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Investigation of firebrand generation from an experimental fire: Development of a reliable data collection methodology

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A B S T R A C T

An experimental approach has been developed to quantify the characteristics and flux of firebrands during a management-scale wildfire in a pine-dominated ecosystem. By characterizing the local fire behavior and measuring the temporal and spatial variation in firebrand collection, the flux of firebrands has been related to the fire behavior for the first time. This linkage is seen as the first step in risk mitigation at the wildland urban interface (WUI). Data analyses allowed the evaluation of firebrand flux with respect to observed fire intensities for this ecosystem. Typical firebrand fluxes of 0.82–1.36 pcs $m^{-2}\ s^{-1}$ were observed for fire intensities ranging between 7.35 ± 3.48 MW m^{-1} to 12.59 ± 5.87 MW m^{-1}. The experimental approach is shown to provide consistent experimental data, with small variations within the firebrand collection area. Particle size distributions show that small particles of area $0.75–5\times10^{-5}\ m^2$ are the most abundant (0.6–1 pcs $m^{-2}\ s^{-1}$), with the total flux of particles $> 5\times10^{-5}\ m^2$ equal to 0.2–0.3 pcs $m^{-2}\ s^{-1}$. The experimental method and the data gathered show substantial promise for future investigation and quantification of firebrand generation and consequently a better description of the firebrand risk at the WUI.

1. Introduction

Structures at the wildland urban interface (WUI) are particularly susceptible to ignition due to firebrand exposure [1,2]. Maranghides and Mell [3] outlined the need for a WUI-hazard scale assessment of the risks arising from wildfires and identified that direct fire and firebrand exposure are the leading cause of the ignition of structures in the WUI. Although there has been a considerable increase in the research activity in the area of firebrands and firebrand exposure in the last decade, no complete description of the problem yet exists. This challenge is compounded by the wide range of environmental and topographical conditions, ecosystems, and structure types that may be present during a WUI fire. Delivering understanding and solutions that are able to fit these diverse conditions continues to be a significant challenge for the fire science community. Most available studies related to firebrands have focused on characterizing the aerodynamics of typical firebrands [4] and analyzing the burning duration of firebrands [5,6] with respect to fire size and wind conditions [7]. Santamaria et al. [8] studied the impact of firebrand accumulation on ignition of wooden materials in inclined, V-shaped configurations. Spotting ignition from firebrands at short distance has been exhaustively investigated at laboratory scale by Manzello et al. [9–11]. Long-distance spotting (> 5 km) was described by Koo et al. [7]. A more detailed literature review, covering most studies related to firebrands and the exposure problem in the WUI, is presented by Caton et al. [1] and Hakes et al. [2].

This study focuses on the development of a methodology for characterizing the generation and flux of firebrands at short distance in large-scale fires, which can provide realistic input data for modelers and for laboratory-scale tests, in order to improve the resistance of WUI structures and communities to ember showers. Until now, there has been very little information available about the relationship between firebrand generation, fuel consumption, fire behavior and

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Nomenclature

BW	black and white
DPT	Differential pressure transducer
FBP	fire behavior package
FCS	firebrand collection site
FMC	fuel moisture content (% dry weight)
I	fireline intensity (kW m^{-1})
L	flame length
LiDAR	light detection and ranging
PT	primary tower in FBP
PNR	Pinelands National Reserve
R (ROS)	fire rate of spread
ST	secondary tower in FBP
SD	standard deviation
TC	thermocouple
TSC	thin skin calorimeter
WNW	west-north-west
WUI	wildland-urban interface
X,Y,Z	locations
Δh_c	heat of combustion (kJ kg^{-1})
Δm	mass consumption (kg)

wind conditions, all combined in a real WUI fire or even in a large-scale field experiments. This understanding must come from detailed studies that cannot be achieved for large-scale wildfires, where accurate measurements are nearly impossible to carry out. For instance, very precise investigation work was carried out by Rissel et al. [12] and Manzello et al. [13] to characterize the size of the firebrands after a WUI fire, but they did not have access to a detailed description of fire behavior, making it impossible to link the firebrand generation to the fire.

The methodology used in this study is in alignment with a framework developed and presented in El Houssami et al. [14] and Filkov et al. [15], which reported integrated numbers of firebrands for local fire conditions and their characteristics (size, mass and origin). The novelty of this study includes the quantification of firebrand flux in time with respect to the local fire behavior, wind speed, fuel consumption, fire intensity, and characterizes the exposure of each sampling location. This information will help in estimating the firebrand flux that can be produced from a typical fire, the characteristics (geometry, mass) of the particles and if it is sufficient to impact a structure. This study falls in the configuration of low wind speed, flat terrain, and homogeneous fuel of the matrix suggested by Maranghides and Mell [3]. Since the methodology is developed with a full set of instruments to accurately measure the firebrands landing ahead of a fire front, it needs to first be tested in relatively controlled conditions at field scale, beginning with low wind speeds. Such a condition is not inherently a drawback for firebrand generation, because it was previously demonstrated that fire-induced drafts at low wind speeds were strong enough to detach bark pieces from tree boles and produce substantial amounts of firebrands [14]. Quantification of firebrand exposure in this way will allow a more complete description of the problem and allow the firebrand fluxes and characteristics to be linked to the fuels and fire behavior.

2. Experimental methods

2.1. Site description

This work was conducted in the Pinelands National Reserve (PNR) of New Jersey, USA. The region is characterized by a cool temperate climate, with a mean annual precipitation of 1160 mm and mean monthly temperatures ranging between 0 and 24 °C, from January to July. The terrain consists of plains, low-angle slopes, and wetlands, with a maximum elevation of 62.5 m. In the region of the study, the forest canopy is dominated by pitch pine (*Pinus rigida* Mill.), with intermittent oaks (*Quercus* spp.). Understory vegetation is composed of a mix of huckleberry (*Gaylussacia baccata*), blueberry (*Vaccinium palladum*), inkberry (*Ilex glabra*), briar (*Smilax rotundifolia*), scrub oak (*Quercus marilandica* and *Quercus ilicifolia*), wintergreen (*Gaultheria procumbens*), and sedge (*Carex pennsylvanica*), listed in relative order of importance. This general area is host to significant research activity, including studies on fire behavior [16] and firebrand generation [14], as well as a fuel management program directed by the New Jersey Forest Fire Service and federal wildland fire managers.

For this study, a burn parcel covering approximately 28 ha was selected, as shown in Fig. 1. The perimeter of the parcel was defined by existing access roads. The locations of measurement sites were first selected on the criteria that the collection of firebrands occur outside of the parcel, to avoid collection of falling debris, which can occur if the fire passes through a measurement site. This was an improvement on the methodology presented by El Houssami et al. [14]. The sites were then positioned based on a determination of the intended ignition pattern, depending on predicted wind conditions, in order to develop a head fire spreading towards the collection sites.

2.2. Fuel characterization

Pre- and post-burn measurements of the surface fuels (shrub and forest floor material) were taken at fifteen randomly selected destructive harvest locations. For each, a 0.5 m^2 area was harvested down to the mineral soil. Pre-burn sampling was conducted within the two weeks prior to the burns, and post-burn sampling was conducted within the following week. All shrub and forest floor materials present down to and excluding the duff layer were dried at 70 °C for a minimum of 48 h, sorted into different fuel classes and types, and weighed. The accuracy of destructive sampling is hindered by the fact that pre- and post-fire samples must inherently be collected in different locations. To handle this, the OpenBUGS (OpenBUGS, version 3.2.3 rev 1012) MCMC simulator11 was used to repeatedly resample and derive the distributional properties of the fuels from the harvested samples. Using these distributions, estimates of pre-burn loading, post-burn loading, and consumption were obtained. Note that standard hourly classifications of fuel diameter size are used here (1-hr: 0.0–6.35 mm; 10-hr: 6.35–25.4 mm).

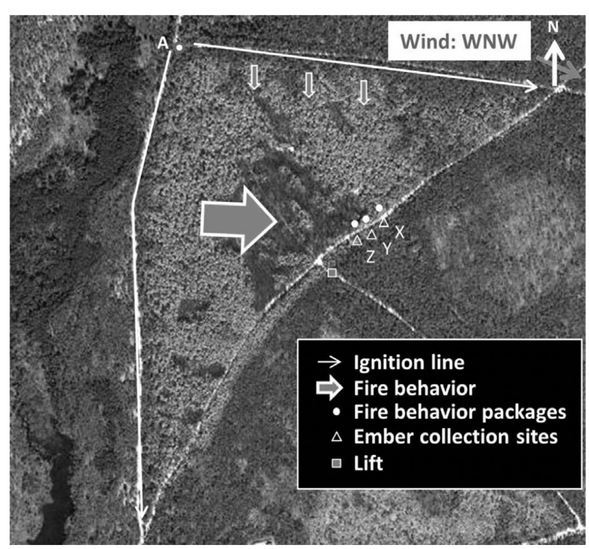

Fig. 1. Satellite image of burn unit (post fire). Indicating, general wind direction, ignition pattern, data collection package locations (Lift, FBP, FCS) and overall fire spread direction. The dark area in the middle of the image corresponds to an area of high consumption of canopy fuel.