Combustion and Flame 194 (2018) 452–463

Contents lists available at ScienceDirect

Combustion and Flame

journal homepage: www.elsevier.com/locate/combustflame

Local measurements of wildland fire dynamics in a field-scale experiment

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A R T I C L E I N F O

Article history:
Received 11 December 2017
Revised 17 February 2018
Accepted 27 May 2018

Keywords:
Wildland fires
Fire dynamics
Fire spread
Field experiment

A B S T R A C T

Local point measurements of fire dynamics in field-scale experiments of wildland fires are highly useful. This is true both for understanding the mechanisms driving fire spread that result in the observed macroscopic behaviors, but also in terms of providing comparison points for numerical tools, such as detailed physics-based fire behavior models. This work describes measurements of temperature, velocity, and radiative heat flux that were made in a field-scale fire experiment in a pine forest, with the aim of providing both of the above benefits. Regions of both surface fire and crown fire were captured and are compared. The crown fire exhibited tall upright flames, compared to the shorter tilted flames of the surface fire. Crown fire resulted in a significant increase in integrated radiative preheating, by a factor of ∼1.75, as well as greater flow sheltering in the downstream region of the fire front. Further, a corrective factor is introduced for oblique sensor placement relative to the fire front, in order to improve the value of these and other measurements, particularly for model comparison. The presented methodology, while able to be improved, is shown to successfully characterize local differences in fire behavior.

1. Introduction

In the study of wildland fire dynamics, local measurements of fundamental physical phenomena can be highly valuable in providing insight into the global, or macroscopic, behavior observed. The importance of these measurements is magnified when they are intended for the testing and development of physics-based fire behavior models. As these models aim to resolve the underlying physics [1], any assessment of model capabilities benefits significantly from such measurements [2]. Therefore, this work aims to add to the available set of such measurements, using a simple but robust methodology.

Conventional theory of wildland fire spread identifies three distinct stages: preheating, flaming, and intermittent flaming and smoldering combustion (e.g. [3]). These stages can be quantified through thermodynamic measurements. Specifically, in this case, we consider measurements of temperature, velocity, and radiative heat flux. To start, gas-phase temperature has a long history in the study of fire science and fire behavior [4], and it can help reveal details of flame spread, flame and plume geometry, and fire-induced turbulence. Flow velocity also provides information on the flame and plume dynamics as well as interactions with the ambient wind [5–7]. And finally, radiative heat flux gives an indication of the intensity of preheating associated with the fire front [8]. While convective heat flux can also be important (whether through heating or cooling) [9], it is not directly a feature of the fire front itself, unlike the other chosen variables. The rate of convective heating to a fuel element is a function of the boundary layer (both velocity and temperature) which forms around the element, as well as the temperature of the element itself [10]. This makes direct measurement of magnitudes related to vegetation elements difficult. However, a sense of the tendency for heating or cooling potential, as well as data for numerical modeling, can be obtained from the gas-phase temperature and velocity measurements. Overall, these three measurements help to understand the nature of energy transfer and oxygen availability, which are necessary to sustain the combustion reaction, and which must be properly represented in a physics-based model of fire spread.

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https://doi.org/10.1016/j.combustflame.2018.05.028
0010-2180/

Nomenclature

A	surface area [m]
a	sensor height (as a proportion of flame height)
C	TSC conduction correction factor
c_p	specific heat [kJ kg^{-1} K^{-1}]
D	sensor distance [m]
F^*	normalized view factor
g	gravitational acceleration [m s^{-2}]
H	flame height [m]
h_c	convective heat transfer coefficient [W m^{-2} K^{-1}]
K	pressure probe correction factor
k	thermal conductivity [W m^{-1} K^{-1}]
L	characteristic length scale [m]
m	mass [kg]
$\overline{Nu}_L$	average Nusselt number
P	pressure [Pa]
Pr	Prandtl number
Q''_{inc}	integral incident radiative heat flux [kJ m^{-2}]
q''_{inc}	incident radiative heat flux [kW m^{-2}]
Ra_L	Rayleigh number
Re_L	Reynolds number
t	time [s]
v	north/south velocity [m s^{-1}]
w	vertical velocity [m s^{-1}]
α	absorptivity, flame height to sensor distance ratio, thermal diffusivity [m^2 s^{-1}]
β	angle between sensor and fire front normal [°]
γ	TSC transient correction factor
ε	emissivity
θ_F	fire approach angle [°]
ν	kinematic viscosity [m^2 s^{-1}]
ρ	density [kg m^{-3}]
σ	Stefan–Boltzmann constant [W m^{-2} K^{-4}]

Subscripts

C,L,R	sensor location (center, left, right)
f	film
g	gas-phase
s	solid-phase
∞	ambient

A number of previous field experiments have investigated some combination of the aforementioned measurements [9,11–20]. These have been conducted in a variety of ecosystems, ranging from grassland [15,18,20], to shrubland [14,16,19], to forests [9,11,12,17]. However, measurement techniques are not typically consistent, and the level of detail provided on the macroscopic fire behavior (e.g. fuel structure and consumption, fire progression), varies significantly. This level of detail is particularly important for the utility of such measurements in terms of both understanding fire behavior and testing numerical models.

To address this need, a collection of wildland fire behavior measurements was obtained during a field-scale experimental fire in the Pinelands National Reserve (PNR). Details of the ecosystem, as well as macroscopic features of fire behavior for the experiment are reported by Mueller et al. [21]. Sites of co-located measurements of temperature, velocity, and radiative heat flux were established, to be within the fire environment at flame level. This was specifically aimed at testing detailed physics-based fire models, as fire behavior will inevitably vary locally throughout a field experiment. Providing a variety of different measurements at the same location means that multiple aspects of the representation of the highly coupled physical phenomena can be evaluated at the same instant. Likewise, by linking these measurements to the global trends of fire progression, a more complete picture of fire behavior can be created.

2. Methods

2.1. Study site

The experiment was conducted in the Pinelands National Reserve (PNR) of New Jersey, USA. The site was a pitch-pine scrub-oak forest, dominated in the canopy by pitch pine (*Pinus rigida Mill.*), with intermittent clusters of post-oak (*Quercus stellata Wangenh.*) and white oak (*Quercus alba L.*) in the sub-canopy. The understory contained a shrub layer of huckleberry (*Gaylussacia spp.*), blueberry (*Vaccinium spp.*), and scrub oaks (*Quercus spp.*).

The measurements discussed here were conducted in the second of two experimental fires, carried out in March of 2014 (EX2 in Mueller et al. [21]). Surface fuels, forest floor and shrub layer, were destructively sampled at 36 pre- and post-fire sample locations. Average initial loading of thin fuel (assumed to contribute to fire spread) was 1.68 ± 0.42 kg m^{-2}. Additionally, pre-fire litter depth ($n = 55$) was 5 ± 2 cm and the shrub layer height ($n = 120$) was 79 ± 19 cm. The forest canopy was characterized with pre- and post-fire airborne Light Detection and Ranging (LiDAR). This was calibrated to estimate fuel bulk density on a 3-dimensional grid with a 10 m × 10 m × 1 m resolution. Average initial loading of thin canopy fuel was 0.98 ± 0.20 kg m^{-2} More details of the study site, including fuel structure, can be found in Mueller et al. [21].

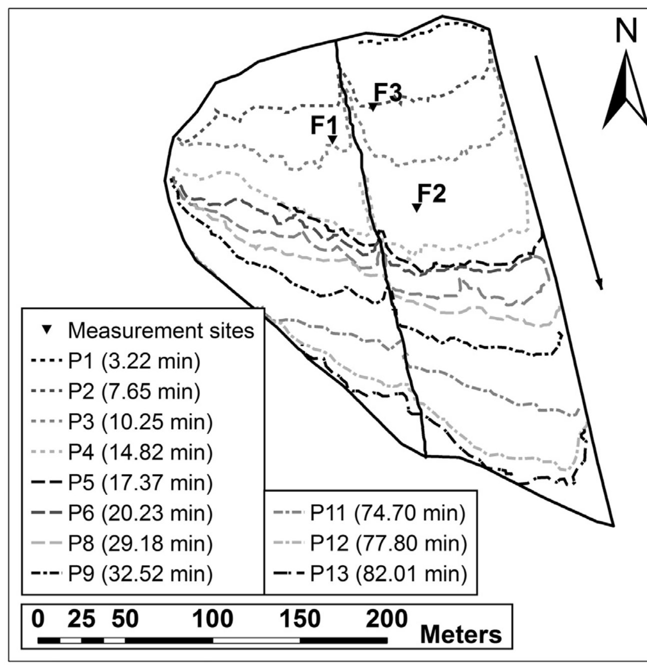

Fig. 1. Positioning of fire measurement sites in the experimental block. Isochrones P1-13 show the progression of the fire.

Local fire behavior, the focus of this investigation, was measured at three sites. These were selected based upon an exploratory survey of the burn block. Locally homogenous density of the shrub layer (based on visual inspection) and avoidance of any direct contact with canopy branches were the two criteria used. The location of these sites (referred to as F1, F2, and F3) are shown in relation to the burn block perimeter and progression of the fire front in Fig. 1.