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A preliminary study of wildland fire pattern indicator reliability following an experimental fire

Albert Simeoni[1], Zachary C Owens[2], Erik W Christiansen[2], Abid Kemal[2], Michael Gallagher[3], Kenneth L Clark[3], Nicholas Skowronski[3], Eric V Mueller[4], Jan C Thomas[4], Simon Santamaria[4] and Rory M Hadden[4]

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Abstract
An experimental fire was conducted in 2016, in the Pinelands National Reserve of New Jersey, to assess the reliability of the fire pattern indicators used in wildland fire investigation. Objects were planted in the burn area to support the creation of the indicators. Fuel properties and environmental data were recorded. Video and infrared cameras were used to document the general fire behavior. This work represents the first step in the analysis by developing an experimental protocol suitable for field studies and describing how different fire indicators appeared in relation to fire behavior. Most of the micro- and macroscale indicators were assessed. The results show that some indicators are highly dependent on local fire conditions and may contradict the general fire spread. Overall, this study demonstrates that fire pattern indicators are a useful tool for fire investigators but that they must be interpreted through a general analysis of the fire behavior with a good understanding of fire dynamics.

Keywords
Wildland fires, field experiments, fire investigation, fire pattern indicators

[1]Jensen Hughes, Framingham, MA, USA
[2]Exponent Inc., Menlo Park, CA, USA
[3]Northern Research Station, USDA Forest Service, Newtown Square, PA, USA
[4]School of Engineering, The University of Edinburgh, Edinburgh, UK

Corresponding author:
Albert Simeoni, Jensen Hughes, 1661 Worcester Road, Suite 501, Framingham, MA 01701, USA.
Email: asimeoni@jensenhughes.com

Introduction

Wildland fires have a dramatic impact on the environment, human life, and property and cause significant economic losses, as demonstrated by the devastating wildfires that have occurred over the past few years.[1] The impact of these fires is expected to increase dramatically[2] with the rapid expansion of the wildland–urban interface (WUI)[3,4] and because changing climate will likely increase the probability and intensity of wildland fires.[5] To face this challenge and properly address the issues related to the ignition of those fires, it is necessary to ensure that their origin and cause are accurately determined.

In the United States, the *Guide to Wildland Fire Origin and Cause Determination* (a revised version of which was published recently)[6] and NFPA 921: Guide for Fire and Explosion Investigations[7] provide guidance on conducting wildland fire origin and cause investigations. This study will refer to the Guide[6] as it is more detailed and it is dedicated only to wildland fire investigation. The Guide presents a systematic method of investigation for the origin and cause determination and relies on fire pattern indicators. A fire pattern indicator is a physical object that displays changes when affected by a fire. An overall fire pattern is derived from the accurate analysis of individual fire pattern indicators and shows the general fire progression. The Guide presents the following 11 indicators:[6] protection, grass stem, freezing, angle of char, spalling, curling, sooting, staining, white ash, cupping, and V or U patterns. The Guide also includes a discussion on the reliability of fire pattern indicators and exceptions that may apply under certain conditions.

The indicators are further divided into two classes: macroscale fire pattern indicators and microscale fire pattern indicators.[6] The macroscale fire pattern indicators are associated with large objects and are easily noticeable, for example, an angle of char on a tall tree. On the other hand, microscale fire pattern indicators are only observable by getting up close to an object, such as studying a blade of glass using a magnifying glass. Interpreting microscale fire pattern indicators typically becomes more important as investigators work closer to the ignition area.

The focus of this article is to provide a first analysis of the fire pattern indicators recorded on one of the two experimental fires conducted in the New Jersey Pine Barrens in Spring 2016. The experimental fires happened in the context of a research project linked to the study of ember production and fire behavior in large-scale, medium- to high-intensity field experiments.[8,9] The fire of interest displayed a high intensity due to passive crowning when going through the study area of the fire pattern indicators. This investigation of indicators is symbiotic with the ember and fire spread studies because the fire behavior and other environmental conditions were observed in detail using a large set of instruments. Several items were planted inside the burn parcel to support the appearance of certain microscale indicators in addition to microscale indicators that appeared on natural vegetation. The analysis of the fire pattern indicators coupled with the measurement of the fire properties provide an exceptional scientific framework to study the reliability of the indicators in the specific conditions of the experimental fires and to complement the studies supporting the *Guide to Wildland Fire Origin and Cause Determination*.[10] The ultimate goal of this research is to provide a scale of reliability for the different indicators and the objects where they appear. Here, we present the framework that we will use further in the field and some preliminary results following our first field experiment. We hope that this work and its future developments will help fire investigators to better use the fire pattern indicators by better understanding their reliability and how they appear in relation to fire behavior. For this study, we focused on the fire behavior as observed through the visual cameras and provided some measurements of the fire properties that were necessary to better understand fire behavior.[9] The interested reader is referred to another article[11] fully dedicated to fire behavior to get more details on this aspect.

Methods

Study site

The experimental fire was conducted in the Pinelands National Reserve (PNR) of New Jersey, USA. The PNR is more than 1 million acres and is host to an active fuel management program by the New Jersey Forest Fire Service and federal wildland fire managers. The climate is classified as cool temperate, with mean monthly temperatures of 0.3°C in January and 24.3°C in July and a mean annual precipitation of 1159 mm. The terrain consists of plains, low-angle slopes, and wetlands, with a maximum elevation of 62.5 m. A burn parcel covering an area of approximately 28 ha was used for the experiments. The forest canopy in the parcel was composed primarily of pitch pine (*Pinus rigida* Mill.), with intermittent oaks (*Quercus* spp.). Understory vegetation was dominated by 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*) in relative order of importance.

Measurement techniques

Point measurements of fire behavior were made using two fire behavior packages (FBPs), each supporting various instruments, such as thermocouples, heat flux sensors, and pressure probes for the measurement of air velocity.[9,11] Additionally, a raised platform (17 m) supported a three-dimensional (3D) sonic anemometer, a visual camera, an infrared camera, and a weather station. Eighteen video cameras were positioned around the FBPs to obtain front, back, and side views of the fire at different view angles, showing fire spread at ground and canopy levels. All the instruments were distributed within the area to be burned, excluding a few cameras to obtain a large view of the fire front and the raised platform, which was situated at the edge of the fire and allowed for the measurement of ambient, near-fire wind, and weather conditions during the time of the fire. Fire indicators were planted in clusters in three different areas on the parcel as shown in Figure 1.

Fifteen destructive harvest locations were randomly chosen before and after the fires. At each location, surface fuels in a 0.5 m^2 area were harvested down to mineral soil. Pre-burn sampling was conducted within the 2 weeks prior to the burns, and post-burn sampling was conducted within the week following treatment. All shrub and forest floor materials present down to and excluding the duff layer (O_i soil horizon) were dried at 70°C for a minimum of 48 h, sorted into different fuel classes and types, and weighed. Since destructive harvest sampling cannot be resampled again after treatments, assessing fuel consumption is challenging. We used the OpenBUGS (OpenBUGS, version 3.2.3 rev 1012) Markov chain Monte Carlo (MCMC) simulator[12] to resample and derive the distributional properties of the fuels in each plot from the harvested samples. These distributions allowed for estimates of pre-burn loading, post-burn loading, and consumption for each fuel type across each burn unit.

An average value for the forest canopy biomass was estimated before and after treatments in three permanent 20 × 20 m plots, using a Riegl Laser Rangefinder (Model # LD90-3100VHS-FLP; RIEGL USA, Orlando, FL, USA). Following the methods described by

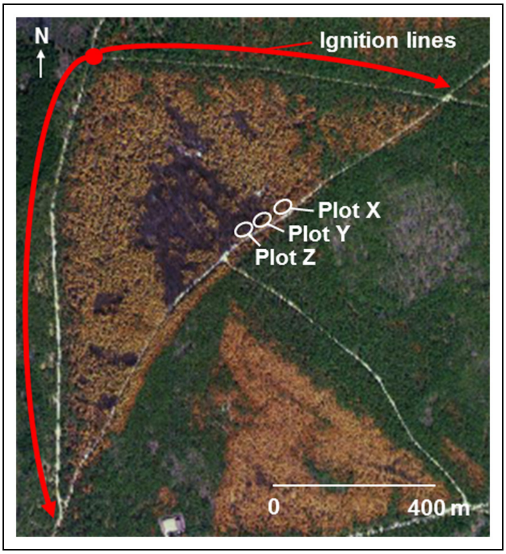

Figure 1. Aerial view of the parcel with the location of the three fire indicator plots and the representation of the two ignition lines along the parcel edges from the same starting point.

Clark et al.,[13] 21 parallel transects spaced 1 m part were paced at a consistent rate with the LiDAR unit and logged to a Trimble Ranger. The device was carried at a height of 2 m, at the top of the shrub layer, providing canopy data above that height. Raw transect data were summarized into 1-m height bins across each plot and were used to estimate available canopy fuel loading from the equation for pitch pine-dominated stands in Clark et al.[13] The available canopy fuels include live and dead needle, as well as biomass with diameters ranging between 0 and 6.36 mm and 6.36 mm and 1 in. We estimated a canopy height of range 14–22 m from the LiDAR data.

In addition to ground estimates, vertical profiles of the canopy were estimated by airborne laser scanning. Data were collected for the two parcels prior to the fire on 1–10 January 2013 and after the fire on 19 April 2016. These data collections were conducted so that they were as identical as possible for the sake of change characterization. A fixed-wing aircraft was used with a Riegl LMS-Q680i LiDAR sensor head (Riegl GmbH, Horn, Austria) on board. The aircraft was flown at an average altitude of 675 m with an average pulse density of 5.12 pulses/m^2. These data were pre-processed using the TIFFs Toolbox for LiDAR Data Filtering and Forest Studies.[14] Canopy bulk density profiles were then estimated from these data through methods presented in Skowronski et al.[15]

Moisture content was estimated for surface and canopy fuel components. Five samples, including the forest floor, shrub, pine needles, and pine twigs, were harvested, weighed wet, dried for 48 h at 70°C, and weighed dry.

Burn conditions

The fire was conducted in the Penn State Forest part of the PNR on 18 March. Figure 2 shows a typical vegetation layout on the parcel. Two simultaneous ignitions of the parcel were carried out by the New Jersey Fire Service, using drip torches along the whole length

Figure 2. Typical vegetation layout on the parcel.

Table 1. Measurements of fuel load (±relative standard deviation) for the vegetation samples collected on the parcel.

Fuel	Pre-burn (T/ha)	Post-burn (T/ha)	Consumption (T/ha)
Canopy (pitch pine)			
Pine needles, twigs up to 2.54 cm in diameter	26.24±0.88	16.48±3.90	9.70±8.72
Surface fuel			
Leaves	0.07±5.68	0.00±0.04	0.04±0.21
Stems up to 6.36 mm in diameter	5.35±0.36	2.04 ±1.19	3.31±1.24
Forest floor			
Fine (diameter below 6.36 mm)	13.94±5.68	4.20±2.50	9.74±6.20
Wood between 6.36 mm and 2.54 cm in diameter	1.31±0.98	0.76±0.64	0.55±1.17

of the roads bordering the western and northern sides of the parcel (see red arrows in Figure 1). Ignitions started from the northwest corner of the parcel (see red dot in Figure 1) at 5:55 p.m. (EST) and lasted for approximately 15 min, until the opposite end of the parcel sides was reached. The duration of the fire was determined to be approximately 25 min, although much of the parcel was consumed in 15 min. During this 25-min period, the mean ambient temperature was around 13.4°C and the mean relative humidity was 21.7%. The wind was also quite constant with a direction of WNW and an average speed of 1.4 ± 0.6 m/s (mean ± 1 standard deviation (SD)). Occasional gusts of 4.4 m/s were observed, as well as lulls of 0.5 m/s (1-min maximum and minimum values).

Fuel moisture content (FMC), expressed as a percentage of water mass over oven dry mass, for all forest floor fuels and surface fuels was 30.6 ± 10.8% and 64.5 ± 7.6%, respectively. For the canopy, pine needle and twig FMC was 122.3 ± 6.9% and 83.5 ± 5.4%, respectively.

The fuel loads for the finest fuels that supported the fire spread are presented in Table 1. For these fine fuels, an average of 37% of the canopy was consumed, as well as 62% of the surface fuels and 67% of the forest floor.

The average vertical profiles of the canopy bulk density, estimated from airborne laser scanning for the returns that fell directly within the spatial extent of plots X, Y, and Z, are

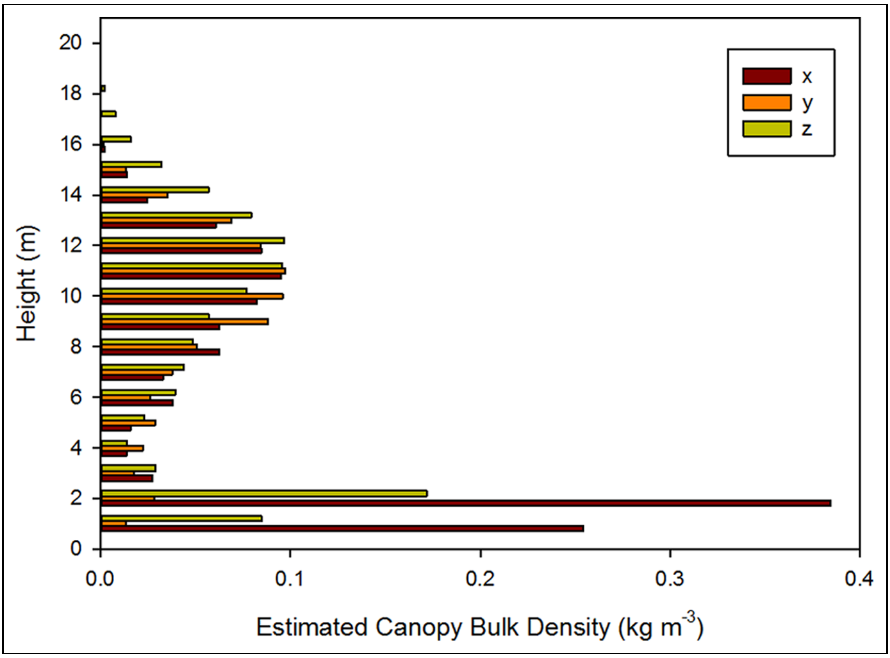

Figure 3. Estimation of the average vertical distribution of the canopy bulk density (kg/m^3) for plots X, Y, and Z.

shown in Figure 3. The pre-fire vertical canopy structure was similar between the three plots, except within the first 0–2 m. X had the largest canopy density—made of shrubs and lower branches of trees—followed by Z and Y. Unfortunately, the airborne laser scanning data did not provide enough sensitivity to estimate the vertical distribution of the fuel consumption through the whole canopy height. The sensitivity was only sufficient to detect fuel consumption in the 0–2 m zone (see Figure 3) with reductions of 41%, 68%, and 70% for plots X, Y, and Z, respectively.

Fire pattern indicators

The 11 fire pattern indicators mentioned in the Guide are as follows:[6]

- *Protection*. When a non-combustible object or the fuel itself shields the unexposed side of a fuel from heat damage.
- *Grass stem*. The charred remains of grass stems will have different appearances depending on the fire spread.
- *Freezing*. Softened heated leaves and branches are bent in the direction of the flow and cool down and stiffen in the same direction.
- *Angle of char*. Formed by the fire spreading along standing fuel (trees, poles, ...).
- *Spalling*. Chipping or splitting of rocks due to heat.
- *Curling*. Heated leaves curled by the heat from the fire.
- *Sooting*. Soot deposit by the fire.
- *Staining*. Deposit of distillates from the fire.

Figure 4. One set of items for creating a fire pattern indicator cluster.

- *White ash*. Zones where ash is coating the ground or the vegetation.
- *Cupping*. Concave or cup-shaped char pattern on small vegetation elements due to the directional nature of heat transfer during fire spread.
- *V or U patterns*. V or U shape associated with typical wildfire progression in the early stages of a fire.

The reader is encouraged to read the section on fire pattern indicators of the Guide to better understand this work and put it in perspective.

Some of the usual types of support for fire pattern indicators were very scarce or not present at all on the parcel. This was due to the type of landscape and ecosystem, as well as the fact that the parcel was located in interior forest, quite far from paved roads. Hence, some supporting items were planted in clusters at different locations (X, Y, and Z in Figure 1) to support the appearance of microscale fire pattern indicator clusters.[6] Figure 4 displays a set of supporting items used at every location. The set consists of fence elements (plastic, wood, and metal), soda cans, aluminum and wooden poles, tomato nets, ornamental bricks, stones and metal flowers, as well as beer bottles (not included in Figure 4).

Due to the type of vegetation, the ignition procedure (line fire), the intense fire behavior, the supporting items used for the indicators (small planted items), and the post-fire weather conditions (rain), it was not possible to observe all the indicators mentioned in the Guide.[6] Only the following ones are described hereafter: protection, freezing, angle of char, spalling, curling, sooting, staining, and cupping. Grass stems, white ash, as well as V or U patterns could not be observed and are not included in the analysis.

Results

Fire behavior

The wind was pushing the western fire line eastward (in the ENE direction), whereas the northern ignition line spread slower because it was not aligned with the wind and was much less influenced by it. The two lines finally joined as the northern line pulled toward the western line, converging in a zone located on the east side of the planted items (left of plot X in Figure 1). When the fire reached the planted items, it was very intense, due to a combination of the fuel layout (ladder fuel) and wind.[11] The fire line was also orientated WSW because of the convergence of the two fires, making the more intense fire line from the west rotate slightly toward the fire line coming from the north ignition.

The fire pattern can be observed in Figure 1. The vegetation close to the ignition lines was only consumed on the ground, showing an untouched canopy for a few meters. Then, the surface fire gained in intensity and the canopy was dried and discolored by the heat from the fire plume. Fair and dark spots show locations of low-intensity surface fires and torching trees, respectively. The large black area in the middle of the parcel and close to the fire pattern indicator clusters represents totally consumed trees, making the blackened soil below visible. This was the area of highest fire intensity, just ahead of the fire indicator study sites. For the three indicator plots X, Y and Z, the fire spread approximately from west to east. The fire was decreasing in intensity when traveling from Z to X, Z being impacted by the fully developed crown fire while X was in the transition area from crown to surface fire (see Figure 1, where the canopy over X is not fully consumed). This decrease was mainly due to the fuel load on the ground as Z contained a very dense layer of shrubs of an approximate height of 2–2.5 m, while X contained lower shrubs around 50–80 cm height. Y was in a transition zone but was mainly covered by thick and high shrubs. However, for all sites the fire had the characteristics of an advancing fire and was not representative of the fire starting to spread around the origin area.[6] The fuel consumption estimated from the airborne laser scanning data in the 0–2 m zone is consistent with the observed fire behavior (reductions of 41%, 68%, and 70% for plots X, Y, and Z, respectively), but not accurate enough to be used in the quantitative analysis below. Hence, in the following, we used the values from the ground measurements (Table 1) to estimate the fire intensity.

The difference in fire behavior can be seen in the flame heights observed in video footage, as shown in Figure 5. Such variability in behavior has been observed previously in this ecosystem and is linked to the fuel structure (ladder fuel) and wind.[11]

A local spread rate of 0.289 ± 0.014 m/s, between plot Z and plot X, was calculated from the timing of the fire arrival, as determined by temperature measurements.[9] Based on video footage (Figure 5) and post-fire assessment, it was assumed that surface fuels were the predominant contributors to fire intensity in the vicinity of plot X. Using the plot average for surface fuel consumption of 1.36 ± 0.64 kg/m^2 (Table 1), the fire intensity was estimated to be 7350 ± 3480 kW/m. At plot Z, however, significant canopy fuel consumption occurred. Adding the plot average for this fuel gives a fire intensity of 12,590 $\pm$5870 kW/m, although it is likely to be on the upper end at plot Z, as the canopy consumption was higher than average in this region (Figure 1).

The range of fire behavior between plots X and Z can also be seen in the time–temperature curves obtained from the thermocouple measurements (Figure 6). At plot X, there was not a strong temperature rise at 5.0 m, and the small temperature increase occurred in advance of the main fire arrival at the ground (0.2 m), suggesting a somewhat tilted plume. At plot Z, however, there was a more significant temperature rise at 5.0 m, with temperatures in excess of 300°C (considered a threshold temperature for the visible flame tip in vegetative fuels[9]) for a significant period of time. Coupled with the significant overlap in temperature rise at the lowest at highest thermocouple, this suggests upright flames extending into the canopy, in agreement with Figure 5.

(a)

(b)

(c)

Figure 5. Still shots from video cameras placed locally at (a) plot Z—across the road, (b) plot X—across the road, and (c) plot X—from above.

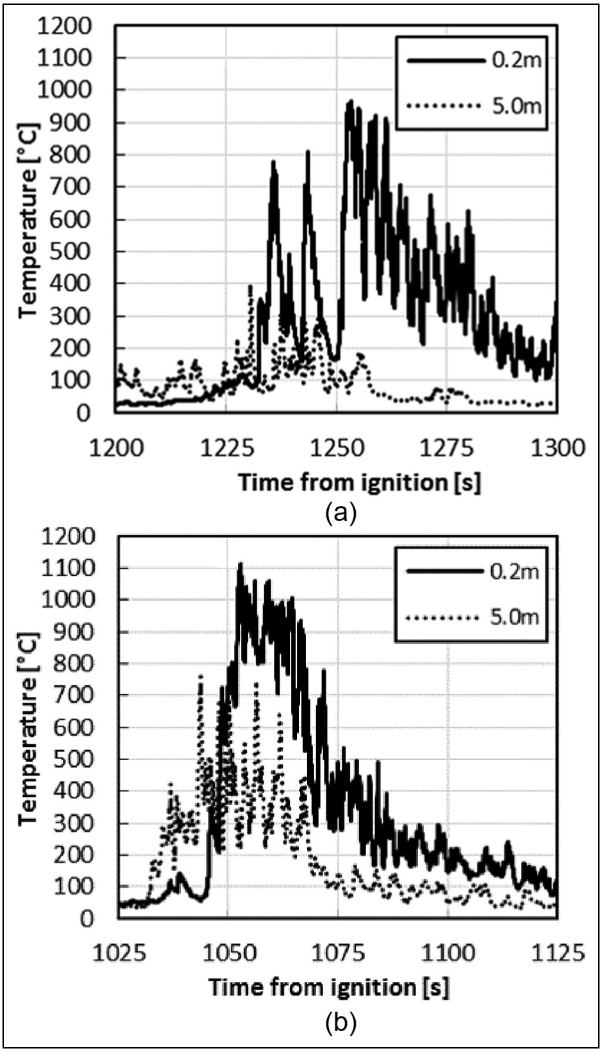

Figure 6. Thermocouple measurements at 0.2 m and 5.0 m for (a) plot X and (b) plot Z.

The temperature data from the six thermocouples at each site were also used to obtain an estimate of flame height.[9] Using a common relationship between flame height and fire intensity,[16] a value of ~1700 kW/m was estimated for plot X and 8600 kW/m was estimated for plot Z. These are lower than the values obtained using the spread and fuel consumption estimates (due to uncertainty in local spread, fuel consumption, and flame height), but still serve to highlight the difference in fire behavior as the transition between crown fire and surface fire occurred between plot Z and plot X.

The analysis of the fire indicators will thus be focused on the determination of the direction of spread in the fully developed fire. For a wildland fire investigation, this would represent the beginning of the analysis when the fire investigator is working from the advancing side of the fire toward the area of origin.[6]

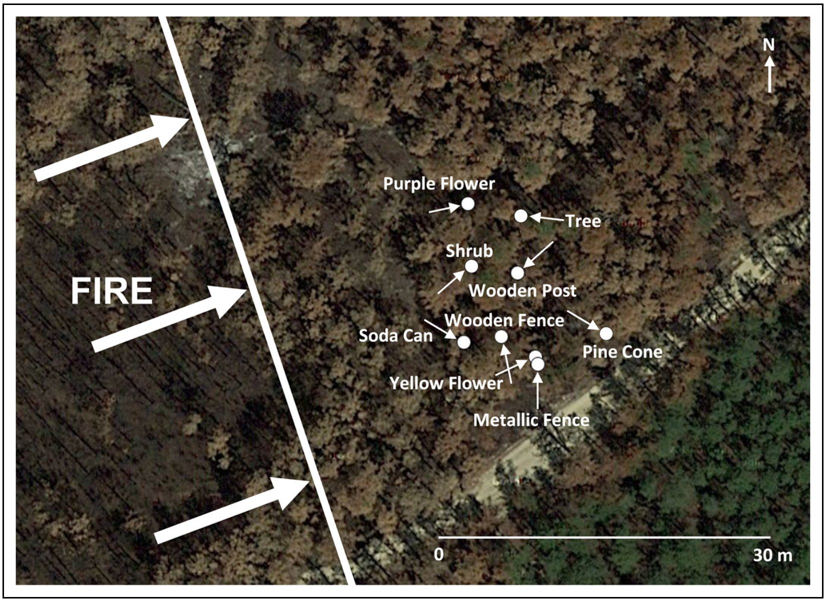

Figure 7. Fire indicators at plot X; the arrows show the direction of heat impact from the fire front.

Fire indicators

Figure 7 displays as a line the overall direction of fire spread as observed with the video cameras, and the arrows pointing to the planted items and trees represent the direction of maximum heat impact. The arrows show that the maximum heat impact generally comes from the fire front as described in the Guide.[6] The direction of maximum heat impact is roughly aligned with the direction of fire spread for the soda can, the purple flower, the shrub, the yellow flower, and the pine cone. The soda can and pine cone are offset by around 45°, which is still in an expected range due to local fire behavior variability.[6] The pre- and post-burn analyses showed that the soda can, which was half-buried in vegetation, did not move during the fire.

Figure 8 shows the microscale fire pattern indicators found on the soda can (Figure 8(a)), the pine cone (Figure 8(b)), the shrub and the wooden pole (Figure 8(c)), and the yellow flower (Figure 8(d)). The soda can revealed staining and protection, the pine cone charring and protection, the shrub freezing and curling, and the flowers a combination of staining and charring of the coating (they were ornamental garden items made of painted steel).

The stain on the soda can was very pronounced and the protection behind it showed untouched pine litter (Figure 8(a)). The pine cone was charred in the direction of the upcoming fire front and the litter behind it was untouched (above the pine cone in Figure 8(b)). The few shrubs that were not totally consumed showed clear freezing in the direction of the fire spread. Curling of the leaves did not exhibit any clear directionality (see freezing direction in Figure 8(c)) because freezing obfuscated any directionality that may have been present. Curling usually happens ahead of the fire front and freezing usually happens behind the fire front, during the time the leaves are cooling down, and will orientate the leaves in the wind direction. This is why the microscale curling indicator is more reliable for low-

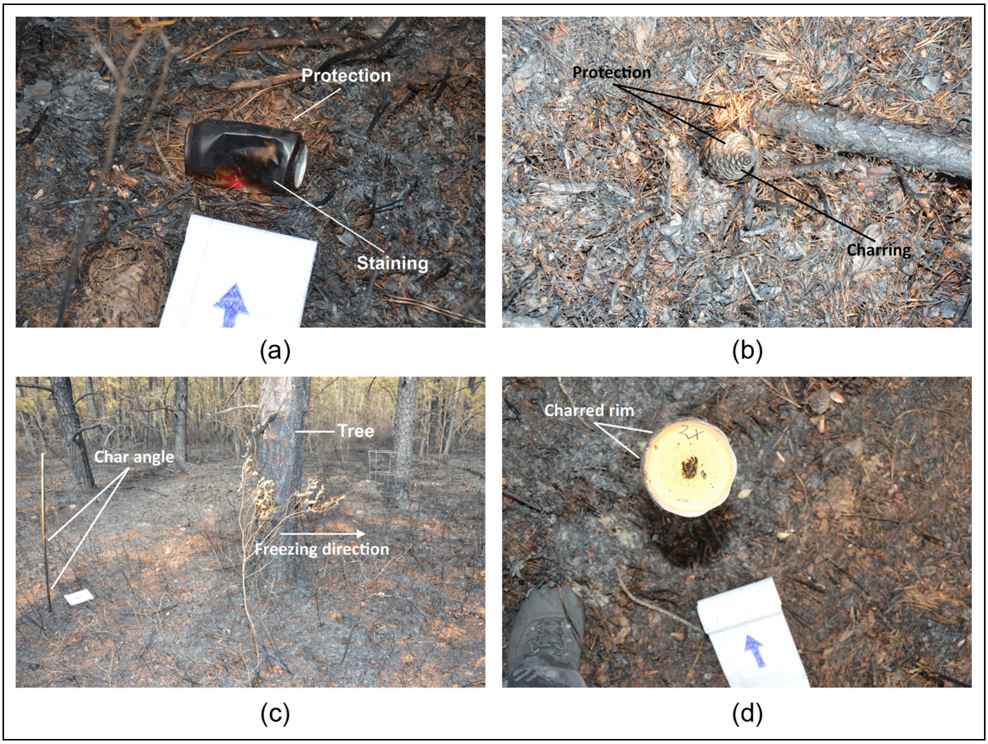

Figure 8. (a) Soda can with staining on one side and protection behind the other side (the fire spread from bottom to top in the image), (b) pine cone with charring on one side and protection behind the other side (the fire spread from bottom to top in the image), (c) shrub with a combination of freezing and curling, and wooden pole with char angle (the fire spread from left to right in the image), and (d) yellow flower with the paint charred on its rim (the fire spread from bottom to top in the image).

intensity, backing fires when freezing is less likely to happen.[6] In addition, this species of shrubs (briar) has a very thick cuticle, which makes curling by the heat from the fire front less likely to happen in the fire direction.[6] The wooden pole showed a clear angle of char (from bottom left to top right of the pole in Figure 8(c)). The low side of the char was located on the side facing the fire, which is characteristic of an advancing fire, according to the Guide.[6] The ornamental steel flowers were planted to identify some natural features, such as logs or trees and allow them to be found after the fire. However, they displayed a very clear staining and charring pattern (see charred rim in Figure 8(d)) that was very consistent with the direction of spread (see "yellow flower" and "purple flower" and their respective arrows in Figure 7). This is attributed to the curved surface of the top the flowers that had an optimal view angle to capture radiative heat coming from the fire front. A tree trunk showed a direction of heat impact opposed to the fire spread (see "Tree" in Figure 7). The tree trunk (see tree in Figure 8(c)) displayed a char angle similar to the one of the wooden pole, consistent with the characteristic of an advancing fire, according to the Guide.[6] Its canopy was mostly intact and did not exhibit much scorching. The other planted items (the plastic fence, one soda can, the aluminum pole, the tomato net, the ornamental bricks, and the beer bottles) did not show a clear directionality and were not included in Figure 7.

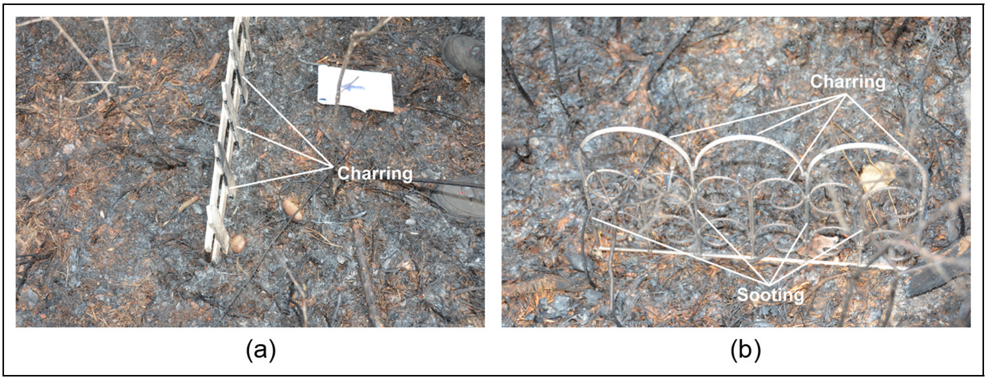

Figure 9. (a) Wooden fence charred on one side (the fire spread from bottom left to top right in the image) and (b) metallic fence charred on one side (the fire spread from bottom left to top right in the image).

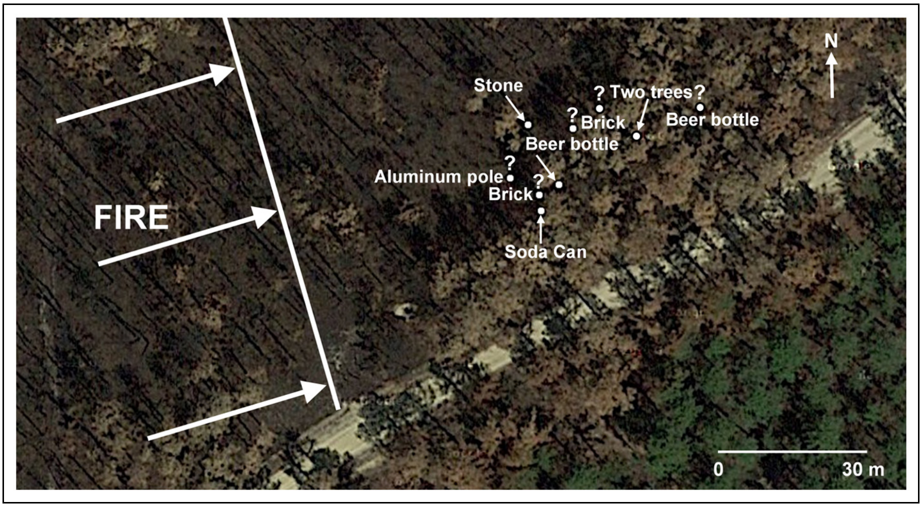

Figure 10. Fire indicators at plot Y; the arrows show the direction of the heat impact from the fire front; the interrogation marks mean that no direction could be determined.

Figure 9(a) and (b) shows the wooden and metallic fences, respectively. The plastic fence was totally consumed. The wood fence exhibited charring and the metallic fence sooting and charring of its coating. These two fences showed a direction of maximum heat impact almost parallel to the fire front, while they should have shown a maximum heat impact on the side exposed to the arriving fire front. This is mostly attributed to the fact that these fence elements were long and very thin and could only show a direction aligned with their orientation on the parcel, which was almost exactly perpendicular to the arrows shown in Figure 7.

Figure 10 shows the indicator cluster for plot Y. The few indicators showing any directionality are very similar to those described for plot X (as seen in Figures 8 and 9) and the

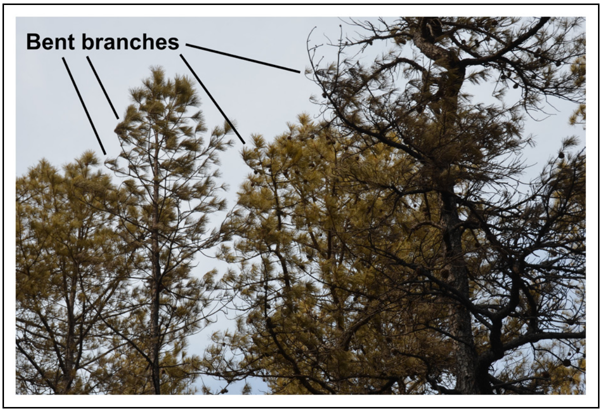

Figure 11. Crown freezing (the fire spread from left to right in the image).

indicators showing no directionality were impossible to read because they were unstained or totally charred, making post-fire photographs useless in this case. The first thing to notice is that most of the items did not display a clear directionality (interrogation marks in Figure 10). Those items are of the same type as those which did not display any directionality for plot X. There are also less items to display because the fire was more intense when passing through Y than when it was passing through X (see Figure 5). For instance, the wooden pole and one soda can were totally destroyed, and the ornamental steel flowers were totally charred and stained. For the items that showed directionality, their angles were all offset from the direction of spread. The stone and soda can exhibited staining, the wooden fence was charred, and two tree trunks were fully charred but showed differential damage. The direction of the damage (more charring on the side opposed to the fire) was consistent with the direction of spread but exhibited an offset angle. This last feature is consistent with a wind vortex flame wrap around the tree trunk,[6] as explained in the following section. The stone and wooden fence, as well as two trees showed the direction of fire spread with an offset angle greater than 45° and the soda can showed an impact direction almost parallel to the direction of fire spread. Overall, this cluster showed a less clear picture of the general fire spread.

No figure was included for plot Z because none of the items displayed a clear pattern. It is worth mentioning that plot Z was located in the most intense zone of the fire (see Figure 5), where all the tree canopy, shrubs, and forest floor fuels were totally consumed (even some of the thicker fuels not displayed in Table 1 fully disappeared). Plot Z displayed very few macroscale indicators as well, because all the vegetation was heavily damaged, blurring the directionality. This is consistent with a very intense head fire.[6]

In addition to the clusters of microscale fire pattern indicators, some macroscale indicators were also noticeable around plots X and Y. Figure 11 shows crown freezing. The direction of freeze (see bent branches in Figure 11) was consistent with the direction of fire spread all around plot X and mostly around plot Y. It was not distinguishable around plot Z because all crowns were fully consumed. The crowns were usually discolored, which showed that the hot gases from the fire plume were softening the small branches that stiffened again in the direction of the flow when cooling down.

Figure 12. Cupping (the fire spread from bottom right to middle left in the image).

Figure 12 displays cupping on shrubs (see the beveled burned branch sections pointed out in the figure), which were clearly showing the direction of fire spread. There was more cupping for the branches facing the fire front (circled in Figure 12) and less cupping in the opposite direction, as it can be seen in the back face of the shrub in Figure 12. This is consistent with the fact that the branches were more exposed to the heat from the fire front when facing the approaching fire.[6] The shrubs were burned to the ground at plot Z, so this feature was not observable there.

Discussion

The specificity of the ecosystem, the ignition procedure, the weather conditions, and the nature of the planted items did not allow for the observation of all the 11 fire pattern indicators from the Guide.[6] The ground in the Pine Barrens is covered by pine needles so very little grass is present, making the grass stems indicator not possible to observe. Most of the planted indicators that could display any sooting (metallic fence and tomato net) were quite thin and the precipitations following the fire made pinpointing any specific direction not possible. Larger indicators mostly displayed charring and not sooting (even if the metallic fence had some). In addition, the aluminum poles did not collect enough soot to provide any meaningful results. Any white ash present after the burn was likely washed away by heavy rains a few hours after the fire. The sandy soil did not have any rocks present on the ground, so some stones and bricks were planted but even if some spalling was observed, it did not indicate any specific fire direction. Only one stone (more than 30 overall) that was located on plot Y was stained enough to show the fire spread direction with an offset angle (see Figure 10). A "U" or "V" pattern could not be observed because of the line ignitions and the lack of slope on the parcel. In general, the planted items supported the appearance of microscale fire pattern indicator clusters that allowed the determination of the average direction of fire spread. The addition of the macroscale indicators, such as freezing, angle of char, and cupping, allowed to align the guessed direction of fire spread based on all indicators to the one determined through the video cameras and the FBPs for plots X and Y.

Macroscale indicators seem to be the most appropriate for an area of intense burning, even after rain impacted the area. Another reason reinforcing macroscale indicators in this experiment is the fuel distribution of this specific ecosystem in three different fuel layers: crown, shrub, and ground. The microscale indicators were mainly influenced by the surface fire and particularly by the flames on the ground. Local heterogeneities on the ground can add significant uncertainty and local fire properties showed variations compared to the general fire spread that included tree crowns and the upper part of the shrub layer. However, when the fire is too intense, it becomes very difficult to read any pattern. Plot Z, where the fire was the most intense, did not allow for the determination of any obvious direction of fire spread. However, it should be noticed that fire pattern indicators were visible around plot Z, before and after the zone where the fire exhibited full crown involvement (large dark area in Figure 1). Thus, it was possible to determine the direction of fire spread around this zone. These observations are consistent with the *Guide to Wildland Fire Origin and Cause Determination*.[6]

However, some indicators showed a lack of consistency that deserves to be noted:

- Some of the tree trunks in plots X and Y displayed wind vortex flame wrap (see Figure 13) due to flame attachment downwind on the trunk. If this effect is mentioned in the Guide,[6] it is attributed to the wind. The wind was quite low (1.4 m/s in average), but the fire was very intense. Thus, most of the damage observed on the leeward side of the trunks was due to the air sucked into the fire front from the back of the fire.
- This fire front influence also applied to crown freezing (Figure 11). For this fire, crown freezing was mostly showing the direction of the spread (ENE as seen in

Figure 13. Still shot from video camera at plot X showing tree trunk with wind vortex flame wrap.

Figure 14. Still shot from video camera at plot Y, showing spotting on plot Y that occurred at the approximate location of the soda can (the wooden fence can be seen on the top right of the spot fire).

Figures 7 and 10) and not the direction of the wind (pointing ESE). The Guide mentions that foliage freezing generally shows the wind direction but can also be due to the draft from the fire.[6] This was the case here due to the low average wind velocity and the gusts of wind did not change the direction of foliage freezing.

- There was a large amount of spotting on the parcel. Figure 14 shows spotting occurring on plot Y, at the approximate location of the soda can (the wood fence can be observed on the right of the spotting fire). This spot fire is likely to have caused the soda can indicator to have pointed north (see Figure 10).
- The flat fence elements could not show any direction that was not perpendicular to them. Fire effects on fences have been studied in detail,[17,18] and this research could be used in the future to understand how larger fence elements are impacted by fire spread.
- Protection as a macroscale indicator was very difficult to observe for the intense part of the fires (in and around plots Y and Z) because a lot of post-fire front smoldering occurred due to the combination of wind and air sucked into the fire front. At some locations, the fire damage was inconsistent with the direction of fire spread.
- The different vegetation layers involved in the fire spread blurred all the microscale indicators on plot Z and most of those on plot Y because a large amount of radiative heat was coming from the crowning fire in addition to the heat created by the surface fire. Heterogeneities in vegetation also influenced the indicators, particularly where the load of surface fuel was very high (plot Z). However, the fire indicators are used to determine the area of origin, and usually, the fires are less intense in their initial stages. Hence, this issue can only arise if a fire is very intense close to the area of origin or spreads back to it at a later stage.
- It should also be noticed that soda cans are very light and can move during a fire, either because of vegetation consumption below them or because of wind or

fire-induced flow. Hence, even if staining on the soda can show the correct direction on plot X (see Figure 8(a)), this specific support for staining should be approached with caution. This remark can be extended to other types of light supports that may be encountered in the field. In the experiment, this specific soda can was half-buried under vegetation, limiting the likelihood of motion due to fuel regression, and it showed protection below it and at its back, increasing the likelihood of a lack of displacement during or after the fire. However, as most of the indicators can show substantial variations in directionality, it reinforces the idea that they must be analyzed in clusters and as a pattern and never in isolation.

Conclusion

This preliminary study of the fire pattern indicators created on an experimental fire shows that the indicators are useful tools for the wildland fire investigator to determine the direction of fire spread to pinpoint the area of origin. However, some discrepancies between indicators and preliminary study of their reliability highlight the fact that the indicators must always be interpreted in the frame of a global analysis of the fire. A very good understanding of the mechanisms driving fire behavior and fire dynamics is also mandatory to understand more complex fire patterns and their underlying uncertainties. The experimental program will be expanded to cover more types of fire pattern indicators and contribute to a more general understanding of the processes creating them. The same experimental protocol will be used with expanded fire behavior measurements to tie better the appearance of the indicators to a quantification of fire behavior. The experiments will also include less intense fires that are more representative of the usual fire conditions around the area of origin. The aim is to develop an experimental database that will be large enough to support a statistical analysis of the reliability of the indicators. Those additional studies will also act as a guide for the potential development of new indicators. Furthermore, we intend to complement the field studies by smaller scale laboratory studies that will allow simulate a large range of fire exposure conditions in a controlled environment.

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Author biographies

Dr. Albert Simeoni is an internationally recognized leader in fire science. He has more than 15 years of experience developing experimental, analytical, and numerical techniques to better understand fire dynamics and to predict fire behavior. He has also spent over 10 years volunteering and working for the Fire Department of North Corsica, France. Starting as a volunteer firefighter, he ultimately led all aspects of fire, wildland fire, and rescue operations, in the capacity of Chief of Fire Station.

Dr. Zachary C. Owens specializes in solving complex problems relating to fluid flow, heat transfer, mass transport, combustion, and thermodynamics. Application areas have included fire and explosion cause & origin investigations, failure analysis of gas turbines and consumer appliances, medical device performance evaluations relating to drug delivery and dermal heating, analysis of multiphase flows for the oil and gas industry, and thermal management of electronics and battery systems.

Dr. Erik W. Christiansen specializes in fire science, combustion chemistry, fluid mechanics, thermodynamics, and heat transfer. He performs origin and cause investigations of fires and explosions, ranging from small residential fires to large-scale industrial incidents to multi-acre wildland fires. Dr. Christiansen has investigated numerous vehicle related fires. He also investigates thermal related failures of consumer appliances; cooking equipment; and HVAC&R systems.

Dr. Abid Kemal analyzes and investigates fires, explosions, and detonations. He carries out work on combustion, thermodynamics, gas dynamics, macro- and micro-scale heat transfer, feedback control of complex dynamic plants and micromachining. He studies air-breathing propulsion systems and stationary gas turbines. Dr. Kemal also maintains an interest in international environmental law and policy and authored the first ever draft of fire laws for the government of Pakistan.

Michael R. Gallagher is the lead research technician at the USDA Forest Service's Silas Little Experimental Forest. He is a PhD. candidate at Rutgers University, and has over 10 years of experience as a wildland firefighter. His research interests include forest biometrics, remote sensing of fuels and fire effects, and wildland fire ecology.

Dr. Kenneth L. Clark is a Research Forester with the USDA Forest Service, Northern Research Station, stationed at the Silas Little Experimental Forest in New Lisbon, New Jersey. His research focusses on fire weather, hazardous fuel assessments, and the use of eddy flux measurements to quantify turbulence, energy, water and carbon dioxide exchanges in the fire environment.

Dr. Nicholas Skowronski is a Research Forester with the USDA Forest Service's Northern Research Station. His work is focused on the characterization of three-dimensional forest structure as it applies to forest productivity, forest disturbance, and wildland fire dynamics. He also investigates the effectiveness of landscape-scale fire management activities and developing techniques to perform large-scale fire risk assessment within WUI communities.

Dr. Eric V. Mueller is a Research Associate at the University of Edinburgh. His topic is focused on the testing and development of physics-based numerical models of wildland fire behavior. His additional research interests include the development of in-situ sensors for measuring fire environments and the study of fluid dynamics in porous media.

Dr. Jan C. Thomas is a Research Associate at the University of Edinburgh. His thesis examines the flammability of porous wildland fuels. His additional research interests include the characterization of firebrand fluxes from real fires and the assessment of structural ignition potential, as well as the emissions from the burning of wildland fuels.

Mr. Simon Santamaria is a PhD student at the University of Edinburgh. His research focuses on the study of ignition of solid fuels with an emphasis on the effects of transient incident heat fluxes and the development of ignition and flame spread theory.

Dr. Rory Hadden is the Rushbrook Lecturer in Fire Investigation at the University of Edinburgh. His research interests include pyrolysis, ignition and flammability of solid fuels with application to the built and natural environments. Rory specialises in experimental work ranging from laboratory scale studies to field scale measurements of fire phenomena with novel sensing methods.