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Utilization of remote sensing techniques for the quantification of fire behavior in two pine stands

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ABSTRACT

Quantification of field-scale fire behavior is necessary to improve the current scientific understanding of wildland fires and to develop and test relevant, physics-based models. In particular, detailed descriptions of individual fires are required, for which the available literature is limited. In this work, two such field-scale experiments, carried out in pine stands under mild conditions, are presented. A particular focus was placed on non-intrusive measurement, as the capabilities of advanced remote sensing techniques, along with more traditional approaches, are explored. A description of the fires is presented, with spread occurring predominantly in the surface fuels with intensities in the range of 200–4400 kW m^{-1}, and punctuated by isolated regions of crown fire. The occurrence of crown fire is investigated and linked to regions of greater canopy density, and it is found that the total fire intensity may increase locally to as much as 21,000 kW m^{-1}. The light winds do not appear to play a direct role in the changes in fire behavior, while fuel structure may be important. The measurements described herein provided a reasonable overall description of the fires, however, the current resolution (both spatial and temporal) falls short of definitively explaining some transitional aspects of the fire behavior, and future improvements are suggested.

1. Introduction

Significant gaps remain in the current understanding of the contribution of different driving mechanisms to the spread of large-scale outdoor fires, such as wildland fires [1]. A particular difficulty lies in the fact that laboratory tests, while offering many insights, cannot fully account for and scale the relevant conditions and phenomena [2]. Thus, field-scale measurements of fire behavior are paramount for increasing the current scientific understanding and developing models of fire behavior, particularly those employing detailed physics-based formulations [3].

Experimental measurement of fire behavior has been conducted in the field for grasslands (e.g. [4–7]), shrublands (e.g. [8–10]), and forested environments (e.g. [11–13]). However, the collection of work is limited by the fact that large scale experimental fires can be dangerous and resource intensive, with a significant potential for shortcomings. High intensity fires can also prove to be difficult to instrument successfully. Further, many studies report only statistics for a series of fires, without examining any particular fire in detail (e.g. [12]). This is valuable for creating empirical models, but does not provide sufficient information required for detailed analysis of singular fires (which often have dynamic behavior in the field), such as comprehensive time histories [4–6,9]. With appropriate measurement, a single spreading fire can offer insight into detailed aspects of fire behavior at different locations in space and time [9]. This kind of analysis is required for exploring the physics and testing detailed models against specific experiments.

In this study, two experimental fires were carried out in the context of several larger objectives, including quantifying the effect of fire (particularly prescribed fire) on fuel loading and structure, and

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Nomenclature

c_p	specific heat (kJ kg^{-1} K^{-1})
I	fireline intensity (kW m^{-2})
m	fuel load (kg m^{-2})
R	rate of spread (m s^{-1})
T	temperature (K)
u	wind speed (m s^{-1})

Greek

Δh_c	heat of combustion (kJ kg^{-1})
Δm	fuel consumption (kg m^{-2})
ρ	gas density (kg m^{-3})

subscripts

$_i$	initial (pre-fire)
$_o$	ambient

providing datasets necessary to test detailed physics-based fire behavior models. However, the current study aims to develop a broad assessment of fire behavior, while examining the capabilities of non-intrusive measurements to fully explain the observations. Detailed measurements of the flame region are ultimately important, particularly for model testing, and were a part of the overall study. Nevertheless, it is worth critiquing how well more general measurements (i.e. characteristics of wind and fuel) can explain the fire behavior. These types of measurements, along with spread rate and some flame geometry, are the most often made in field-scale experiments, as wind and fuel are known to drive fire behavior. However, it must be examined whether these efforts are sufficient to increase the current understanding of the underlying mechanisms. This work also provides the baseline inputs necessary for the subsequent modeling of fire behavior in this type of environment [14].

Here, we take advantage of the relatively recent development and improvement of advanced remote sensing techniques, which allow for detailed measurement of both fuel structure and local fire behavior for individual fires. Aerial infrared (IR) and Light Detection and Ranging (LiDAR) sensors were utilized to monitor the fire spread and canopy fuel structure, respectively. Fuel measurements were supplemented by destructive sampling, and ambient wind conditions were recorded outside the burn areas. An assessment of the respective influences of fuel and wind conditions on changes in fire behavior was carried out to understand their relative importance.

2. Methods

2.1. Study site

The two experiments (EX1 and EX2) were carried out in the Pinelands National Reserve (PNR) of New Jersey, United States. This reserve covers an area of approximately 445,000 ha, and is the site of an active prescribed fires program by the New Jersey Forest Fire Service (NJFFS) and federal wildland fire managers. This is intended to reduce fuel loads and thus mitigate fire risk [15]. The climate is classified as cool temperate, with mean monthly temperatures of 0.3 °C in January and 24.3 °C in July, and mean annual precipitation is 1159 mm. The basic geography is a relatively flat coastal plain with low-angle slopes and a maximum elevation of 63.5 m, with primarily well-drained sandy soil [16]. Upland forests of pine and oak dominate this landscape, which have an extensive history of prescribed fire treatments and wildfire, and wetlands and short statured pine plains also occur [17,18].

The forest type was pitch-pine scrub-oak, 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.) (Fig. 1a). Pre-existing access roads were used as the block perimeters, and both blocks were split by an unmaintained fuel break - oriented north to south (Fig. 1b,c).

The experiments were carried out in early March, before the growth of new vegetation in the spring. The window between snow melt and deciduous leaf expansion corresponds to the time which prescribed fires are conducted by the NJFFS in the PNR, putting this study directly the context of conditions typically observed during prescriptive management operations. Additionally, a large majority of major wildfires in the PNR occur prior to leaf expansion. Therefore, an understanding of fire behavior during this time is relevant to fuel management and wildfire suppression activities.

Both fires were initiated with the wind linearly along the length of the north road (~330 m and ~207 m long, respectively), using a gasoline drip torch. Flame fronts progressed as head fires in a south

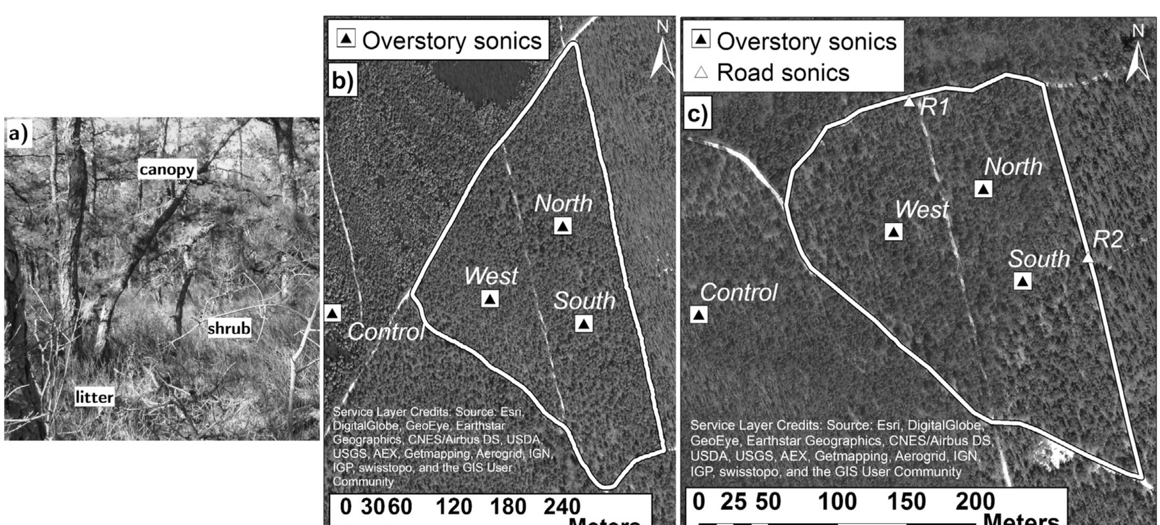

Fig. 1. (a) Typical pre-burn vegetation conditions, representative of both experiments, and layout of the (b) EX1 and (c) EX2 burn blocks, with anemometer locations noted.