 10 m) plots in the New Jersey Pinelands. We compared dormant season burns conducted in March 2018 to growing season burns in May 2018, and compared "natural" fine fuel loadings (~ 0.5 kg m^{-2}) to augmented fuel loadings (~ 1.0 and 1.5 kg m^{-2}). Here we focus on reporting patterns of turbulence and convective heat flux in buoyant plumes.

Materials and methods

Our experimental design incorporated much of the same instrumentation and integration times used previously in small-scale laboratory combustion experiments and instrumented large-scale prescribed fires, and included arrays of 0.25 mm diameter, K type thermocouples (Omega Engineering) and an overhead IR camera (FLIR Systems Inc. A655SC) to measure flame arrival times, gas temperatures, and radiant intensity. Sonic anemometers (R.M. Young 81000v) and custom radiant heat sensors were used to quantify turbulence and convective and radiate heat fluxes above flame fronts. Thermocouples and sonic anemometers were logged at 10 Hz using CR-3000 dataloggers (Campbell Scientific). The instrumentation set up is shown in Fig. 1. Terrestrial laser scanning (TLS) and standard census measurements were used estimate forest structure, initial fuel loading and fine-scale variation in fuel consumption, and fuel moisture contents. Ambient meteorological variables were measured from 3, 10 and 20 m towers within 200 m of the 100 m^2 plots. Fires were ignited as either backing or head fires, depending upon ambient wind conditions. Interactions of ambient weather conditions, fuel loading, and fuel moisture content with fire behavior (rate of spread, flame heights, flame residence times, and radiant and convective heat fluxes) could then be quantified. Relationships between convective heating and vertical and horizontal wind velocities, and between fire behavior and turbulent kinetic energy (TKE) were also evaluated.

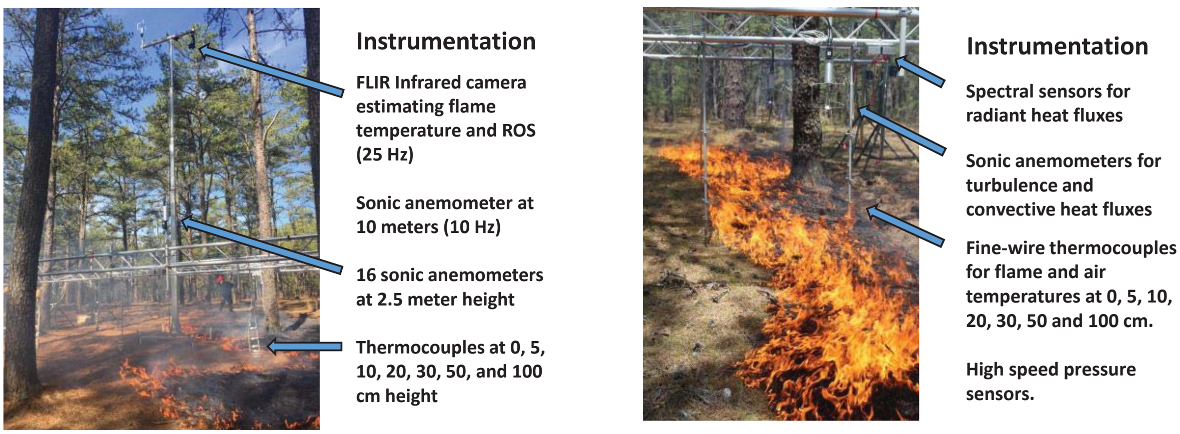

Figure 1. Instrumentation used for the 100 m^2 burn experiments. Four trusses were spaced approximately 2 meters apart over fuel beds. A FLIR IR camera and a single sonic anemometer were mounted at 10 m on a tower located in the middle of the plot. Sixteen sonic anemometers, radiant heat sensors, and pressure sensors were mounted in a 4 by 4 arrangement on the trusses. Thermocouple arrays were mounted every 1.2 m along the two center trusses.

Results

Nineteen experiments were conducted during March, May and September 2018. Rate of spread (ROS) and heights of flame fronts ranged from < 0.5 m min^{-1} and < 0.2 m during backing fires conducted at low ambient windspeeds to 2-3 m min^{-1} and 0.4 ± 0.2 m during fires ignited with the wind during periods of higher ambient windspeeds. Peak heat-release rates ranged between < 5 kW and 53 ± 7 kW, with the highest values occurring during head fires with augmented fuel loads. Rate of spread of flame fronts averaged for the extent of the burn was a strong function of mean windspeeds, while variation in ROS was linked to fine-scale wind fields sampled at 2.5 m above the fuel beds by the 4 by 4 array of sonic anemometers. Thermocouples located immediately above fuel beds remained near ambient temperatures and then heated up rapidly to 850-950 °C when flame fronts arrived, indicating the entrainment of cool air into the base of approaching flame fronts. In contrast, uppermost thermocouples located at 0.5 and 1.0 m height above fuel beds showed the greatest variability in the timing and magnitude of maximum temperature values. During fires ignited with the wind, early time of arrival of heated gasses at the uppermost thermocouples was typically a function of ambient windspeeds, indicating the progressive tilting of buoyant plumes. Tilt of buoyant plumes was also detected by sonic anemometers mounted 2.5 m above fuel beds (Fig. 2). A commonly occurring pattern was documented by a linear array of four sonic anemometers that were oriented perpendicular to the flame front during a fire ignited with the wind on March 17, 2018. The third and fourth sonic anemometers located 6.5 and 9 m downwind from the point of line ignition detected convective heating associated with enhanced vertical windspeed almost immediately following ignition (Fig. 2a and 2b).

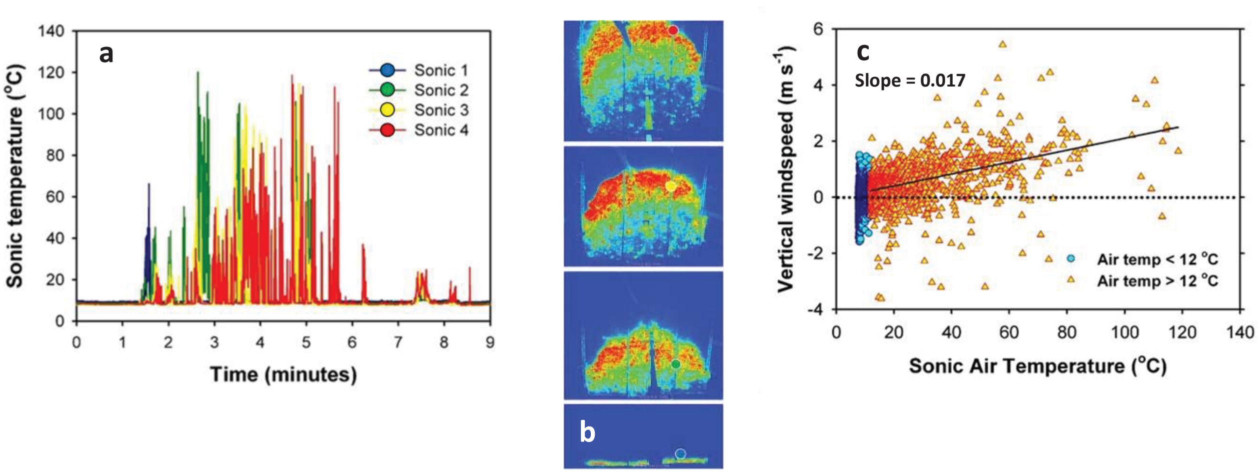

Figure 2a. Time series of air temperature measured at 10 Hz using sonic anemometers mounted at 2.5 m height along one of the inner trusses during a fire ignited with the wind on March 17, 2018. Ignition occurred at approximately 1.5 minutes beneath sonic #1. 2b. Overhead infrared camera imagery showing fire line progression. Sonic anemometers are color-coded, with blue above the point of ignition and red furthest downwind. 2c. Relationship between gas temperature and vertical windspeed measured using a sonic anemometer in a buoyant plume at sonic anemometer #3, indicated in yellow in Figs. 2a and 2b.

The relationship between air temperature and vertical windspeed in convective buoyant plumes measured using sonic anemometers was a linear function for all fires (Fig. 2c). Although sonic air temperatures and perturbations to vertical and horizontal wind velocities measured at 2.5 m height were greatest during fires with augmented fuel loads ignited with the wind, the slope of this relationship was consistent for dormant and growing season burns, and across the range of fuel loadings measured. However, the relationship was height dependent, with an increasing slope with height above the flame front, as detected by sonic anemometers mounted at 1.5 and 3.5 m heights during a series of experiments in May 2018 (Fig. 3).

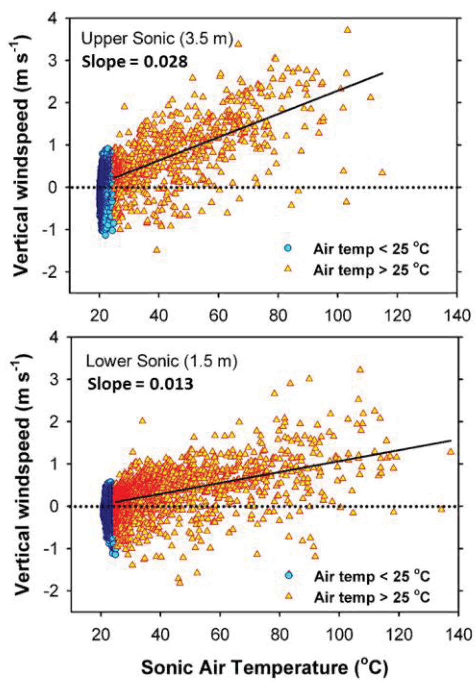

Fig. 3. The relationship between sonic air temperature and vertical windspeed measured at 10 Hz using sonic anemometers mounted at 1.5 m and 3.5 m heights above fuel beds during a fire ignited with the wind.

Discussion

To begin to address the knowledge gaps in our understanding of combustion processes and fire behavior across spatial scales, we designed and conducted a series of intensively-instrumented experiments which were replicated on 100 m^2 plots, contrasting dormant season vs. growing season conditions, and natural vs. augmented fine fuel loads. We designed this first series of intermediate-scale experiments to incorporate simplified fuel bed structure by eliminating the drag forces introduced by understory vegetation, while incorporating the effects of overstory canopy structure. In previous large-scale field combustion experiments, complex three-dimensional fuel bed structures complicated the interpretation of factors contributing to overall fire behavior (e.g., Muller *et al*. 2017). Here we focused on comparisons of patterns of turbulence and convective heat flux measured previously during small-scale laboratory experiments and large-scale operational prescribed fires, and how these factors influenced fire propagation and fuel consumption. We found that a number of observations are consistent across scales.

During small-scale laboratory measurements, flame heights ranged between > 0.1 and 0.9 m and peak HRRs ranged between 6 and 50 W m^{-1} for pitch pine needle loadings of 0.2 to 1.8 kg m^{-2}, which encompassed the range of fuel loadings during the intermediate-scale measurements reported here, and of fine litter during a majority of the large-scale field experiments (Campbell-Lochrie *et al*. 2018). Significant logarithmic relationships between fuel loading, flame heights and peak HRRs were detected during laboratory experiments. Similar results were obtained during the intermediate-scale experiments reported here, although the effects of variation in ambient windspeeds and fuel moisture contents on fire behavior were also apparent. In addition, igniting fires with the wind compared to backing fires altered flame heights and ROS, although longer flame residence times during backing fires resulted in nearly equivalent amounts of fuel consumption. Rate of spread, flame lengths and total heat release were somewhat lower during the intermediate-scale experiments compared to field observations during operational prescribed fires, where ROS ranged between 2-5 m min^{-1} during backing fires where flame lengths were approximately 0.3 to 1.5 m height. During large-scale field experiments, significant relationships between initial loading and consumption of fuels on the forest floor have been documented, with initial loading explaining 70% of the variation in fine litter consumption, and 76% of the variation in 1- and 10-hour wood consumption (Clark *et al*. 2015, Mueller *et al*. 2017). Integrated (total) heat-release values calculated for these operational prescribed fires were larger than for the intermediate-scale experiments. However, when estimated consumption of only fine litter was used to calculate total heat release during operational prescribed fires, values were similar to those measured during the intermediate-scale experiments.

A number of patterns of turbulence and convective heating were also similar across scales. Consistent with patterns documented during small-scale experiments, we detected the inflow of relatively cool air into the base of approaching flame fronts during all intermediate-scale experiments. We also documented tilting of convective plumes, which was greatest during fires ignited with the wind when ambient winds were relatively strong. The relationship between convective heating and vertical windspeed velocity in buoyant plumes was consistent across the range of fuel loadings and direction of ignition. An increase in the slope of this relationship with height above flame fronts in buoyant plumes was documented when sonic anemometers were located at 1.5, 3.5 and 10 m heights above the 100 m^2 plots. The observed increase in the slope of the relationship between convective heating and vertical windspeed velocity is consistent with measurements during large-scale burns, where slopes averaged 0.015, 0.025 and 0.040 when sonic anemometers were mounted at 3 m, 10 m and 20 m heights above the forest floor. However, inflow of cool air and extended periods of negative vertical windspeeds indicating downdrafts behind flame fronts documented during more intense large-scale prescribed fires have not been observed during the 100 m^2 burns.

Overall, intermediate-scale, 100 m^2 instrumented burns offer promise in unraveling some of the factors controlling fire behavior during planned wildland fires, and in reconciling results from small-scale laboratory and large-scale field experiments. A number of phenomena are consistent across scales, including flame heights, peak HRRs, and patterns of cool air inflow and buoyant plume tilt in the vicinity of flame fronts. Future work will include fuel beds with more complex structure to incorporate the effect of drag forces associated with understory vegetation on turbulence and buoyant convective plumes, and the nesting of intensively-instrumented 100 m^2 plots within larger-scale prescribed burns.

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