AN INFRARED APPROACH TO FOREST FIRE BEHAVIOR QUANTIFICATION

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ABSTRACT
Quantitative documentation of fire behavior is important in understanding aspects of physical fire behavior. We describe the use of infrared technology to document on-the-ground fire behavior observed during the International Crown Fire Modelling Experiment (ICFME) in the Northwest Territories, Canada. Digital infrared images, taken by a camcorder-sized camera from a helicopter hovering over the fire, provided continuous documentation of the fire behavior. Because of the infrared wavelength of 7.5–13 microns, the camera can easily observe fires even through dense smoke. After processing and analysis, the infrared data can provide quantitative estimates of rates of spread, temperatures, and reaction intensities (kW/m²) observed during these fires on a pixel basis across the entire experimental plot. These data can be used for better fire behavior estimates at any temporal and spatial scales during the fire than estimates obtained from an average plot value. The ability to observe how the fire actually grew and spread over the entire plot provides valuable information on the factors affecting the fire’s behavior.

Combined with Geographical Information System (GIS) techniques, a digital analysis approach can allow forest fire researchers a better understanding of what influences the fire behavior (e.g., fuel types, fuel loads, slopes, and microclimatic factors). Ultimately, more accurate fire behavior models can be developed from the data obtained from remote sensing and on-the-ground sampling. Because fire behavior can be better defined spatially over the plot by using the infrared data and GIS analysis, correlating fire effects (e.g., mortality) with observed fire behavior can now be better explained.

keywords: forest fire behavior, infrared, International Crown Fire Modelling Experiment, monitoring, Northwest Territories, observation, rate of spread, reaction intensity, temperature.


INTRODUCTION
Quantitative documentation of fire behavior is an important aspect of forest fire research that is necessary for the understanding of physical fire behavior dynamics and other related aspects (e.g., plume dynamics, emissions, fire effects). In the past, fire monitoring has been difficult because of the variations within the study areas (e.g., size, terrain, fuel type), smoke that conceals fire behavior and prevents visual documentation, and safety concerns for research personnel during the fires. Most ground-based estimates, especially of rates of spread, focus on looking at specific points rather than recording on a continuous basis over the entire study area. This prevents the documentation of the variation in fire behavior (e.g., rates of spread, junction zones) caused by different influences (e.g., fire pattern, fuel characteristics).

Rate of spread and frontal fire (fireline) intensity (Byram 1959) are very important to quantify in any fire (Alexander 1982) and are always monitored on experimental fire sites. A quantitative measurement of rate of spread in experimental fires is critical because rate of spread is used to calculate frontal fire intensity (Byram 1959). Researchers have used these types of data in the development of Forest Fire Behavior Prediction Guidelines (e.g., Forestry Canada Fire Danger Working Group 1992). Often spread predictions for these types of guidelines have been based on averages obtained from small experimental burning plots (e.g., McRae 1985, 1999; Stocks 1987; Alexander et al. 1991).

Conventional (on-the-ground) rate-of-spread documentation relies on a systematic grid system on experimental plots. The spatial resolution of these grid systems is often very coarse. For example, Stocks (1987) used 10 × 10-m spacings on typical plot sizes of 0.4 ha. Up to the early 1980s, research personnel using
stopwatches would record when the fire reached the individual grid points. These times would later be used to determine the fire’s rate of spread based on the distance between the grid points (usually marked by metal stakes). Because of safety concerns for personnel working in the burn area, remote methods have been developed to record when the fire reached the grid points. Initially, sawhorses in view of researchers were placed outside of the fire area. Numbered weights hung over the sawhorses were strung to individual grid points with wire (Stock and Walker 1972). String, which was used to attach this wire to the metal stakes found at each grid point, would burn through quickly when the fire reached it, allowing the weight to drop. As individual weights dropped, personnel assigned to monitor the sawhorse documented the time each weight dropped. Eventually electronic timers (Blank and Simard 1983) and thermologgers (Taylor and Dalrymple, this volume) were developed and used as remote timing devices. (An electronic timer is an electronic clock that is activated when a solder connection is melted by the passing fire. A thermologger is a miniature thermocouple-activated datalogger that records the time of activation when temperatures exceed 100 °C.) These devices are buried at each grid point to prevent their destruction by the fire, making them much simpler to set up quickly before a fire than the laborious sawhorse method. Data are safely and easily retrieved from these devices after the fire.

There are two interpretation problems associated with a grid-system approach in documenting fire spread. The first is that any rate-of-spread value obtained is an average based on the distances between the grid points. The spatial resolution can be poor when the grid points are widely spaced. Therefore, any variability in rate of spread within the grid cannot be captured. Changes in the wind or subtle changes such as the fuel characteristics could cause such variability. The second problem is that a grid system works best when the firefront is spreading as a continuous linear front. However, on slower spreading fires the firefront can be quite erratic and develop many fingers. The top portion of the finger can be well past a grid point, passing beside it long before the bottom portion of the finger actually reaches the grid point to activate the timer. Under these conditions, algorithms (Eenigenberg 1987) written for calculating rate of spread and direction, based on knowing the times when the fire reached three grid points, may give erroneous results, making it appear that the fire is moving in a direction other than its true direction of travel. In addition, special fire effects such as junction zones cannot be documented under the coarse-grid system used. To avoid this problem many timers would have to be deployed in a very tight grid system. However, this would prove to be impractical given the time needed to bury a large number of timers. In addition, researchers would disturb the experimental site as they walked and knelt on the forest floor (compacted) to install the many timers.

The most recent approach in documenting fire spread has been the use of infrared technology. Basically, this technique uses an infrared camera flown from an aerial platform (e.g., helicopter). The advantage of this technology is that smoke does not obscure the infrared wavelength, so the spreading firefront can be observed aerially. Therefore, the dense smoke common on any large fire is not a problem. In this paper we describe our current infrared system used for fire observations at the International Crown Fire Modelling Experiment (ICFME) in the Northwest Territories (Alexander et al. 2001).

THE INFRARED SYSTEM AND IMAGE COLLECTION METHOD

Commercial infrared cameras are now readily available for wildfire behavior observation. Unlike their bulky predecessors (McRae et al. 1989), these compact cameras are the size of a small video camcorder. We used a FLIR ThermaCAM® PM 575 infrared camera for our observations (FLIR Systems, Portland, OR). This camera weighs almost 2.5 kg and uses a microbolometer sensor that eliminates the mechanical cooling system of older cameras. A rechargeable and replaceable battery powers the camera for up to 2 hours of operating time. The camera has an array format of 320 × 240 pixels and measures in the 7.5–13 micron spectral bandwidth. It can record temperatures up to 1500 °C, which is well within the normal temperature range found on wildfires. This ability to record high temperatures prevents over-saturation of the image pixels by the fire’s temperatures. The camera’s thermal spectral bandwidth allows sensing of background details with the geo-features required for spatial registration of individual images. This is important for determining where the fire is actually located within the experimental plot. A wide-angle lens is utilized to cover a larger area at a lower altitude. Avoiding high altitudes is important because the camera infrared bandwidth cannot penetrate through cloud water vapor. Camera sensors provide data within ±2% of actual temperatures with a spatial resolution of 1.3 milliradians that is equivalent to a 1.0-m pixel size when the camera is flown at an altitude of 800 m above ground level. Digital images can be recorded on
Table 1. Fire weather and Canadian Forest Service Fire Weather Index (FWI) System component values measured in two International Crown Fire Modelling Experiment plots, Northwest Territories, documented with infrared imaging during selected experimental fires, 1998–1999.

<table>
<thead>
<tr>
<th>Plot</th>
<th>Date</th>
<th>Temperature (°C)</th>
<th>Relative humidity (%)</th>
<th>Wind speed (km/h)</th>
<th>FWI System componenta</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>29 Jun 1999</td>
<td>20.6</td>
<td>47</td>
<td>7.9</td>
<td>89.3 54 380 5.8 80 19</td>
</tr>
<tr>
<td>8</td>
<td>4 Jul 1998</td>
<td>30.2</td>
<td>26</td>
<td>11</td>
<td>91.9 37 343 9.8 58 24</td>
</tr>
</tbody>
</table>

a Abbreviations: BUI = Buildup Index, DC = Drought Code, DMC = Duff Moisture Code, FFMC = Fine Fuel Moisture Code, FWI = Fire Weather Index, and ISI = Initial Spread Index. Further definitions of the FWI System components may be found in Canadian Forest Service (1987).

b Measured at a height of 10 m.

INFRARED IMAGE PROCESSING

Initial image processing allows us to quickly quantify various fire behavior parameters such as firefront location times, rates of spread, and spatial distribution of temperatures. Further image processing can allow us to estimate reaction (kW/m²) and frontal fire intensities (kW/m). The former intensity can be calculated using direct theoretical equations (Gray 1957); the latter intensity is obtained by combining other fuel data in a GIS analysis. Procedures for processing the infrared imagery have been developed during the project. To ensure that the images remain useful in the analysis, three key objectives must be observed to complete the image processing: 1) spatial registration (scaling) of all fire images onto a selected geo-referenced image, 2) retention of the calibrated temperature values found for each pixel on the image, and 3) temporal registration of all images using a time stamp to indicate when the individual images were taken. Special software had to be written to accomplish the latter two objectives.

It is impossible for the helicopter to be completely steady, due to atmospheric turbulence. The result is that each image collected can be quite different from any other given the altitude and heading of the helicopter. These differences would make the spatial composite of the images impossible without having ground control points (i.e., the hot geo-reference points) or significant geo-references (e.g., plot corners). The first step in the image processing is to split each recorded image into two file extension formats: bitmap (BMP) and MATLAB. The reason for this is that the BMP format saves the detailed background features that are necessary for good image registration, but the calibrated temperature value for each pixel found in the fire is lost. The MATLAB format is used to save the calibrated temperature values for each pixel provided that the camera is operating in the proper temperature dynamic range. However, MATLAB format fails to
Figure 1. A time series (1a–1h) using digital aerial infrared imagery showing fire spread on Plot 2, International Crown Fire Modelling Experiment, Northwest Territories. Colors on the images correspond to average temperature values for each pixel. The three hot geo-reference points (bright spots) can be observed on the 50-m wide firelines. The time stamp in the upper left corner shows local standard time (LST).
save any significant background or geo-reference points since the background temperatures are always lower than the dynamic range needed for the fire. Once processed, the two formats are synthesized to form one image that consists of pixels with calibrated temperatures for the fire and the detailed background information needed for image registration. A temperature threshold greater than 30 °C was used to identify which pixels were showing fire versus background information.

Once all the synthesized images were produced the spatial registration was conducted. If a particular hot reference point was not completely discernable, selected geo-reference points (e.g., plot corners) were used as replacements. The pixel size of 2.0 m was determined by counting the number of pixels between the three hot reference points and estimating the pixel size from the surveyed ground distances between the points. Besides pixel size, calculating the rate of spread requires knowledge of the time that each image was taken, which is provided by a time stamp placed on an image as it was collected. Maximum temperatures experienced during the burns were shown in intervals of 50 °C. It should be noted that these temperatures are an average determined over the entire pixel area and are lower than the maximum temperatures experienced at some points within the pixel. Image enhancement allowed us to filter out the effect of hot gases rising in the plume so we could pinpoint the exact fireline location at any time.

For Plot 2, we selected 84 from a total of 164 images to be registered. Suitability was generally based on the fact that the image had to contain all reference points and the entire fire. All fire images were registered on one selected geo-referenced image taken before ignition. All selected images had a time stamp placed on them to assist in firefront location in the analysis. Geomatica software (PCI Geomatica 2001) was used in this spatial registration.

For additional analysis, we relied on GIS analysis using ArcInfo and ArcView software (ESRI, Redlands, CA). This allowed us to interpolate the time that the fire arrived at each pixel to produce a time image. Isolines can be placed on these time images to show the exact location of the firefront at any time interval throughout the fire. In our analysis, we used time intervals of 10, 30, and 60 seconds. Error in the locations of the geo-reference points on composite images generated a possible misregistration rate of about 1–2 pixels. This misregistration affected the estimated rate of spread and densified fire isolines at the plot edges.

### RESULTS AND DISCUSSION

Processed digital imagery provides a powerful visual interpretation of the fire (Figure 1). Each image has a time stamp that allowed for precise time records and post-reconstruction of the fire. Researchers can quickly determine when and where ignition took place, and the exact location of the firefronts at any specific time during the experimental fire. Thus, this provides a permanent record of the fire growth. Given the helicopter altitude during the fire, the pixel size of our infrared imagery for Plot 2 was 1.0 × 1.0 m. While plot size and pixel size in the images could have been made larger had we flown at a lower altitude, in reality a helicopter is never a completely stationary platform but rather always shifting because of atmospheric turbulence. Even in calm conditions the pilot can have a difficult time remaining stationary, as it is more stable to fly the aircraft into a headwind. Although it results in a smaller pixel size, additional flying altitude ensures that the entire plot is always being monitored. The 2-m spatial resolution is much higher than for the conventional placement of traditional timers or thermologgers at the grid points of ICFME, which had a grid sampling spacing of 30 × 15 m on the 150 × 150-m plots.

We used GIS layers of the digital infrared imagery to locate the firefront at different times throughout the experimental burn (Figure 1a–h). This information provides a method of tracking the shape and movement of the firefront. For Plot 2, fire spread was obviously poor along the first third of the ignition line in the northeast corner of the plot (Figure 1d). However, the rest of the ignition line spread well and formed a well-developed head. Further analysis showed how the main firefront changed direction during the actual fire. For example, the main fire head, which was initially moving down the length of the plot (east to west), changed direction at 14:24:56 local standard time (LST) and began moving diagonally to the northwest across the plot (Figure 1d). The infrared observation provided documentation of the ignition sequence and timing. The initial ignition started on the north side close to the northeast corner but wrapped around to include the entire east side of the plot (Figure 1a). The north side was finally fully ignited starting at 14:24:12 LST (Figure 1c–d). At 14:27:40 LST, in conjunction with a major shift in wind direction, the burn boss decided to ignite the south side of the plot (Figure 1e–h).

Figure 2 shows the firefront location at 30-second intervals throughout the burn. However, these time isolines can be drawn at any time interval desired. As
the time isolines used to show the firefront locations are increased (i.e., from 60 to 10 seconds), it becomes easier to visually observe where the fire slowed down possibly due to lulls in the wind. In these cases, the closeness of the isolines makes it obvious where this has occurred. The images show the entire plot was not burned (Figure 2). A GIS overlay of the forest–fuel information might show whether this had any effect on the location of these unburned areas.

Rate-of-spread values (Figure 3) were easily obtained once the preliminary data from Figure 2 were produced. Coupled with fuel consumption information, a GIS analysis could quickly produce a frontal fire intensity value (kW/m) for the individual pixels found on the plot. This detail (2.0 × 2.0-m pixel size) would be much higher than previously obtained by the averages obtained from a grid-based sampling method (e.g., 30 × 15-m grid size of ICFME). Such detail will be important to better understand different fire behavior (e.g., spotting) and fire effect (e.g., crown scorching) phenomena. In addition, no junction zones were observed given the usual opportunity to form associated with multiple ignitions.

Maximum temperature values were also documented for the burn (Figure 4). However, these temperatures are usually lower than actual maximum values found during the fire due to being an average spatial value over the pixel area rather than for a specific point within the pixel. A relationship between temperature and intensity allows for a direct estimation of reaction intensity (kW/m²) if required. The same type of temperature analysis can be made for any time period during the fire. This range of temperatures would provide a visual image of where the main fire activity (intensity) was at these times. Such a record may be useful to correlate fire phenomena observed during the fire (e.g., spotting, whirlwinds) and effects of the fire (e.g., tree mortality).

We demonstrated the value of having infrared coverage on Plot 8 where an unusual fire behavior phenomenon was recorded. In this case, a strip is clearly visible on the images where there is no fire (Figure 5). This strip stretches from about the midpoint of the ignition line to the main fire front. This phenomenon was evident right up to the point when the crown fire dropped out of the trees due to a wind lull. Examina-

Figure 2. Fire location on Plot 2, International Crown Fire Modelling Experiment, Northwest Territories, as determined from analysis of infrared imagery. Fire spread is shown at 30-second intervals since time of ignition.
Figure 3. Rate of spread (m/min) of a fire on Plot 2, International Crown Fire Modelling Experiment, Northwest Territories, as determined from analysis of infrared imagery.

Figure 4. Maximum temperatures for each pixel observed for a fire on Plot 2, International Crown Fire Modelling Experiment, Northwest Territories, as determined from analysis of infrared imagery.
FIRE BEHAVIOR QUANTIFICATION USING INFRARED IMAGES

Figure 5. An “unburned street” that appeared in infrared imagery of a fire on Plot 8, International Crown Fire Modelling Experiment, Northwest Territories. With winds blowing left to right across the image, this fire behavior phenomenon was due to the Terra-torch’s missing an 8- to 10-m segment of the ignition line.

The imagery of Plot 8 clearly shows that the fire stopped spreading during a lull in the wind. Conventional grid-based sampling during this same time period would have indicated that the fire was still advancing because the algorithms used to estimate rate of spread would have averaged the fire’s rate of spread over the distance between the grid points. This would obscure periods when the fire slowed down or stopped within the grid. The location of the fire when such a lull occurs can have drastic effects. If the lull occurs when the fire has just passed a grid point, the algorithm can indicate that the fire is spreading when in fact it is not. If the lull occurs just before the fire reaches the next grid point, the algorithm would indicate that the fire is spreading more slowly over most of the area than it actually was. Such interpretation errors can cause problems with later fire reconstruction and correlation with fire effects, especially when the grid sampling is coarse.

We also observed fire spotting in our images, but only if the spot became large enough to affect the average pixel temperature. Since our intent was to cover fire spread, our high flying altitude during the imaging was not conducive to detecting small spots that occurred during the fire. If observation of spotting was a priority in our research goals, it would have been better to use the infrared camera at a lower altitude to increase the pixel size and thus improve our chances of detecting those spots.

One of the benefits of GIS analysis of the infrared data is that final results can be reproduced visually in map form. This allows users of the data to quickly grasp how the various fire variables being examined changed over the experimental fire area.

CONCLUSIONS

We described a new method of monitoring and documenting fire behavior using infrared and GIS technology. The temporal and spatial resolution of infrared images is superior to ground-based measurements that rely on course grid patterns. The final GIS products showing various fire behavior parameters can be easily overlaid with other information (e.g., fire effect, wind field, fuel loading) to develop better models. Results are consistent and standardized using the analysis software. This minimizes observer bias that can occur in point-based observations estimated on the ground. All points during the fire have multi-temporal behavior would have been missed without infrared technology because these events were not visible or capable of being recorded by any of the on-the-ground research methods presently used.
measurements to better understand fire behavior once
the firefront has passed. Digital and video images pro­
vide excellent visual documentation of the fire.

Presently there are no viable alternatives to this
approach. Although high spatial resolution images are
now possible from infrared-equipped satellites, these
satellites are usually not overhead or, if present, can­
not remain overhead for the entire period of burning.
In addition, because the satellites are not usually
directly overhead, only oblique images are possible, 
thus making reliable analysis impossible.

Negative aspects of the infrared technology present­
ed here are the initial cost of the equipment, the avail­
ability and cost of a helicopter to use for observing the
fires, and the cost of developing the procedures need­
ed for completing the image registration and analysis.
We conclude, however, that the benefits of the final
products easily outweigh the added expense.

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