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DOMINGOS XAVIER VIEGAS
LUÍS MÁRIO RIBEIRO

Understanding Fire Response to Spatial Variations in Vegetation Distribution and Wind

Daniel Jimenez*[1]; Natalie Wagenbrenner[1]; Cyle Wold[1]; Paul Sopko[1]; Daniel Gorham[2]; Joe O'Brien[3]; Robert Spencer[4]; Matthew Nolasco[4]

[1]Fire Science Laboratory, Rocky Mountain Research Station, USDA Forest Service, Missoula Montana, USA, {dan.jimenez@usda.gov}
[2] Insurance Institute for Business & Home Safety, Rock Hill, South Carolina, USA, {dgorham@ibhs.org}
[3] Centre for Forest Disturbance Science, Southern Research Station, USDA Forest Service, Athens, Georgia, USA, {joseph.j.obrien@usda.gov}
[4]Tall Timbers Research Station & Land Conservancy, Tallahassee, Florida, USA, {mnolasco@talltimbers.org}

**Corresponding author*

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Abstract

Fire spread can be characterized as a continuous sequence of ignitions. Ignition is a local phenomenon, governed by complex interactions between temporal and spatial variations in fuel and environment. Seemingly insignificant changes in vegetation orientation or spacing can significantly affect the ignition process and result in fire either bridging a gap in fuels or extinguishing at the gap boundary. This study seeks to improve understanding of ignition by exploring the physics underlying fire's response to gaps in vegetation under the influence of wind, fuel conditions and microtopography. A series of 70 experiments were conducted at the US Forest Service Missoula Fire Science Laboratory (MFSL) and the Insurance Institute of Business & Home Safety (IBHS) wind tunnel facilities to test fire's response to fuel discontinuities under varying wind conditions and fuel moistures. Winds speeds ranged between 0.5 to 9 m/s over 4 different levels. Fuel moistures varied between dry (2-6%) and wet (8-17%) by weight gravimetrically. Fuel discontinuity gap sizes varied from 10 to 160cm. Fuels consisted of long leaf (Pinus palustris) pine straw. Fuel loading was 0.56 kg/m^2 and packing ratio was 0.02. Six replicates were performed at each gap bridging threshold, three at the minimum gap and three at the minimum plus one for statistical significance and probability. Under all wind speeds and moisture conditions the gap threshold between fire bridging and fire extinction was 10cm.

1. Introduction

Fire professionals within land management agencies in the United States recognize that vegetation and environmental heterogeneity collectively drive fire behaviour and fire effects on soil and plants (SERDP, 2014). The interactions between energy transport in wildland fires and the spatial distribution of fuels and wind are complex. While intuition and anecdotal observations provide some guidance, the current state of wildland fire science lacks full understanding of the dependency between fire and the spatial distribution of wind and fuels (Arno, 1997). Improved understanding of how fire responds to changes in vegetation type and density combined with wind and topography would improve the ability of the fire science community to effectively model fire behaviour and the capability of operational fire managers to use fire as a land management tool (Finney, 2013).

Experienced fire practitioners recognize that seemingly insignificant changes in wind, topography (slope or aspect) or vegetation orientation can influence fire intensity and spread (Hessburg, 2005; Camp, 1995; Ottmar, 1996). The sensitivity of fire to variations in fuel element geometry, location, and orientation as well as local air flow complicates effective fire-based land management. The dependence of fire intensity on local winds is readily recognized, but we do not yet know which scales are most relevant. Knowledge gaps pertinent to this effort include: 1) dependence of ignition on wind; 2) relative contribution of radiant and convective heating across fuel gaps as a function of burning conditions; 3) probability of ignition success as a function of fuel moisture; 4) ignition critical scales for fuel composition, load, and distribution; 5) dependence of fuel consumption as a function of arrangement of spatial discontinuities within the fuel matrix (Anderson, 1969; Anderson, 2010; Butler, 2004).

2. Methods

The underlying hypothesis for this work is that ignition is a dose verses response mechanism. The dose is total energy absorbed by fuel particles and the response is ignition or extinction. This study seeks to identify the minimum energy dose to affect ignition through study of fire's interaction to gaps in the fuel array. To address these knowledge gaps, a series of laboratory burn experiments were completed at two different wind tunnel facilities, the US Forest Service Missoula Fire Science Laboratory (MFSL) located in Missoula, MT and the Insurance Institute for Business & Home Safety (IBHS) located in Rock Hill, SC. The lower wind speed experiments were conducted at MFSL wind tunnel while the upper wind speed experiments were conducted at the IBHS test facility. Windspeed was digitally controlled at each test facility and ranged from 0.5 to 9 m/s at 4 different levels. Fuel beds of long leaf (Pinus palustris) pine straw (nominally 2.5-3.5 m wide by 5-12 m long) were constructed with artificially imposed gaps (10 to 160 cm wide) in the fuel bed (Figure 1). Pine straw fuels were conditioned in an environmental chamber to achieve desired dry (2-6%) and wet (8-17%) fuels moisture levels.

Figure 1 – Fuel bed with pine straw fuels and discontinuous fuel gap layout at IHBS wind tunnel

Fuels were evenly distributed on the burn bed once they were weighed and measured. Light detection and ranging (LiDAR) was used to characterize the 3-dimensional distribution of fuels for each test bed. Local microscale (<1 m) winds were measured at the fuel gap using mechanical 2-dimensional (horizontal and vertical) anemometers combined with fine scale wind simulations. Local energy transport within and above fuel gaps were characterized using established *in-situ* heat flux sensors and methods (Butler, 2004). Infrared and visible imagery of flames and fuels from both horizontal and nadir orientations characterized flame presence and geometry, and kinetic and radiometric fuel surface temperature at the fuel gap. For each wind speed and fuel moisture level, the fuel bed was burned with decreasing gap width until the fire bridged the gap. Once this gap width is identified four replicates, two at the threshold and two at the threshold plus one, were burned under the same environmental conditions to verify the results and aid in the statistical analysis. Measurements for each burn experiment included whether the fire successfully bridged the gap (Yes or No), fire front progression (rate of spread, ROS) using in-situ thermocouples and overhead infrared imagery, radiative and convective energy release from the flames, wind speed, fuel moisture, gap size, relative humidity, ambient air temperature. From these data a statistical dose verses response relation will be developed and analysed to identify critical spatial scales in fuels that affect ignition and subsequent fire spread. Lab and field-scale data will be used to evaluate a new heat transfer based coupled fire/atmosphere model.

3. Experimental Design

We hypothesize that fire can be characterized as a continuous sequence of ignitions and the physical processes governing fire are directly linked. We intend to differentiate ignitions across gaps based on incident energy transport and not from ember transport. This fundamental approach seeks to improve understanding of physical fire scales, identify critical fuel spatial and temporal scales in three dimensions and improve understanding of fuel consumption and fire effects. In order to differentiate ignitions across the gap a series and visual and infrared cameras were deployed from multiple positions.

A series of 70 experiments were conducted at the US Forest Service Missoula Fire Science Laboratory (MFSL) and the Insurance Institute of Business & Home Safety (IBHS) wind tunnel facilities to test fire's response to fuel discontinuities under varying wind conditions and fuel moistures. MFSL is a research facility owned and operated by a US Forest Service and is located in Missoula, MT. The facility encompasses several buildings, including the main test chamber that is equipped with a low-speed wind tunnel capable of generating wind speeds from 0.5-3.0 m/s. This low-speed wind tunnel has a 3x3m cross section and is 26.2m long. IHBS is a $40M research facility owned and operated by a consortium of insurance companies and is located in Richburg, SC. The facility encompasses several buildings, including the main test chamber that is equipped with a vertical wall comprised of 105 interlinked, process-controlled fans. The fan bank is capable of generating hurricane force winds in excess of 54 m/s.

Variables to be tested include wind speed (0.5-9 m/s), fuel moisture (dry and wet) and gap size (10 to 160 cm). Test order was chosen at random to eliminate bias. For each test, fuels were weighed and measured for moisture content to achieve a consistent fuel load (0.56 kg/m2) and a packing ratio (0.02). Fuels were conditioned in an environmental chamber to achieve dry (2-6%) and wet (8-17%) moisture levels. Fuels were evenly distributed on the burn bed once they were weighed and measured. The pre-determined gap size was left void of fuel. Fuel was place at the downwind edge of the gap at the same pre-determined loading and packing ratio.

Each fuel bed at the IHBS test facility was measured using light detection and ranging (LiDAR) prior to ignition. Four separate scans were performed on each burn bed in order the characterize the 3D nature of the fuels. The LiDAR unit used was a Leica BLK360. The laser scans at 830nm wavelength, has a range of 0.6 - 60m, scans up to 360,000 pts/sec and a 3D point accuracy of 6mm at 10m and 8mm at 10m. Most of the points within the fuel bed scans were within 20m. Fuel beds were not scanned at the MFSL due to the complexity and space limitations associated with the wind tunnel design.

Each burn was instrumented with a vast array of sensors. A fire behaviour sensor array was placed at the leading edge of the receiving bed to measure incident heat flux, 2-dimensional wind flow and air temperature. The sensor array contained a total of three Medtherm® heat flux sensors to measure total, radiant and convection incident energy on the receiving bed. The sensor array contained five 2-dimensional Keil static wind probes to measure horizontal and vertical wind velocity at the receiving bed. Finally, the sensor array contained five type K thermocouples to measure air temperature at the receiving bed. All sensors on the fire behaviour array scanned at 180 Hz. The sensor array was constructed of a 5.1 x 15.2 cm metal stud on wooden supports to provide a flush surface between the fuel bed and receiving bed. The gap was filled with 5.1 x 10.2 cm metal studs on wooden supports that were each instrumented with three type K thermocouples to measure air temperature in the gap. The list of imaging sensors used can be seen in Table 1.

Table 1: Visual and infrared sensors used during IBHS test burns.

Sensor	Resolution	Frame Rate	Orientation	Range	Field of View
GoPro	2.7k	24 fps	end, side, nadir	N/A	infinite
Sony	4k	30 fps	side	N/A	infinite
FLIR Duo IR & Visible	640 x 512 4k	30 Hz 24 fpm	side side	-300C - 1035C N/A	45º 56º x 45º
FLIR A655sc	640 x 482	25 Hz	nadir	300C - 2000C	45º
Optris PI 400	382 x 288	27 Hz	nadir	-20C - 900C	13º

These imagers were deployed in several configurations to monitor fire rate of spread, flame geometry, flame impingement across the fuel gap, ember transport across the fuel gap, fuel particle temperature and radiant energy release. The GoPro cameras were placed in three separate configurations: end view, side view and nadir view (Figure 2). This imagery will be used to quantify flame geometry and fire rate of spread. The Sony camera was oriented side view at the gap to measure flame geometry as well as flame impingement on the receiving bed.

Figure 2: In order; GoPro screen capture of end view, side view at the gap and nadir view of burns.

Two infrared cameras were deployed during the MFSL experiments, and three infrared cameras were deployed during the IBHS experiments for each of the test burns. Ground control points were established for each infrared camera for image rectification. The Optris PI400 was oriented nadir to the fuel bed. The narrow field of view (FOV) on the Optris made it ideal for determining fuel particle temperature, whether fire crossed the gap and if ignition was derived from ember transport or flame impingement. The FLIR A655sc was oriented nadir to the fuel bed for the IBHS experiments. The wide angle on the A655sc allowed for full view of the fuel bed and was used primarily for fire rate of spread and radiate energy release. The FLIR Duo is a dual infrared and visible high-resolution imager. This camera was oriented to the side and above the gap and was primarily used to determine fuel particle temperature, whether fire crossed the gap and if ignition was derived from ember transport or flame impingement. (Figure 3).

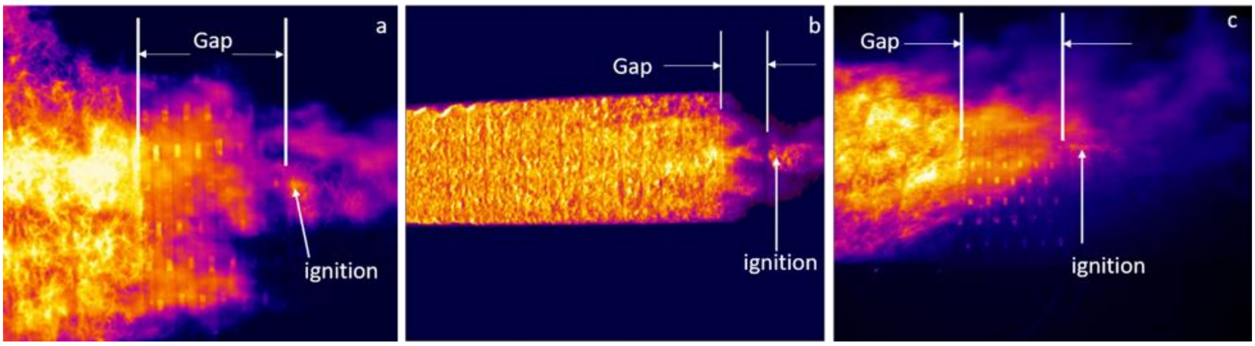

Figure 3: (a) imagine from the Optris PI400, (b) image from the FLIR A655sc, (c) image from the FLIR Duo.

4. Results

Four test scenarios were designed for the both the MFLS and IBHS test facilities. These include, 1) low wind speed/dry fuels, 2) low wind speed/wet fuels, 3) high wind speed/dry fuels and 4) high wind/speed wet fuels. The test scenarios were chosen at random to eliminate bias. All tests in a series were completed before changing to the next set of parameters to maintain consistent weather conditions. For each wind speed and fuel moisture level, the fuel beds were burned with decreasing gap width until the fire bridges the gap. Once the gap width was identified, four replicates were burned under the same environmental conditions to verify the results and aid in the statistical analysis. Two replicates were burned at the gap size where fire crossed the gap to identify probability of a false positive and two replicates were burned at the increased gap size where fire did not cross to identify probability of a false negative result. Table 2 outlines the results from the four test scenarios.

Table 2: Summary of test results showing wind speed, fuel moisture, gap size and whether the fire crossed the gap.

Test Series	Wind Speed (m/s)	Fuel Moisture	Gap Size (cm)	Crossed Gap (Y/N)	Replicate Crossed (Y/N)
MSFL					
Low Wind/Dry Fuel	0.5	Dry	10 17	Yes No	Yes/Yes No/No
Low Wind/Wet Fuel	0.5	Wet	15 23	Yes No	Yes No/No
High Wind/Dry Fuel	1.0	Dry	39 46	Yes No	Yes/Yes No/No
High Wind/Wet Fuel	1.0	Wet	23 39	Yes No	Yes/Yes No/No
IBHS					
Low Wind/Dry Fuel	6	Dry	100 110	Yes No/No	Yes/No No/No
Low Wind/Wet Fuel	6	Wet	90 100	Yes No	No/No No/No
High Wind/Dry Fuel	9	Dry	150 160	Yes No	Yes/Yes No/No
High Wind/Wet Fuel	9	Wet	120 130	Yes No	Yes/Yes No/No

The data suggests that the incident energy threshold required to cross the fuel gap is extremely narrow, in each case the separation distance was equal to or less than 10 cm. The low wind speed wet fuels scenario initially crossed a gap of 90 cm, but neither replicate crossed suggesting a false positive at this setting. This test scenario will be repeated at a future date. Comparing data between the two test facilities shows linear alignment, but mid-range wind speeds are lacking (Figure 4).

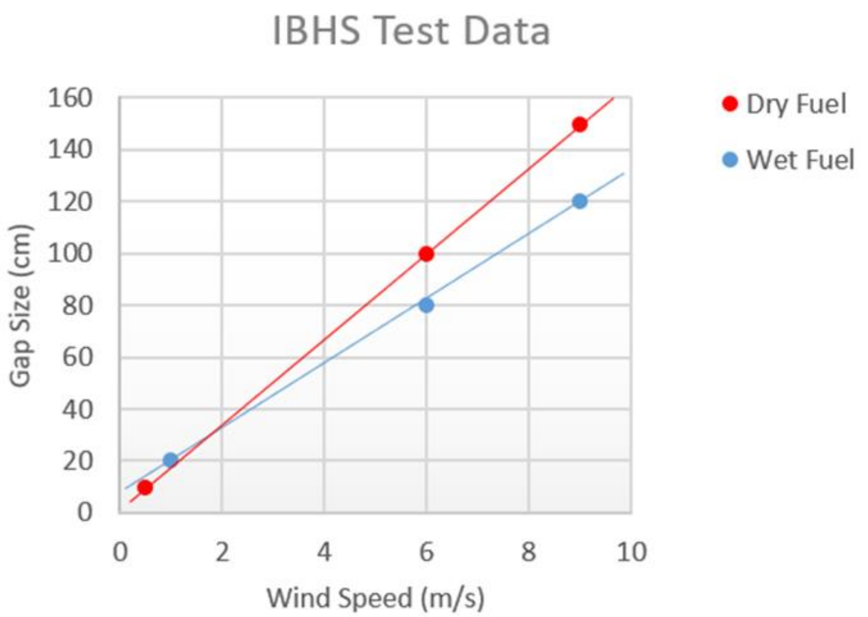

Figure 4: Test results comparing low wind speed data collect at FiSL and high wind speed data collected IBHS.

This poster will outline the methods, experimental design, and initial results from the data collected to date.

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