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<th>Journal:</th>
<th>Canadian Journal of Forest Research</th>
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<tr>
<td>Manuscript ID:</td>
<td>cjfr-2018-0094.R1</td>
</tr>
<tr>
<td>Manuscript Type:</td>
<td>Note</td>
</tr>
<tr>
<td>Date Submitted by the Author:</td>
<td>07-Jun-2018</td>
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<tr>
<td>Complete List of Authors:</td>
<td>Page, Wesley; USDA Forest Service Rocky Mountain Research Station, Missoula Fire Sciences Lab Wagenbrenner, Natalie; USDA Forest Service Rocky Mountain Research Station, Missoula Fire Sciences Lab Butler, Bret; USDA Forest Service Blunck, David; Oregon State University, College of Engineering, School of Mechanical, Industrial, and Manufacturing Engineering</td>
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<tr>
<td>Keyword:</td>
<td>fire behaviour, firebrand, maximum spot fire distance, torching, torching trees</td>
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<tr>
<td>Is the invited manuscript for consideration in a Special Issue? :</td>
<td>Not applicable (regular submission)</td>
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An analysis of spotting distances during the 2017 fire season in the Northern Rockies, USA

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Abstract: The wildfires that burned in the Northern Rockies region of the USA during the 2017 fire season provided an opportunity to evaluate the suitability of using broad-scale and temporally-limited infrared data on hotspot location to determine the influence of several environmental variables on spotting distance. Specifically, relationships between the maximum observed spot fire distance for each unique combination of fire and day and geo-referenced environmental data on wind speed, vegetation, and terrain, along with specific fire characteristics (size, fire perimeter shape, and growth) were assessed. The data were also utilized to evaluate a popular theoretical model developed by Albini (1979) for predicting the maximum spotting distance for single and group tree torching. The results indicated a significant positive relationship between the maximum observed spot fire distance and an interaction between fire growth and wind speed. Significant negative relationships between maximum spotting distance and fire perimeter shape, canopy height, and terrain steepness were also discovered. The evaluation of Albini’s (1979) model suggested that selecting a high estimate of potential wind speed was important in order to minimize the likelihood of under-predicting maximum spotting distance.
Introduction

The wildfires that burned within the Northern Rockies region of the USA during the 2017 fire season were some of the largest and most expensive to manage in recent memory. In total, approximately 628,000 ha burned mostly over a 3-month period (July-September), in which nine fires exceeding 16,000 ha in size cost about 193 million US dollars to manage (NICC 2017). A wet winter and spring followed by hot, dry, and windy conditions in June and July led to above average fire danger and fire behaviour that resisted suppression efforts (NIFC 2017). During large fire events in the USA the National Infrared Operations program (NIROPS) is frequently requested to assist fire managers in gathering and interpreting Infrared (IR) data to relay consistent and reliable information on fire position (Zajkowski et al. 2003). A team of IR technicians, interpreters, and pilots are assembled to deploy and operate aircraft-mounted IR equipment that is suited to detect small heat sources (i.e. 15-20 cm in diameter) over vast areas in a short amount of time (40.5 km² per minute) (Greenfield et al. 2003). If weather conditions permit, data acquisition for multiple large fires is attempted during the night/early morning hours with the final image resolution dependent upon the height of the plane above ground level. The raw data is processed by IR interpreters to produce geo-corrected products that are then transmitted to fire managers.

Since the mid-1960s a variety of mathematical models have been proposed whose purpose is to predict the distance that firebrands originating from a wildland fire can travel given various assumptions about firebrand size, burnout time, and the ambient environmental conditions (Pastor et al. 2003). The determination of the maximum distance that firebrands can travel and
ignite new fires disconnected from the main fire front (i.e. spot fires) has received considerable
attention as these spot fires have the potential to be the most detrimental from the standpoint of
suppression operations (Alexander 2000). Of the various proposed models, the most common
operationally-applied model in the USA is that of Albini (1979). Albini’s (1979) model predicts
the maximum distance that cylindrical particles originating from a convection column produced
by a single tree or group of torching trees can travel and ignite new fires. The spotting distances
produced by the model represent the theoretical farthest limit that firebrands can travel and not
necessarily the distance that firebrands will travel. The model is widely applied and incorporated
into several fire behavior prediction systems that are presently used operationally in the USA,
including, FARSITE (Finney 2004), the Wildland Fire Decision Support System (Noonan-
Wright et al. 2011), and BehavePlus (Andrews 2014). Despite the wide use of the model
operationally, its performance has rarely been evaluated in the field, as gathering the required
inputs can be quite difficult (Albini et al. 2012).

Although the NIROPS program has been collecting data on large fires in the US for several
years, there are few published studies that have directly utilized this data source. Several
inherent limitations with the IR data have previously been identified (Zajkowski et al. 2003), but
as far as the authors are aware no attempt has been made to determine if the data are of suitable
quality and quantity to evaluate spotting distances. In this study we used the NIROPS data
collected during the 2017 fire season in the USA Northern Rockies region to analyze the
influence of several environmental, vegetation, and fire related variables on maximum spotting
distance and to make comparisons with predictions from Albini’s (1979) maximum spot fire
distance model. We provide details about the methodology used as well as the results from the
statistical analysis. Information related to the limitations and issues encountered with using the
NIROPS data is presented in addition to their possible effects on assessing spotting distance.

Materials and methods

NIROPS data collection and preparation

All available NIROPS data captured during the 2017 fire season in the USA Northern
Rockies region was downloaded from the National Interagency Fire Center (NIFC) FTP website
and organized by fire name and date (Available from
2018]). The available data represent those fires and dates that received a request for a flight,
usually via the Planning Section associated with an Incident Management Team, and were not
omitted due to weather, technical issues, or availability. The IR flights were usually conducted
between 1900 and 0500 local time with the resulting images processed by an IR interpreter and
uploaded to the NIFC FTP site shortly thereafter. The IR interpreter’s main role was to process
the raw IR images to determine the boundary of the heat perimeters, the location of hot spots,
and then configure the data and perimeter information into a format suitable for distribution to
fire managers. The images were primarily gathered using the Phoenix Imaging System coupled
with a dual-channel line scanner (3-5 and 8-14 μm bands) capable of detecting hotspots between
15 to 20 cm in diameter with an image resolution of 6.3 m per pixel at 3000 m above ground
level (Greenfield et al. 2003). The processed data are available in several formats, but the ESRI
Shapefiles (*.shp) and the IR interpreter daily log were extracted for processing.

The NIROPS-produced shapefiles of interest in this study were isolated heat (points), intense
heat (polygons), and associated heat perimeters (polygons). The intense heat polygons attempt
to delineate areas of relatively high hot spot density that are generally representative of active or recent fire activity. The heat perimeter polygons represent interpreted fire perimeters based upon the captured heat signatures associated with the main fire as well as the perimeter of smaller heat sources not connected to the main fire perimeter (Fig. 1). The heat perimeters are sometimes modified based upon fire perimeter data captured in the field, usually with Global Positioning System devices, during the feedback process between the Planning Section of an Incident Management Team and the IR interpreter.

Spot fire identification and distance from the main fire perimeter was assessed by scripting an automated process in R using the geosphere, raster, rgdal, and sp packages (Pebesma and Bivand 2005; R Core Team 2015; Bivand et al. 2016; Hijmans 2016; Hijmans 2017). Specifically, for each fire, the associated shapefiles were ordered by date and sequentially loaded to: (1) identify spot fires, (2) remove duplicate spot fires identified in previous time steps, (3) calculate the size of the main fire area (m$^2$) as well as the ratio of the perimeter-to-area (m$^{-1}$, fire perimeter shape), (4) calculate fire growth based on the percent increase in fire area since the previous time step, (5) calculate the proportion of the main fire area that contained intense heat, (6) determine the size of each spot fire (m$^2$) as well as the geographic location of its centroid, and (7) calculate the distance from each spot fire’s centroid to the nearest main fire perimeter (m).

As noted in the Data analysis section (below), the available data was subset to include only data associated with consecutive day IR flights so that each spot fire’s date of origin was known. The actual elapsed time between the IR flights varied according to the return times, which ranged from approximately 16 to 30 hours with a mean of 24 hours. Spot fires were defined as polygons less than 10 ha in size not connected to the main fire perimeter and isolated heat sources (points) that fell outside of the main fire area. The 10 ha size threshold was arbitrarily selected based
upon an expectation that as spot fires grow larger they become more likely to create additional spot fires (i.e. a spot from a spot), which could introduce a bias towards longer spotting distances. Sensitivity analysis of the calculated spotting distances to different size thresholds indicated the greatest sensitivity at sizes less than approximately 2-5 ha, which resulted in decreasing spotting distances. Thus, the 10 ha threshold was deemed a compromise to minimize biases towards either shorter or longer spotting distances.

Initial assessment of the data indicated that additional quality control would be needed to verify long-range spot fires. Spot fires that were >2.5 km from the main fire perimeter were verified by utilizing the IR interpreter’s daily log and the fire perimeters in the days following their initial detection. In total, 48 long-range spot fire occurrences were evaluated and 38 were removed from the dataset with approximately half of those removed described in the IR interpreter’s daily log as being associated with campgrounds, railroad tracks, or warming fires. The other half of the removed spot fires were not directly associated with a cause in the IR interpreter’s daily log but were judged as unrealistic (e.g. > 20 km) and failed to reappear as hot spots on the IR images in the following days.

Due to the low temporal resolution of the IR data, the time difference between when a spot fire was detected by an IR flight and when it was originally created could result in an under-estimation of actual firebrand travel distance as the main fire front likely continued to approach the spot fire before detection (see Results and discussion for more detail). To address this issue with the given data a correction factor was added to the spot fire distances based upon an estimate of the local average fire spread rate, the spot fire size and shape at the time of detection, and a fixed ignition delay time. This correction factor was calculated for polygon-based spot
fires (i.e. non-points) and added to the initial spot fire distance to obtain the final spot fire distance that was used in the analysis.

The calculation of the correction factor for each spot fire that was a polygon encompassed 6 primary steps. First, an average local fire spread rate \( \text{ROS}_A, \text{m min}^{-1} \) was estimated by determining the distance the main fire perimeter traveled in the vicinity of each spot fire during the 24-h period that the spot fire originated (TD, m) and the time difference between return IR flights (TT, min; eq. 1).

\[
(1) \quad \text{ROS}_A = \frac{T_D}{TT}
\]

Second, the length-to-breadth ratio (LB) of each polygon was calculated by estimating the maximum length (ML, m) and width (MW, m) of each polygon using the \textit{lakemorpho} package in R (Hollister and Stachelek 2017; eq. 2).

\[
(2) \quad LB = \frac{ML}{MW}
\]

The \textit{lakemorpho} package estimates the maximum length of a polygon by finding the longest point-to-point distance between equally-spaced points along the perimeter. The number of points along each perimeter was set to a minimum of 100 and increased by 25 points for every additional 0.4 ha increase in size. The maximum width was taken to be the line that intersected and was perpendicular to the line of maximum length. Third, the head fire to back fire spread ratio (HB; eq. 3) was calculated following Alexander (1985), which assumes the fire’s point of origin is the rear foci of an ellipse.

\[
(3) \quad HB = \frac{\left(LB + (LB^2 - 1)^{0.5}\right)}{\left(LB - (LB^2 - 1)^{0.5}\right)}
\]

Fourth, head fire spread distance for each spot fire (HF, m) was estimated using HB and the maximum length of each polygon (eq. 4).
Fifth, based on the assumption that the heading portion of the spot fire was moving at the same average rate as the main fire, which was probably not the case for the first 20-30 minutes (McAlpine and Wakimoto 1991), the time required to cover the head fire spread distance was calculated (HT, min; eq. 5).

\[ HT = \frac{HF}{ROS_A} \]  

This time (HT) was then added to an estimated ignition delay, i.e. the time between when the firebrand landed and subsequent ignition and spread, which was set to a constant of 5 minutes following the range of values reported by Alexander and Cruz (2006), to obtain the total time after the firebrand landed, ignited the spot fire, and spread until detected by the IR flight (T, min). Finally, the correction factor (CF, m) was calculated following eq. 6:

\[ CF = ROS_A \cdot T \]

**Environmental data**

To assess the influence of important environmental factors on spotting distance, additional data were collected (Table 1). Hourly wind speeds (m s\(^{-1}\)) for the duration of each fire were estimated at 10-m height and 250-m resolution by using the Point Initialization feature and mass-conserving model within WindNinja (Forthofer et al. 2014). WindNinja simulates the effects of complex terrain on the wind field, including local changes in wind speed and direction, by minimizing the changes in the initial wind field while conserving mass. The Point Initialization feature integrates observations from local weather stations to help drive the simulation and force the output to match the observations (within 0.1 m s\(^{-1}\)). The simulation domain was set to a 20 x 20 km box centered on each fire with all weather stations located within 5 km of the center and available via the MesoWest/Synoptic Labs API (Available from...
https://synopticlabs.org/api/mesonet/ [accessed 16 February 2018]) used for Point Initialization.

The output raster grids were arranged according to the 24-h period (0-2300 local time) that the spot fires originated and raster grids of the mean and maximum wind speed values at each cell location for each 24-h period within the domain were produced.

Vegetation-related data were retrieved from the LANDFIRE project for each fire (LF 1.4.0) (Rollins 2009). Specifically, raster grids of canopy cover (%), canopy height (m·10), and biophysical setting were compiled and resampled to 250-m resolution within the Northern Rockies region. Biophysical setting was used to classify cells as belonging to specific cover type groups in order to facilitate the utilization of Albini's (1979) spot fire model; see Albini (1979) *spot fire model comparison* section below. The primary tree species identified within the Northern Rockies region that corresponded to those available within Albini’s (1979) model were: Engelmann spruce (*Picea engelmannii* Parry), lodgepole pine (*Pinus contorta* var. *latifolia* Dougl.), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), grand fir (*Abies grandis* (Dougl.) Lindl.), and ponderosa pine (*Pinus ponderosa* P. & C. Lawson).

Terrain related information, including slope position, elevation, and various metrics of terrain complexity were compiled in 250-m raster grids for the Northern Rockies region. Specifically, slope position was calculated within a Geographic Information System (GIS) based on the topographic position index (Jenness 2006) and included six categories: Valley, Lower Slope, Flat Slope, Middle Slope, Upper Slope, and Ridge. For each fire perimeter the mean and maximum elevation (m) that occurred within the main fire area was identified as well as the standard deviation of elevation (m). For each spot fire, the distance from the lowest to highest elevation points (m) was identified within a circle having a 4 km radius centered at the spot fire location.
The difference in elevation between the lowest and highest points (m) was also found within the same area.

**Data analysis**

The environmental data were used to capture specific information related to the spot fire with the maximum distance for each unique combination of fire and day, referred to as a ‘fire-day’. For each fire-day the geographic location of the spot fire with the maximum distance was identified and the data (i.e. wind speed, slope position, vegetation, etc.) from the grid cell nearest to the spot fire along the main fire perimeter were extracted. Additionally, the mean, maximum (continuous variables), and the mode (categorical variables) values for each variable were calculated for the grid cells located immediately adjacent to the nearest cell and for all grid cells located within the main fire area.

Prior to analysis, the dataset was modified to include only those fire-days that had a spot fire and spot fires for which the date of origin was known; i.e. the spot fires associated with the first day of each fire as well as spot fires associated with non-consecutive day IR flights were removed. Additionally, spots fires associated with fires where the mean canopy cover was less than 5% were removed in order to focus the analysis on spot fires originating from torching trees.

To investigate the effects of the environmental variables on maximum spotting distance, linear mixed-effects regression analysis was performed in R using the *lme4* and *lmerTest* packages (Bates et al. 2015; Kuznetsova et al. 2017). Linear mixed-effects analysis evaluates the effects of the environmental variables of interest (fixed-effects) while accounting for the random effects between subjects (i.e. the individual fires). Initial analysis of the maximum spotting distances among individual fires indicated substantial variability (Fig. 2) and thus confirmed the
usefulness of the mixed-effects approach. The model parameters were estimated using
maximum likelihood techniques and the dependent variable (maximum spot fire distance) was
transformed using the natural logarithm to address heteroscedasticity in the residuals. Fire was
treated as a random effect (random y-intercepts) while the environmental variables were treated
as fixed-effects. The environmental variables and relevant interactions were included in the
model and a backward selection process was used to remove non-significant ($P$-value > 0.05)
independent variables until a final model was obtained. The $P$-values reported in this study have
the same meaning as is used in other hypothesis testing, that is, the probability of rejecting the
null hypothesis when it is true. The predictive power of the final model was assessed using the
‘r.squaredGLMM’ function in the $\text{MuMIn}$ package (Nakagawa and Schielzeth 2013), which
employs methods to estimate the proportion of variance explained by the selected model using
only the fixed effects (marginal $R^2$) and both the fixed and random effects (conditional $R^2$).

Albini (1979) spot fire model comparison

A comparison between the observed maximum spotting distance for each unique fire-day and
the predicted theoretical maximum spot fire distance from Albini’s (1979) model was completed.
To obtain predictions from Albini’s (1979) model a command line version (Available from
https://github.com/firelab/behave [accessed 4 June 2018]) was used along with the inputs from
the environmental variables previously described. Table 2 displays the required inputs for
Albini’s (1979) model and how the specific input values were obtained. Two wind speed
scenarios were used based on whether the mean or maximum 24-h wind speed raster grids were
utilized to extract the wind speed information. Additionally, the comparisons were made across
a range of torching tree numbers as it was not possible to gather or estimate this value from our
dataset. The raw errors (predicted theoretical maximum distance – observed maximum distance)
were calculated for each fire-day and grouped by each wind speed and torching tree scenario to evaluate model performance. The proportion of fire-days in which the raw errors were positive (i.e. an over-prediction) was also calculated to assess performance.

**Results and discussion**

*NIROPS data and spot fire distance*

Estimating spotting distances using the NIROPS data required understanding and mitigating several potential issues (Table 3). The primary issue that had the most potential to affect the broad scale results was related to the unknown time between when a spot fire occurred and when it was detected by the IR flight. If a spot fire occurred shortly before the flight, the distance from the centroid to the main fire perimeter is a relatively accurate representation of spotting distance; however, if a spot fire occurred well before the flight, the advance of the main fire front likely results in a calculated spotting distance that is shorter than the true distance. In an effort to address this issue a correction factor was calculated and added to the spot fire distances based upon an estimated local average fire spread rate, the size and shape of the spot fire, and a fixed ignition delay (Fig. 3A). The majority of spot fires were small, with mean and median sizes of 0.47 and 0.13 ha respectively, which resulted in small correction factors that were mostly between 20 and 80 m, although some exceeded 450 m. Analyses with and without the correction factor indicated it had little influence on the results, which suggests that the effects of poor IR temporal resolution on spotting distance may be limited. Despite these results, it is important to acknowledge that the low temporal resolution of the NIROPS data is an inherent limitation of this data source and should be addressed in any future analyses.
The compiled dataset of spot fire distances contained 7214 unique spot fires that occurred on 48 fires over the course of 447 unique fire-day combinations. Approximately 94% of all spot fires had estimated distances that were ≤ 500 m, with a maximum verified distance of 2.7 km (Fig. 3B). The distribution of spot fire distances obtained in this study is similar to other distributions produced using theoretical models in terms of the shape and range of values (Wang 2011; Koo et al. 2012; Martin and Hillen 2016). In several simulation scenarios, both Wang (2011) and Koo et al. (2012) characterized the majority (>50%) of firebrands as landing less than 300-350 m from their source, depending upon various modeling assumptions such as burnout time, firebrand shape, and initial mass. Profuse, short-range spotting (< 500-800 m) has also been observed in other wildfires, especially those burning in Australian Eucalypt stringybark forests, where long-distance spotting (e.g. > 5 km) has been noted to require extended firebrand burnout times and extreme burning conditions (Cruz et al. 2012; Hall et al. 2015).

It is worth noting that such short-range spotting distances imply that the main fire front was moving slowly at the time the spot fires were detected. Alexander and Cruz (2006) reported that for spread rates greater than approximately 20 m min\(^{-1}\), spotting distances in excess of 300 m are needed in order for newly ignited spot fires to contribute to forward spread and avoid being overtaken by the main flame front. As the majority of spot fires detected with the NIROPS data were < 500 m from the main fire perimeter, it is probable that the main fire front was moving slowly at the time of the IR flight since a fast-moving fire front would have likely overtaken most of the spot fires before they could have been detected. The estimates of the local average fire spread rate compiled to calculate the correction factors confirmed that the spread rates were generally low (i.e. < 1 m min\(^{-1}\)) but did approach 12 m min\(^{-1}\) for some fires.
The maximum spotting distances for each unique fire-day had mean and median values of 436 and 355 m, respectively. Additionally, there were 31 unique fire-days in which the maximum recorded distance exceeded 1 km, with the farthest verified distance of 2.7 km, which occurred sometime during September 6 on the Monahan fire on the Flathead National Forest in northwest Montana. These maximum distances are similar to distances observed on other large fires that have occurred in the northern Rocky Mountains, including 2-3 km witnessed on August 8, 1936 during the Galatea fire in the Canadian Rockies (Fryer and Johnson 1988), ~1 km between August 29 and 30, 1967 on the Sundance Fire in northern Idaho (Anderson 1968), and 1-2 km during the 2003 fire season in British Columbia (Beck and Simpson 2007). However, in this dataset we did not record the extreme distances that have also been observed, such as the 16-19 km distances seen during a 26 km fire run over 9 hours on September 1, 1967 during the Sundance Fire (Anderson 1968).

The linear mixed-effects analysis of maximum spotting distance produced a model that identified several significant relationships with the environmental, vegetation, and fire-related variables and explained approximately 13 and 38% of the total variability based on the fixed effects alone and both the fixed and random effects, respectively (Table 4). A significant positive relationship between the maximum spot fire distance and an interaction between the maximum 10-m wind speed recorded within the main fire perimeter using the mean 24-h wind speed grid and fire growth was identified. According to the proposed statistical model, fires that grew substantially compared to the previous day (> 50% increase in growth) and had relatively high wind speeds (> 10 m s\(^{-1}\)) had the potential to produce spot fire distances in excess of 1 km (Fig. 4A). The importance of wind speed on potential spotting distance is well known (Albini 1983; Pastor et al. 2003), but the dependence on fire growth suggests that both wind and other
conditions that are associated with large fire growth (e.g. convection column development) are needed for long-range spotting to occur. This finding is in line with several theoretical (Lee and Hellman 1970; Albini 1979; Woycheese et al. 1999; Albini et al. 2012) and experimental (Tohidi and Kayne 2017) analyses that emphasize the importance of characteristics of the convection column, heat release rate, or lofting height in their estimation of potential spotting distance. Three variables in the mixed-effects model analysis had negative relationships with maximum spot fire distance; the difference in elevation between the highest and lowest point within a 4 km radius circle centered at the spot fire, mean canopy height within the fire area, and the perimeter-to-area ratio of the main fire. As the difference in elevation between the highest and lowest elevation points decreased (i.e. the terrain became flatter), the maximum spot fire distance increased (Fig. 4B). This terrain effect is similar to the one proposed by Albini (1979) for torching trees in which steep elevation gradients in complex terrain decrease potential spotting distance when spot fires originate in a valley bottom or on the leeward side of slopes. The proposed model also suggested that as the perimeter-to-area ratio decreased (i.e. the fires become more elliptical) the maximum spot fire distance increased. Eccentricity in fire shape is associated with increases in effective wind speed, where the combined influence of wind and slope increases the length to width ratio of fires, which is a result of fast spreading, higher intensity fires that facilitate long-range spotting (Anderson 1983; Alexander 1985).

Albini (1979) spot fire model comparison

The comparisons of the observed maximum spotting distances with the predictions from Albini’s (1979) model indicated that the proportion of fire-days with an over-prediction (i.e. raw error > 0) varied primarily according to the wind speed scenario used to run the model (Fig. 5). When the 24-h mean wind speed grids were utilized, Albini’s (1979) model had a tendency to
produce maximum spotting distances that were less than observed, with fewer than 45% of the
fire-days having an over-prediction, which resulted in an average under-prediction of
approximately 186 m across the range of torching tree numbers considered (Fig. 5A). However,
when the 24-h maximum wind speeds grids were utilized, the majority of fire-days had an over-
prediction, which was on average approximately 149 m (Fig. 5B). Given the unknowns in
regards to the static and dynamic factors, both local and broad scale, that influence spotting
distance it is difficult to determine the reasons for the observed under-predictions produced by
Albini’s (1979) model. Low quality and inappropriate inputs such as inaccurate wind speed
information or the failure of Albini’s (1979) model to incorporate additional important factors
may have led to some of the under-prediction bias. The results of this analysis suggest that in
terms of operational application it is important to utilize the high end of wind speed forecasts or
model simulation results when making predictions with Albini’s (1979) model. This will
increase the likelihood that Albini’s (1979) model provides an over-estimate of maximum
spotting distance, which is more desirable than an under-estimate in terms of operational
application.

Although rare, previous comparisons of predictions from Albini’s (1979) model against
actual observations suggest that it usually over-predicts maximum spot fire distance (Albini et al.
2012). During the 1980 Mack Lake Fire in Michigan, Simard et al. (1983) found that predictions
were in good agreement with observations, with a predicted distance of 0.54 km compared to an
observed of 0.40 km. Likewise, Rothermel (1983) reported that for two cases on the Lily Lake
Fire in Utah, the predicted low, mid-range, and high estimates exceeded the actual spotting
distance for one case and the predicted high estimate exceeded the actual distance for another
case.
Summary and conclusions

An analysis of the broad-scale and temporally-limited data collected by the NIROPS program during the 2017 fire season in the Northern Rockies region of the USA was completed. The results revealed that the majority of spotting distances were $\leq 500$ m and that medium-range spotting (1-3 km) was somewhat rare, being observed on only 31 of 447 possible unique fire-days. The analysis also identified several environmental variables that were related to maximum spotting distance, including the ridge to valley elevation difference around the spot fire, fire perimeter shape, canopy height, and an interaction between fire growth and wind speed. A particularly important finding was that a combination of high wind speeds and substantial fire growth increased the likelihood of observing spotting distances in excess of 1 km. Comparisons of the dataset with predictions from a popular model developed to identify the theoretical upper limit of spotting distance indicated that fire behavior modelers should use the high end of wind speed forecasts or wind model simulation results to help ensure that the predictions are conservative and over-estimate potential spotting distance.

Although the analysis of spotting distances with the NIROPS data indicated that there were several significant statistical relationships that were corroborated by previous findings from theoretical, experimental, and empirical observations it is important to acknowledge the limitations with this data source. We found that manual quality control procedures were needed to verify long-distance spot fires as well as a methodology to address a known bias produced by the time difference between when a spot fire is initially created and when it is detected by an IR flight. Despite these limitations it appears that the data produced by the NIROPS program may be a resource to consider utilizing in future research.
Acknowledgements

This work was supported by the Joint Fire Science Program through Project 15-1-04-9, the National Fire Plan through the Washington Office of the Forest Service Deputy Chief for Research, and the Wildland Fire Management Research Development & Application Program.

We gratefully acknowledge review of the manuscript by M.E. Alexander, the Associate Editor, and two anonymous reviewers.

References


Table 1. Variables analyzed to explain maximum spotting distance during the 2017 fire season in the Northern Rockies, USA. Note that GIS refers to a Geographic Information System and R refers to the packages geosphere, raster, rgdal, and sp within the R computing environment (Pebesma and Bivand 2005; R Core Team 2015; Bivand et al. 2016; Hijmans 2016; Hijmans 2017).

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<th>Variable</th>
<th>Source</th>
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<tr>
<td>Interpreted infrared data</td>
<td>National Interagency Fire Center FTP website</td>
<td>Geospatial infrared data (heat perimeters, intense heat polygons, and isolated heat points) captured approximately every 24-h for significant fires during the 2017 fire season in the USA Northern Rockies.</td>
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<tr>
<td>-Main fire size (m²)</td>
<td>R</td>
<td>Area within the main fire heat perimeter.</td>
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<tr>
<td>-Perimeter-to-area ratio (m⁻¹)</td>
<td>R</td>
<td>Ratio of the total length of the main fire perimeter to the area within the main fire perimeter.</td>
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<td>-Fire growth (%)</td>
<td>R</td>
<td>Percent increase in fire size compared to the previous approximately 24-h period.</td>
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<tr>
<td>-Proportion of main fire area as intense heat</td>
<td>R</td>
<td>Proportion of the main fire area that was classified as intense heat according to the infrared interpretation.</td>
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<tr>
<td>10-m wind speed (m s⁻¹)</td>
<td>WindNinja (Forthofer et al. 2014)</td>
<td>Gridded hourly wind speeds in a 20 x 20 km region surrounding each fire, estimated at 10-m height and 250-m resolution for the duration of each fire.</td>
</tr>
<tr>
<td>-24-h mean</td>
<td>R</td>
<td>Grids of the average 10-m wind speed at each grid cell for every 24-h period (0-2300 local time) for the duration of each fire.</td>
</tr>
<tr>
<td>-24-h maximum</td>
<td>R</td>
<td>Grids of the maximum 10-m wind speed at each grid cell for every 24-h period (0-2300 local time) for the duration of each fire.</td>
</tr>
<tr>
<td>Vegetation</td>
<td>LANDFIRE (Rollins 2009)</td>
<td>The percent cover of a forested canopy over the ground’s surface, 250-m resolution.</td>
</tr>
<tr>
<td>-Canopy cover (%)</td>
<td>LANDFIRE (Rollins 2009)</td>
<td>The average height of the top of the vegetated canopy, 250-m resolution.</td>
</tr>
<tr>
<td>- Canopy height (m·10)</td>
<td>LANDFIRE (Rollins 2009)</td>
<td>Vegetation type that may be dominant on the site, based on the current and historical disturbance regime, 250-m resolution.</td>
</tr>
<tr>
<td>-Biophysical setting (283 levels)</td>
<td>LANDFIRE (Rollins 2009)</td>
<td>The average, maximum, and standard deviation of elevation within the main fire area, based on a 250-m resolution digital elevation model.</td>
</tr>
<tr>
<td>Terrain</td>
<td>LANDFIRE (Rollins 2009)</td>
<td></td>
</tr>
</tbody>
</table>
-Slope position (6 levels)  GIS (Jenness 2006)  Slope position based on the topographic position index (Jenness 2006): Valley, Lower Slope, Flat Slope, Middle Slope, Upper Slope, and Ridge.

-Ridge to valley elevation difference (m)  R  The difference between the highest and lowest elevation points within a 4 km radius centered at each spot fire location.

-Ridge to valley elevation distance (m)  R  The distance from the lowest to highest elevation points within a 4 km radius centered at each spot fire location.

**Table 2.** Required inputs to run Albini’s (1979) maximum spot fire distance model and the data source utilized for the present study.

<table>
<thead>
<tr>
<th>Required input</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Downwind canopy height (m)</td>
<td>Assumed to equal the mean canopy height obtained from the grid cells nearest to the spot fire within the main fire perimeter.</td>
</tr>
<tr>
<td>Torching tree height (m)</td>
<td>Set to be equivalent to the downwind canopy height.</td>
</tr>
<tr>
<td>Spot tree species</td>
<td>Assigned based on the LANDFIRE Biophysical Setting classification for the grid cell nearest the spot fire within the main fire perimeter.</td>
</tr>
<tr>
<td>Diameter at breast height (cm)</td>
<td>Estimated using the canopy height and height-diameter relationships published for the Inland Empire Variant of the Forest Vegetation Simulator for each tree species (Keyser 2015).</td>
</tr>
<tr>
<td>6.1 m wind speed (m s⁻¹)</td>
<td>The maximum 10-m wind speed recorded for the 24-h period during which the spot fire originated from all grid cells within the main fire area. Transformed to the equivalent speed at 6.1 m height assuming a logarithmic wind profile and neutral atmospheric stability (Campbell and Norman 1998). Two wind speed scenarios were evaluated based on whether the 24-h mean or maximum wind speed grids were utilized.</td>
</tr>
<tr>
<td>Ridge-to-valley elevation difference (m)</td>
<td>Calculated as the difference in elevation between the highest and lowest elevation points within a circle having a 4 km radius centered at the spot fire location.</td>
</tr>
<tr>
<td>Ridge-to-valley horizontal difference (m)</td>
<td>Calculated as the distance from the lowest to highest elevation points within a circle having a 4 km radius centered at the spot fire location.</td>
</tr>
<tr>
<td>Spotting source location</td>
<td>The classified slope position (Jenness 2006) from the grid cell located nearest to the spot fire within the main fire perimeter. All ‘middle slope’ classifications were assumed to be on the windward side of the slope.</td>
</tr>
<tr>
<td>Number of torching trees</td>
<td>Varied from 1 to 10 trees.</td>
</tr>
</tbody>
</table>
Table 3. Potential issues with using the National Infrared Operations (NIROPS) data to assess spotting distance.

<table>
<thead>
<tr>
<th>Issue</th>
<th>Description</th>
<th>Possible effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data availability</td>
<td>(1) NIROPS data are not consistently available for all fires and days.</td>
<td>(1) Missing data for smaller fires and inconsistent data for larger fires makes it difficult to determine when spot fires originated.</td>
</tr>
<tr>
<td>Data quality</td>
<td>(2) Heat sources that are unlikely to have originated from the fire are sometimes included. Examples include isolated heat sources from train tracks and campfires from nearby campgrounds. (3) Inherent limitations with the infrared technology, including, attenuation, heat source temperature (e.g. can only detect heat on the surface of targets), saturation, and the effects of cloud cover (Zajkowski et al. 2003; Allison et al. 2016). (4) Raw data requires post-processing by a qualified infrared interpreter.</td>
<td>(2) Additional quality control is needed, which is aided by the use of the infrared interpreter daily log. (3) Cloud and canopy cover sometimes obscure portions of fires, which potentially hide spot fires. (4) Unknown effects due to different interpretations of infrared images.</td>
</tr>
<tr>
<td>Fire specific events</td>
<td>(5) Difficult to determine the influence of fire suppression operations (e.g. firing operations) on spot fire distance.</td>
<td>(5) If firing operations away from the main fire do not join the main fire and/or remain small by the time of the NIROPS flight, they may incorrectly be included as spot fires, potentially increasing the average spot fire distance.</td>
</tr>
<tr>
<td>Spot fire origin (space and time)</td>
<td>(6) The exact time and location that the firebrand(s) were produced are unknown. Spot fire distance is calculated as the distance from the centroid to the nearest perimeter at the time of the flight.</td>
<td>(6) Underestimation of true spot fire distance as the main fire perimeter potentially has advanced closer to the spot fire by the time of the NIROPS flight. Additionally, difficult to directly assess the effects of temporally varying weather (e.g. wind speed) on spot fire distance.</td>
</tr>
<tr>
<td>Spot fire source</td>
<td>(7) The type of fire behavior (e.g. crowning) and source (e.g. live tree, snag) that produced the firebrand(s) are unknown.</td>
<td>(7) Validation of existing spot fire models is difficult as many are based on knowing the source of the spot fire (e.g. crown fires (Albini et al. 2012), torching trees (Albini 1979)).</td>
</tr>
</tbody>
</table>
Table 4. Fixed effects parameter estimates resulting from the mixed-effects regression analysis of the natural logarithm of maximum spot fire distance (dependent variable) against several environmental variables. Standard errors (SE) are reported along with the Satterthwaite approximations for degrees of freedom.

| Parameter                          | Coefficient | SE   | Standardized coefficient | Degrees of freedom | t-value | P-value (>|t|) |
|------------------------------------|-------------|------|--------------------------|--------------------|---------|--------------|
| Intercept                          | 7.4202      | 0.4133| -                        | 78                 | 17.95   | <0.001       |
| Ridge to valley elevation difference (m) | -0.0011    | 0.0002| -0.24                    | 313                | -4.31   | <0.001       |
| Canopy height (m·10)               | -0.0038     | 0.0019| -0.15                    | 52                 | -2.02   | 0.049        |
| Perimeter to area ratio (m⁻¹)      | -81.1301    | 29.8116| -0.16                    | 195                | -2.72   | 0.007        |
| Fire growth (%)                    | 0.0069      | 0.0048| 0.18                     | 447                | 1.43    | 0.154        |
| Mean 10-m wind speed (m s⁻¹)      | -0.0377     | 0.0259| -0.04                    | 411                | -1.46   | 0.146        |
| Fire growth x Wind speed           | 0.002       | 0.001 | 0.07                     | 446                | 2.03    | 0.043        |
Figure captions

Fig 1. Location of the fire perimeter and spot fires for the Sheep Gap fire located on the Lolo National Forest in Montana, USA on August 31, 2017 at 2236 hours local time.

Fig 2. Boxplots of the calculated maximum spot fire distances for the individual fires used in the analysis.

Fig 3. Range of correction factors calculated to compensate for the low temporal resolution of the infrared data (A). Distribution of spot fire distances for all spot fires assembled in the dataset (All) and for spot fires with the maximum distance for each unique fire-day combination (Maximum) (B).

Fig 4. Predicted maximum spot fire distance across increasing fire growth and mean 10-m wind speed (A) and increasing fire growth and ridge to valley elevation distance (B). The model predictions are based on the results from the linear mixed-effects analysis using mean values for the other significant predictor variables gathered from a random fire in the dataset. Note the change in axis direction for the ridge to valley elevation difference and mean 10-m wind speed variables.

Fig 5. Boxplots of the raw error (Albini’s (1979) model prediction – observed maximum spot fire distance) for each unique fire-day across an increasing number of torching trees based on using the 24-h mean wind speed values (A) and the 24-h maximum wind speed values (B).
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