Crown Fire Behavior in Conifer Forests Synthesis

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Project Title: Crown fire behavior characteristics and prediction in conifer forests: A state of knowledge synthesis

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Status: Completed

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General Description: The National Wildfire Coordinating Group (NWCG) glossary indicates that extreme fire behavior is defined as fire behavior that cannot be predicted using existing models, methods, and technologies.
Synthesis of Knowledge of Extreme Fire Behavior: Volume I for Fire Managers

Paul A. Werth, Brian E. Potter, Craig B. Clements, Mark A. Finney, Scott L. Goodrick, Martin E. Alexander, Miguel G. Cruz, Jason A. Forthofer, and Sara S. McAllister

Chapter 8: Crown Fire Dynamics in Conifer Forests

As for big fires in the early history of the Forest Service, a young ranger made himself famous by answering the big question on an exam, "What would you do to control a crown fire?" with the one-liner, "Get out of the way and pray like hell for rain." —Norman Maclean (1992)

Introduction

There are broad types of fires that are commonly recognized in conifer-dominated forests on the basis of the fuel layer(s) through which they are spreading:

- Ground or subsurface fire
- Surface fire
- Fire
- Crown fire

Ground or subsurface fires spread very slowly with no visible flame. Surface fires can spread with the wind or upslope, and backing surface fires burn into the...
Volume II for Fire Behavior Specialists, Researchers and Meteorologists

Chapter 9: Crown Fire Dynamics in Conifer Forests

Welcome to the Instructor Companion Site for Fire on Earth: An Introduction

Welcome to the website for Fire on Earth: An Introduction by Andrew C. Scott, David M.J.S. Bowman, William J. Bond, Stephen J. Pyne and Martin E. Alexander. This website gives you access to the rich tools and resources available for this text.

On this website you will find:

- Powerpoints of all figures from the book for downloading.
- PDFs of all tables from the book for downloading.
- Links to additional resources including key fire websites, videos and podcasts.
- Additional teaching material – an exercise in using charcoal data.

Resources are displayed in two ways:

- Using the menu at the top, select a chapter. A list of resources available for that particular chapter will be provided.
- Using the menu at the top, select a resource. This will allow you to access a particular resource section. You will then have the option of selecting resources within the section or going directly to a specific chapter.
9 summary articles in special issue of FMT
August 2014
Introduction to Basic Concepts of Crown Fires
Fire intensity is the rate of energy release, or rate of heat release, per unit time per unit length of fire front.
Available Crown Fuel Load: needle foliage, lichens, small dead and live (a proportion) twigs < 1 cm in diameter

Ladder or bridge fuels: bark flakes, lichens, needle drape, boles branches (live & dead), understory conifers, tall shrubs
Types of Crown Fires
C.E. Van Wagner’s (1977) three types of crown fires is the most widely recognized classification:

- Passive crown fire
- Active crown fire
- Independent crown fire
Torching does not constitute passive crowning as it generally does generate any kind of forward fire spread.
Understanding Crown Fire Behaviour based on Empirical Observations and Measurements in the Field
Observations and measurements of crown fire activity

• Key to our understanding of crown fire dynamics
• Provides benchmark data for empirical-based model development and performance evaluation
• Serves as reality-checks for simulation studies

Experimental fire, Ontario, Canada
Wildfire, Victoria, Australia
Porter Lake Project, Spruce-Lichen Woodland Stand, Northwest Territories, Canada
Big Fish Lake Project, Lowland Black Spruce Stand, North-central Alberta, Canada
A Historical Note: The First Wildfire Case Study?

1926 Quartz Creek Fire, Kaniksu National Forest – adjacent to the Priest River Experimental Forest, northern Idaho

Crown Fire Initiation
Van Wagner’s (1977) Crown Fire Initiation Model

Vertical fire spread into the overstory canopy will occur when the surface fireline intensity ($I_s$) attains the critical value $I_o$ as determined by $z$ and $m$.

- $I_s < I_o$: Surface Fire
- $I_s \sim I_o$: Surface Fire - Crown Fire Transition
- $I_s > I_o$: Crown Fire!
Canadian Forest Fire Behavior Prediction System

Inputs
- FBP System Fuel Type
- FFMC, ISI & BUI
- Wind Speed & Direction
- Percent Slope
- Upslope Direction
- Elevation Lat./Long.
- Date
- Elapsed Time Point or Line Ignition

Canadian Forest Fire Behavior Prediction (FBP) System

Outputs
- Primary
  - Head Fire Rate of Spread
  - Fuel Consumption
  - Head Fire Intensity
  - Fire Description (Crown Fraction Burned & Type of Fire)
- Secondary
  - Head, Flank & Back Fire Spread Distances
  - Flank & Back Fire Rates of Spread
  - Flank & Back Fire Intensities
  - Elliptical Fire Area & Perimeter
  - Rate of Perimeter Growth
  - Length-to-Breath Ratio
Under-prediction of crowning potential when Van Wagner (1977) model implemented in U.S. fire modeling systems.

From Alexander and Cruz (2014)
Cruz, Alexander and Wakimoto (2003)  
Crown Fire Initiation Probability Models

Four different logistic regression models that use crown base height \((CBH)\) and/or 10-m open wind speed \((U_{10})\) and components of the Canadian Forest Fire Weather Index System \((FFMC – Fine Fuel Moisture Code; DC – Drought Code; ISI – Initial Spread Index; BUI – Buildup Index):\)

**LOGIT1:** \(CBH, FFMC, U_{10}, DC\)  
**LOGIT2:** \(CBH, ISI, DC\)  
**LOGIT3:** \(CBH, ISI, BUI\)  
**LOGIT4:** \(ISI, DC\)

Logistic regression model requires three environmental inputs and one fire behaviour descriptor:

- 10-m open wind speed \((U_{10})\)
- Canopy base height (CBH) or fuel strata gap \((FSG)\)
- Estimated fine fuel moisture \((EFFM)\); and one fire behavior
- Surface fuel consumption \((SFC)\) class (<1, 1-2, >2 kg/m\(^2\))

Threshold for crown fire occurrence judged to be 50% probability.
Cruz, Alexander and Wakimoto (2004) 
Crown Fire Occurrence Probability Model

Effect of 10-m Open Wind Speed ($U_{10}$) under variable Fuel Strata Gap ($FSG$)

Assume:
- $EFFM = 6\%$
- $SFC = 1-2$ kg/m$^2$

Threshold for crown fire occurrence (0.5)
Download and install CFIS

Crown Fire Initiation Spread (CFIS) System

CFIS is a software tool incorporating several recently developed models designed to simulate crown fire behavior. The main outputs of CFIS are:

1. the likelihood of crown fire initiation or occurrence;
2. the type of crown fire (active vs. passive) and its rate of spread; and
3. the minimum spotting distance required to increase a fire's overall forward rate of spread.

The primary models incorporated into CFIS have been evaluated against experimental and wildfire observations. CFIS has applicability as a decision support aid in a wide variety of fire management activities ranging from near-real time prediction of fire behavior to analyzing the impacts of fuel treatments on potential crown fire behavior.

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More information

Download CFIS software tool (exe; 5.3 MB)

NEW! Download Canopy Fuel Stratum Characteristics Calculator (Cruz et al. 2003) Version 1.1 (xls; 350 kb)

Download "Introducing the Canopy Fuel Stratum Characteristics Calculator" poster (pdf; 481 kb)

Curious how CFIS outputs compare with NEXUS and FlamMap? Check out: Comparison of crown fire modeling systems used in three fire management applications (Scott 2006; RMRS-RP-58)

Check out: JFS Crown Fire Behavior Synthesis Project

http://www.frames.gov/partner-sites/applied-fire-behavior/cfis/
Crown Fire
Rate of Spread and Intensity
Experimental crown fires used in the development of the Canadian FBP System plotted

Points of note:

• No passive crown fires with $CBD < 0.05 \text{ kg/m}^3$

• No active crown fires with $CBD < 0.11 \text{ kg/m}^3$

from Cruz, Alexander and Wakimoto (2005)
Canadian Forest Fire Behavior Prediction System: surface and crown fire rates of spread

Mature Jack or Lodgepole Pine (C-3) Fuel Type
Rothermel (1991) Rate of Spread “Model” for Wind-driven Crown Fires

A statistical correlation between the predicted surface fire rate of spread for Fuel Model 10 (wind reduction factor 0.4) and 8 western U.S. wildfire observations.

\[
\text{Ave. Crown Fire ROS} = 3.34 \times \text{Surface Fire ROS}
\]
Cruz, Alexander and Wakimoto (2005)  
Crown Fire Rate of Spread Models

- Data available 37 crown fires (24 active and 13 passive; all from Canada)
- Number of variables examined
- The criterion for active crowning (CAC) introduced:

$$CAC = \frac{\text{Predicted Active Crown Fire ROS}}{CBD}$$
Cruz, Alexander and Wakimoto (2005)  
Crown Fire Rate of Spread Models: The Equations

**Active Crown Fires:** \( CAC \geq 1.0 \)

\[
CROS_A = 11.02 \times (U_{10})^{0.9} \times CBD^{0.19} \times \exp(-0.17 \times EFFM)
\]

**Passive Crown Fires:** \( CAC < 1.0 \)

\[
CROS_P = CROS_A \times \exp(-CAC)
\]

where \( CAC \) is the criterion for active crowning dimensionless), \( CBD \) is the canopy bulk density (kg/m\(^3\)), \( U_{10} \) is the 10-m open wind speed km/h), \( EFFM \) is the estimated fine fuel moisture (%), \( CROS_A \) is the active crown fire rate of spread (m/min), and \( CROS_P \) is the passive crown fire rate of spread (m/min).

Rothermel model under-predicts by a factor of 2.6-3.8 and shows little sensitivity to burning conditions.

The Cruz et al. (2005) model slightly over-predicted.

after Cruz and Alexander (2010)
Byram (1959) indicated that his fire intensity-flame length equation would under-predict the flame length for “… high intensity crown fires because much of the fuel is a considerable distance above the ground.”

He suggested, on the basis of personal visual estimates, that “… this can be corrected for by adding one-half of the mean canopy height …” to the flame length value obtained by his equation. Thus, the equation for crown fire flame lengths ($L_c$) taking into account stand height ($SH$) becomes:

$$ L_c = 0.0775 \cdot (I)^{0.46} + (SH/2) $$

Rothermel (1991) suggested using Thomas’ (1963) relation to estimate the flame lengths of crown fires from fire intensity:

$$ L_c = 0.0266 \cdot (I)^{2/3} $$
Crown
Fire
Flame
Heights/Lengths
None of these methods seem to work consistently well based on comparisons against experimental crown fires undertaken in Canada. Take, for example, the following experimental crown fires in red pine plantations ($SH = 15$ m) documented by Van Wagner (1977).

<table>
<thead>
<tr>
<th>Exp. Fire</th>
<th>Obs. $L_c$ (m)</th>
<th>Predicted $L_c$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C4</td>
<td>19.8</td>
<td>Byram (1959) 15.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Thomas (1963) 20.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Butler et al. (2004) 28.8</td>
</tr>
<tr>
<td>C6</td>
<td>30.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Byram (1959) 15.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Thomas (1963) 21.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Butler et al. (2004) 29.4</td>
</tr>
</tbody>
</table>
General Observation Based on Experimental Crown Fires:

The flame front depth increases as fire intensity increases rather than a corresponding increase in the vertical flame length.
Alexander’s Simple Rule of Thumb for Crown Fire Flame Heights:
2-3 x Stand Height for Active Crown Fires
1983 Roise Creek “Case Study”

Dick Rothermel

Rod Norum
Rod Norum found that Fire Behavior Fuel Model 9 Rate of Spread X 1.2 worked best for predicting head fire spread rates in Alaskan black spruce. For flame lengths and in turn fire intensities he recommended using Fire Behavior Fuel Model 5.
1983 Rosie Creek Fire, Fairbanks, Alaska
BEHAVE Predictions

Estimating 1-hr Time Lag (TL) Fuel Moisture Content (FMC) as per Rothermel (1983)

Temperature: 23.3 deg °C
Relative Humidity: 33%

Reference Fuel Moisture: 5%
Adjust for shading, time of year (i.e., month), time of day, slope steepness, aspect and elevation: 3%

Dead Fuel Moisture Content: 5% + 3% = 8%

Assumptions (as per Rothermel 1983):
10-hr TL = 8% + 1% = 9%
100-hr TL = 8% + 2% = 10%

Assume 100% for Live Moisture Content as per Rothermel (1983, Table II-2, p. 13)
1983 Rosie Creek Fire, Fairbanks, Alaska

BEHAVE Predictions

Estimating the Mid-flame Wind Speed

20-ft (6.1) Open Wind Speed: **13 mph**
(20.9 km/h)

Rod Norum has suggested a Wind Reduction Factor of **0.2** for Alaskan black spruce.

Dick Rothermel has suggested a Wind Reduction Factor of **0.4** for Fire Behavior Fuel Model 5

Mid-flame Wind Speed = **13 x 0.2 = 2.6 mph** for Fire Behavior Fuel Model 9

Mid-flame Wind Speed = **13 x 0.4 = 5.2 mph** for Fire Behavior Fuel Model 5
**1983 Rosie Creek Fire, near Fairbanks, Alaska**

Major run of Rosie Creek Fire: June 2, 1983

<table>
<thead>
<tr>
<th>Fire Behavior Characteristic</th>
<th>BEHAVE System</th>
<th>CDN FBP System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head Fire Rate of Spread (m/min)</td>
<td>1.2</td>
<td>31.4</td>
</tr>
<tr>
<td>Flame Length (m):</td>
<td>1.0</td>
<td>10+</td>
</tr>
<tr>
<td>Fire Intensity (kW/m):</td>
<td>259</td>
<td>41 995</td>
</tr>
</tbody>
</table>
FCCS (Schaaf et al. 2007) Model Evaluation: Comparison Against Wildfires in Black Spruce Forests (data from Alexander and Cruz 2006)

Model output showed under-prediction trend by a factor of 2.
Cronan and Jandt (2008) Study

High fire spread predictions based on CFIS
Donnelly Dome Fire – June 13, 1999
The situation should be considered as "explosive" or super critical in the upper portion of the class. The characteristics commonly associated with extreme fire behavior (e.g., rapid spread rates, continuous crown fire development, medium- to long-range spotting, firewhirls, massive convection columns, great walls of flame) is a certainty. Fires present serious control problems as they are virtually impossible to contain until burning conditions ameliorate. Direct attack is rarely possible given the fire's probable ferocity except immediately after ignition and should only be attempted with the utmost caution; an escaped fire should in most cases, be considered a very real possibility. The only effective and safe control action that can be taken until the fire run expires is at the back and up along the flanks.

*from Alexander and Cole (1995)
“Operational Use” of the FBP System
Wildfire Monitoring and Case Study Documentation
Thank you for your attention? Questions? Comments?