Proceedings for the 6th International Fire Behavior and Fuels Conference
April 29 – May 3, 2019, Albuquerque, Marseille, Sydney
Published by the International Association of Wildland Fire, Missoula, Montana, USA

Linking Dynamic Empirical Fire Spread Models: Introducing Canadian Conifer Pyrometrics

Daniel D.B. Perrakis*
Natural Resources Canada-Canadian Forest Service, Victoria, British Columbia, Canada, Daniel.Perrakis@canada.ca

Miguel G. Cruz
CSIRO, Canberra, Australian Capital Territory, Australia, Miguel.Cruz@csiro.au

Martin E. Alexander
Wild Rose Fire Behaviour, Leduc County, Alberta, Canada, mea2@telus.net

Stephen W. Taylor
Natural Resources Canada-Canadian Forest Service, Victoria, British Columbia, Canada, Steve.Taylor@canada.ca

Jennifer L. Beverly
Faculty of Agricultural, Life & Environmental Sciences, University of Alberta, Edmonton, Alberta, Canada, jbeverly@ualberta.ca

Introduction

Fire and resource managers routinely use fire behaviour prediction tools for decision support in wildfire management and operations. The Canadian Forest Fire Danger Rating System (CFFDRS) consists of tools for rating fire danger and forecasting fire behaviour that have been used by virtually all land management agencies in Canada for several decades (Taylor and Alexander 2006). The CFFDRS consists of two major subsystems – the Canadian Forest Fire Weather Index (FWI) System (Van Wagner 1987) and the Canadian Forest Fire Behavior (FBP) Prediction System (Forestry Canada Fire Danger Group 1992, Wotton et al. 2009).

The FBP System is based on the analysis of several hundred experimental fires, operational prescribed burns and wildfires documented over a 30 year period. The current list of FBP System fuel types was designed to match the dominant fire-prone vegetation communities across Canada, with discrete fuel complexes defined by simple descriptive characteristics consistent with forest cover data available in the latter part of the 20th century (Van Wagner 1990). The list is not meant to be exhaustive but rather a reflection of existing empirical fire behaviour knowledge.

Fuel consumption and fire spread rate equations exist for each FBP System fuel type and enable predictions using a small number of inputs (primarily the FWI System components). This simplicity has facilitated the use of the system in operational wildfire forecasting and pre-suppression preparedness planning where time and data are scarce. However, the simplicity also limits its application in non-standard fuel conditions.

* Corresponding author: 506 West Burnside Road, Victoria, British Columbia, V8Z 1M5, Canada; Daniel.Perrakis@canada.ca.

Today, forest cover data is much more readily available and at a much higher resolution than in previous decades, and the lack of flexibility of the FBP System fuel structure parameters is sometimes limiting. For instance, the present version of the FBP System cannot be used to model the effects of hazard mitigation treatments such as thinning and pruning on potential fire behaviour. This is because the FBP System fire spread rate and fuel consumption functions are parametrized on the basis of fixed values for the canopy base height (CBH), canopy fuel load (CFL), and surface fuel load of each forest fuel type (Forestry Canada Fire Danger Group 1992). In addition, the Fine Fuel Moisture Code (FFMC) component of the FWI System, a required input to the FBP System, is calibrated for a single vegetation model – the 'generalized pine forest' (Van Wagner 1974) – and does not reflect the effects of variable stand type or structure on fine fuel moisture.

Objectives

Several studies completed in the years following the release of the FBP System in 1992 offer greater flexibility for modifying the inputs representing both fuel and moisture parameters. Cruz et al. (2003, 2004, 2005) developed models of crown fire initiation and spread (CFIS; Alexander et al. 2006) by reanalyzing the documented experimental burns originally used to develop the FBP System. The CFIS models introduced dynamic stand structure inputs while maintaining the empirical convention and local relevance of the FBP System database. In addition, analysis of a large dataset of historical moisture content observations across Canada has also been completed (Wotton and Beverly 2007). This work resulted in new equations for adjusting FFMC values to reflect stand conditions more precisely.

The objective of this project was therefore to develop a new framework for a fire behaviour prediction scheme based on the FBP and CFIS systems that combines dynamic fuel moisture and dynamic fuel structure models for predicting fire spread in conifer forests.

Methods and model development

We presently introduce a conceptual scheme, tentatively called 'Canadian Conifer Pyrometrics' (CCP), that links four separate modelling steps into a coherent system for predicting surface fire rate of spread (ROS), crown fire initiation thresholds, and crown fire ROS. The flow and interactions between the inputs and outputs of the various modelling components are as follows (Figure 1):

1. Weather observations are used to calculate the components of the FWI System, including the diurnal FFMC (Lawson et al. 1996) and the Duff Moisture Code (DMC). The Wotton and Beverly (2007) equations are used to calculate stand-specific fine fuel moisture content (mc_{WB}) using FFMC, stand type, density (from crown closure), season, and DMC.
2. The probability of crown fire initiation (CFI and p_{CFI}) is then estimated using a logistic regression model (as per Cruz et al. 2004). For the CCP CFI model, the predictors will consist of mc_{WB}, estimated surface fuel consumption (SFC) and fuel strata gap (FSG, a variation on CBH; see Cruz et al. 2004).
3. Surface fire is predicted when p_{CFI} is below a threshold value (50% or other). A simple surface fire rate of spread (SROS) model was fitted using aggregated observations from the FPB System database, based on the initial spread index (ISI) component from the FWI System.
4. When crown fire initiation is predicted, then type of crown fire and crown fire rate of spread (CROS) are calculated using the Cruz et al. (2005) models and approach. The criteria for active crowning (CAC; as per Van Wagner 1977) determines whether the canopy bulk density (CBD) is sufficient to carry fire between crowns, in which case

the active crown fire rate of spread ($CROS_a$) model applies. The passive crown rate of spread model ($CROS_p$) applies when CBD is too low to support active crown fire. Since the Cruz et al. (2005) CROS models were fitted using the Rothermel (1983) tables of estimated fine fuel moisture content ($EFFM_R$), a transformation step is required to remove bias between the $EFFM_R$ and mc_{WB}. This allows for the stand condition-sensitive mc_{WB} fuel moisture estimate to be linked with the process of crown fire initiation and spread.

The final outputs can be processed alone for individual predictions or used in additional processing applications, such as along a continuum of wind speed values (Figure 2; see below). The result is a fire behaviour modelling system built on empirical data that potentially offers much greater flexibility with respect to conifer fuel complexes than the existing FBP System.

Model implementation and discussion

While the details of some of the CCP model linkages are still being finalized, a working system has been implemented for testing purposes. A prototype visualization tool called FuelGraph (Figure 2) was developed using Microsoft Excel (Microsoft Corp., Redmond, Washington, USA). FuelGraph displays CCP outputs in an interactive chart that illustrates how predicted spread rate and crown fire behaviour are sensitive to varying fuel structure and fire danger conditions. FWI System components, stand characteristics, and other model inputs are entered by users. Wind speed is displayed on the X-axis, and the crowning threshold, ROS and type of fire (i.e. surface, passive crowning, or active crowning) are shown as outputs along the Y-axis. The effects of fuel structure on moisture content, crown fire initiation and ROS are evident, and comparing predicted fire behaviour in different stands is easily accomplished.

For present users familiar with the FBP System, we expect that the most significant challenges to using the CCP system for operational or scenario-based fire behaviour prediction will involve the additional investment required in measuring or estimating certain required inputs (e.g. CBD and SFC). While separate calculators and models exist to estimate these values (e.g. Reinhardt et al. 2006, De Groot et al. 2009, Alexander and Cruz 2014, Ottmar 2014), their use will need to be evaluated and expanded for use with the CCP system.

In addition to predicting ROS in natural forest stands, CCP may provide insight into potential fire behaviour in stands that have undergone structural modifications (i.e. removal of biomass) to mitigate fire hazard. For example, Figure 2 shows predicted fire behaviour and type of fire in a dense pine stand under high fire danger conditions (FFMC 92, DMC 80). Under these conditions, crown fire initiation (> 50% probability) would be reached at wind speed of 9 $km{\cdot}h^{-1}$. Following a hypothetical fuel reduction treatment that increases FSG (4.5 m to 7 m) and decreases CBD (0.22 $kg{\cdot}m^{-3}$ to 0.07 $kg{\cdot}m^{-3}$), the new stand structure would reach the threshold of passive crowning behaviour (with 50% probability) at 13 $km{\cdot}h^{-1}$ wind speed; active crown fire would occur at 33 $km{\cdot}h^{-1}$. A SFC value of 1.5 $kg{\cdot}m^{-2}$ is assumed for both stand conditions. However, the use of CCP for such simulations should be approached with caution as the extent to which data from natural stands can be used to represent fuel-modified stands has yet to be determined. Additional study and testing are still required at this time.

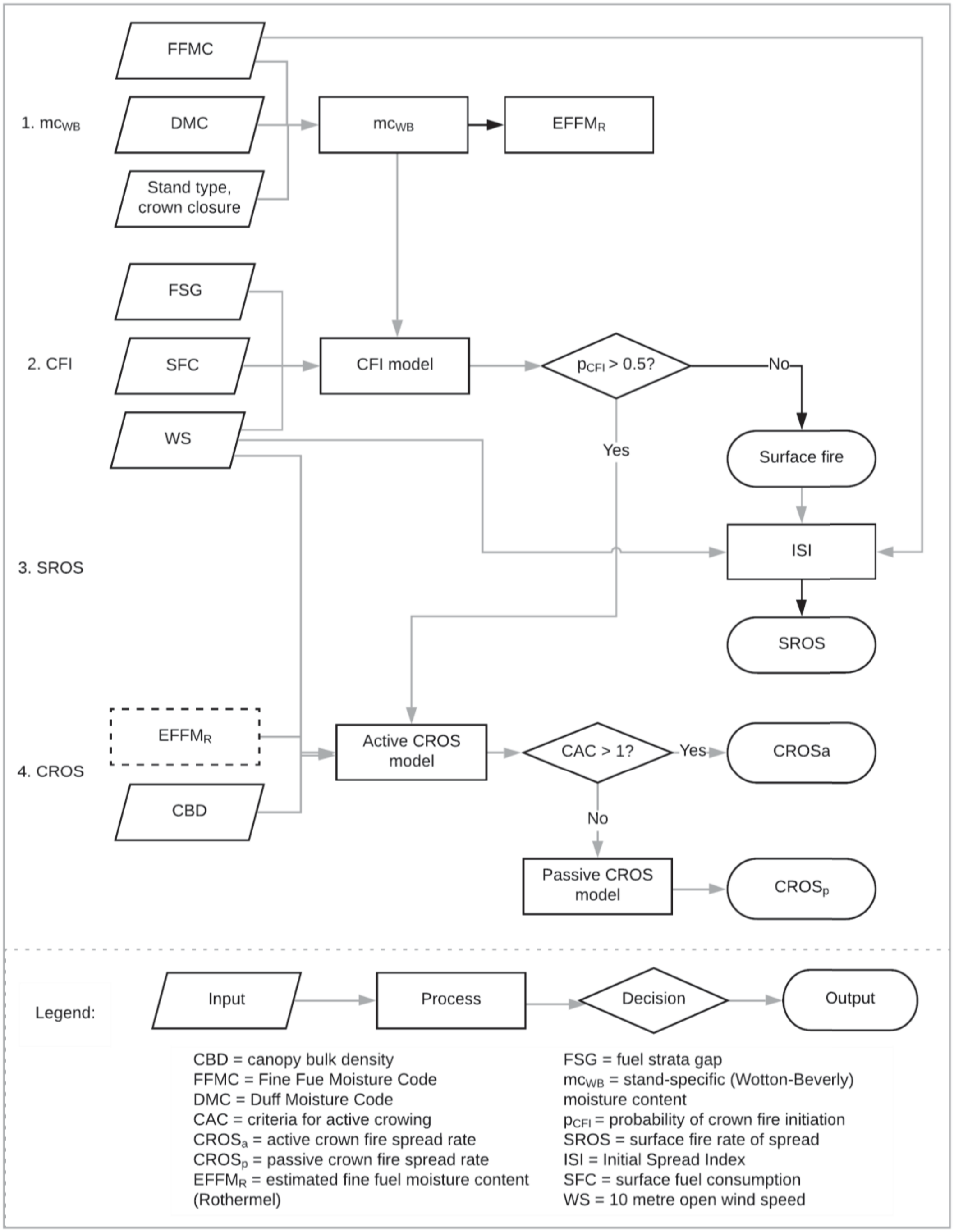

Figure 1. Flowchart for the CCP system. The four linked components are as follows: 1: The Wotton & Beverly (2007) moisture content model (mc_{WB}); 2: Crown fire initiation (CFI) and probability of CFI (p_{CFI}), from a data reanalysis as per Cruz et al. (2004; in prep.); 3: Surface fire rate of spread (SROS), a simple analysis based on ISI or wind speed alone (in prep.); and 4: Crown fire rate of spread (CROS), including separate processes for passive ($CROS_p$) and active ($CROS_a$) crown fire spread (Cruz et al. 2005).

Using FuelGraph, CCP outputs can easily be compared with existing FBP System outputs. An FBP System fuel type line can be overlaid on the FuelGraph output screen (green line in Figure 2, not actively displayed) to compare model predictions between the FBP System and

CCP. This can help facilitate training and understanding within the fire management community.

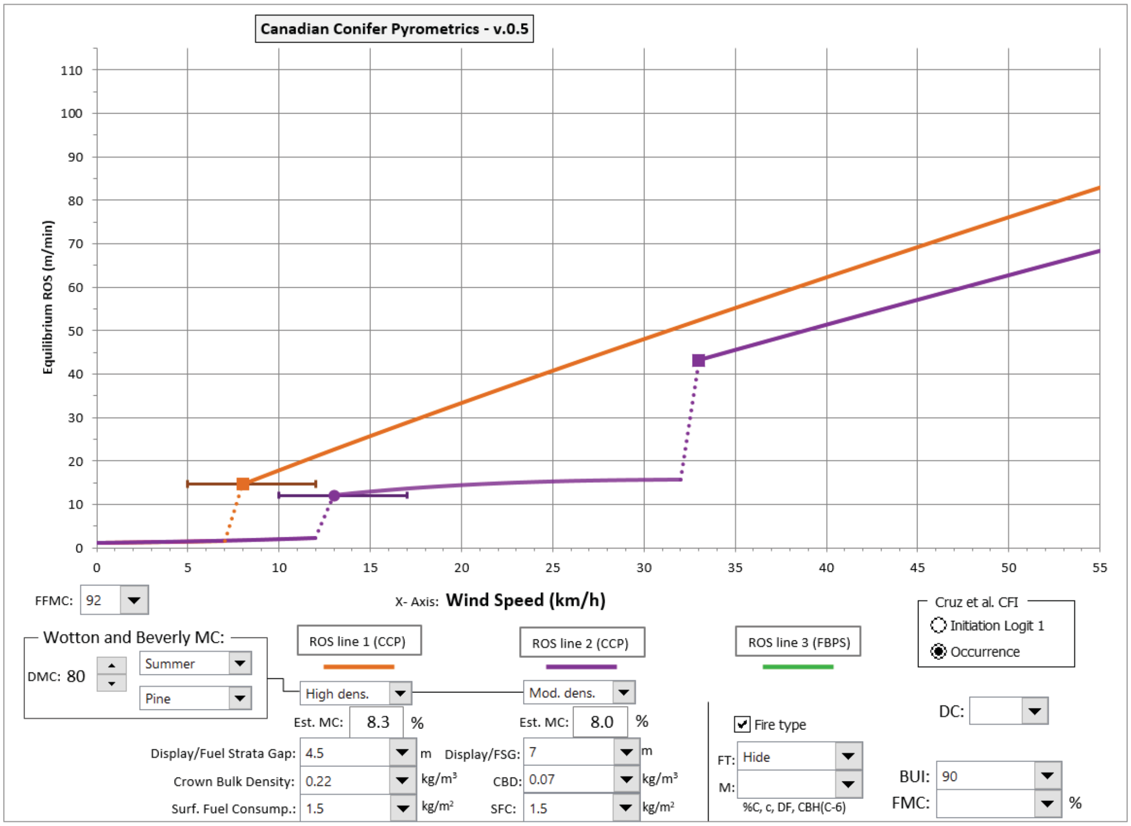

Figure 2. Screen capture of Canadian Conifer Pyrometrics-FuelGraph tool, showing examples of predicted fire behavior in two stands with varying structure under similar weather and fuel moisture conditions. The filled circle symbol (purple line) indicates the initiation of passive crown fire behaviour (50% probability) and the square symbol, where separate, indicates the initiation of active crowning. Where the circle symbol is missing (orange line), the prediction is for immediate transition between surface fire and active crown fire behaviour (50% probability). Horizontal error bars show the 70% confidence band (15-85%) for crown fire initiation. See text for abbreviations.

In conclusion, CCP is presented here as a concept and a modelling scheme that is currently under development (‘version 0.5’) but potentially offers several advantages to current users of the FBP System. Additional work is in progress to finalize the various statistical models within CCP. These include a reanalysis of the logistic regression of crown fire initiation (Cruz et al. 2004) as well a transformation to remove any bias between the two models of fuel moisture content (mc_{WB} and $EFFM_R$) to incorporate the use of the Cruz et al. (2005) CROS models. The effects of more complex influences on fire behaviour (e.g. slope, aspect, solar radiation) are not considered at this time but may be explored in future versions. At present, the FuelGraph tool is being distributed to invite review and evaluation by researchers and fire managers and we expect to incorporate this feedback prior to eventual release of CCP as an operational tool.

References:

Alexander ME, and Cruz MG (2014) Tables for estimating canopy fuel characteristics from stand variables in four interior west conifer forest types. *Forest Science* **60**, 784-794.

Alexander ME, Cruz MG, and Lopes AMG (2006) CFIS: A software tool for simulating crown fire initiation and spread. *In* Vth International Conference on Forest Fire Research, 27-30 November 2006 (DX Viegas, ed.). Amsterdam, The Netherlands. Elsevier B.V.

Cruz MG, Alexander ME, and Wakimoto RH (2003) Assessing the probability of crown fire initiation based on fire danger indices. *Forestry Chronicle* **79**, 976-983.

Cruz MG, Alexander ME, and Wakimoto RH (2004) Modeling the likelihood of crown fire occurrence in conifer forest stands. *Forest Science* **50**, 640-658.

Cruz MG, Alexander ME, and Wakimoto RH (2005) Development and testing of models for predicting crown fire rate of spread in conifer forest stands. *Canadian Journal of Forest Research* **35**, 1626-1639.

De Groot W, Pritchard J, and Lynham T (2009) Forest floor fuel consumption and carbon emissions in Canadian boreal forest fires. *Canadian Journal of Forest Research* **39**, 367-382.

Forestry Canada Fire Danger Group (1992) 'Development and structure of the Canadian Forest Fire Behavior Prediction System.' Information Report ST-X-3, Forestry Canada, Science and Sustainable Development Directorate (Ottawa, Ontario, Canada).

Lawson BD, Armitage OB and Hoskins WD (1996) 'Diurnal variation in the Fine Fuel Moisture Code: tables and computer source code.' FRDA Report 245. Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre and BC Forest Service (Victoria, British Columbia, Canada).

Ottmar RD (2014) Wildland fire emissions, carbon, and climate: modeling fuel consumption. *Forest Ecology and Management* **317**, 41-50.

Reinhardt E, Lutes D, and Scott J (2006) 'FuelCalc: A method for estimating fuel characteristics'. p. 273-282 *in* Andrews, PL, Butler, BW, comps. Fuels Management: How to Measure Success, 28-30 March 2006, Portland, Oregon.' Proceedings RMRS-P-41, USDA Forest Service, Rocky Mountain Research Station (Fort Collins, Colorado, USA).

Taylor SW, and Alexander ME (2006) Science, technology, and human factors in fire danger rating: the Canadian experience. *International Journal of Wildland Fire* **15**, 121-135.

Van Wagner CE (1974) 'Structure of the Canadian forest fire weather index.' Publication No. 1333, Environment Canada, Forestry Service (Ottawa, Ontario, Canada).

Van Wagner CE (1977) Conditions for the start and spread of crown fires. *Canadian Journal of Forest Research* **7**, 23-34.

Van Wagner CE (1987) 'Development and structure of the Canadian Forest Fire Weather Index System.' Forestry Technical Report 35, Canadian Forestry Service (Ottawa, Ontario, Canada).

Van Wagner CE (1990) Six decades of forest fire science in Canada. *The Forestry Chronicle* **66**, 133-137.

Wotton BM, Alexander ME, and Taylor SW (2009) 'Updates and revisions to the 1992 Canadian Forest Fire Behavior Prediction System.' Information Report GLC-X-10, Natural Resources Canada, Canadian Forest Service, Great Lakes Forestry Centre (Sault-Ste.-Marie, Ontario, Canada).

Wotton BM, and Beverly JL (2007) Stand-specific litter moisture content calibrations for the Canadian Fine Fuel Moisture Code. *International Journal of Wildland Fire* **16**, 463-472.