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Crown fire behavior characteristics and prediction in conifer forests: a state-of-knowledge synthesis

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Cover photo: Crowning associated with the Jackpine Fire in the Willmore Wilderness Park, Alberta, Canada, at 4:29 pm MDT on July 4, 2006. Photo by Emile Desnoyers, Alberta Sustainable Resource Development.

Abstract

Joint Fire Science Program (JFSP) project 09-S-03-1 was undertaken in response to JFSP Project Announcement No. FA-RFA09-0002 with respect to a synthesis on extreme fire behavior or more specifically a review and analysis of the literature dealing with certain features of crown fire behavior in conifer forests in the United States and adjacent regions of Canada.

The key findings presented are organized along nine topical areas: types of crown fires; crown fire initiation; crown fire propagation; crown fire rate of spread; crown fire intensity and flame zone characteristics; crown fire area and perimeter growth; crown fire spotting activity; models, systems, and other decision aids for predicting crown fire behavior; and implications for fire and fuel management.

A total of 16 management implications are discussed at some length, involving the following subjects:

- Classification of crown fires
- Flames don't have to extend into the lower canopy for crowning to occur
- Unsubstantiated coupling of crown fire behavior models
- Defining canopy fuel stratum characteristics
- Evaluating models to predict canopy fuel stratum characteristics
- The myth of the "crown fire-proof" conifer forest
- Lack of physics-based model evaluation in predicting crown fire behavior
- Van Wagner's criteria for active crown fire spread is a robust concept
- Foliar moisture content has little or no effect on crown fire rate of spread
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- Alternative models for predicting the characteristics of crown fire behavior
- Evaluation of fuel treatment effectiveness

From the standpoint of relationships to other recent findings on the topic of crown fire behavior in conifer forests, four areas of ongoing work were identified:

- Crown fire potential in mountain pine beetle-attack lodgepole pine forests
- Physics-based fire behavior models

- Crown fire potential in other forest types
- Experimental crown fires

From a practical point of view, future work is needed in the following areas:

- Systematic documentation of crowning wildfires for model evaluation purposes
- Development and testing of flame size model for crown fires
- Defining the threshold for vertical fire spread in terms of ladder/bridge fuels and canopy bulk density
- Crown fuel consumption data collection and model evaluation
- Application of ensemble or multiple simulation methods to the prediction of crown fire behavior

The following type/number of deliverables emanated from Project JFSP 09-S-03-1:

- Book chapters – 5
- Special issue of *Fire Management Today* - 1
- Journal articles – 16
- Conference papers and technical journal notices - 13
- Software – 2
- Workshop – 1
- Other contributions – 7
- Websites – 2

Collectively, the references associated with the book chapters and journal articles, constitutes a comprehensive bibliography on the subject of crown fire behavior in conifer forests.

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Background and purpose

On September 24, 2008, the Joint Fire Science Program (JFSP) released Project Announcement No. FA-RFA09-0002. In that announcement, there was the indication that JFSP was interesting in sponsoring projects that synthesize existing information in a form that is useful to land managers. The goal was to present information on topics of importance to land managers that have a sufficient base of existing knowledge to support a synthesis and management interpretation. Within the announcement, the following kinds of questions were asked of prospective applicants:

- What sources of information are available to support a synthesis? Seminal publications and other highly referenced scientific papers should be part of the collection of information.
- Is there a sufficient body of science to warrant the need for a synthesis of this topic at this time?

One of the topics mentioned in the announcement issued by JFSP was an interest in a synthesis on extreme fire behavior and specifically:

> *An examination of the state of the science underlying predictions of extreme fire behavior, and an assessment of the appropriate uses and limits of this information.*

The National Wildfire Coordinating Group (NWCG) defines the term "extreme fire behavior" as (from NWCG Incident Operations Standards Working Team 2006):

> *"Extreme" implies a level of fire behavior characteristics that ordinarily precludes methods of direct control action. One or more of the following is usually involved: high rate of spread, prolific crowning and/or spotting, presence of fire whirls, strong convection column. Predictability is difficult because such fires often exercise some degree of influence on their environment and behave erratically, sometimes dangerously.*

The interest in an extreme fire behavior synthesis by JFSP was the direct result of a problem statement prepared by the NWCG Fire Behavior Committee (Robert Ziel, Co-Chair, personal communication, 2008). The NWCG Fire Behavior Committee pointed out that the term or phrase "extreme fire behavior" is commonly used by throughout the wildland fire community. However, the "definition frames the subject in terms of human capabilities and perceptions, in part because the supporting science has not been refined sufficiently to characterize it objectively". The JFSP Governing Board ended up approving the funding of Project 09-2-01-11 (Extreme Fire Behavior State-of-the-Science Synthesis) led by Principal Investigator Paul A. Werth. The original synthesis called for the following components or chapters:

- Complex terrain influences and interactions
- Critical fire weather patterns
- Fire interactions
- Convection column/plume dynamics

- Fire whirls/vortices
- Crown fire development spread

A second proposal entitled "TOWARDS A SYNTHESIS ON EXTREME FIRE BEAHVIOR: Characteristics and Prediction of Crown Fire Behavior in Conifer Forests" was submitted by the present authors in connection with the JFSP announcement released in September 2008. Rather than attempting to address all the various aspects of extreme fire behavior phenomena, the focus of the proposal was on synthesizing the available information on crown fire behavior as related to conifer forests.

The view was that a critical synthesis on crown fire behavior must rest upon as solid a foundation of knowledge as is possible at this time. The feeling was that a sufficient body of scientific, peer-reviewed literature of a practical nature existed at the time in order to undertake such a synthesis that would be useful to fire managers from the standpoint of fire and fuel management planning and near-real time prediction of crown fire behavior. The same could not necessarily be said for spotting, fire vortex development, and large-scale fire-atmospheric interactions.

Unfortunately, this second proposal was not approved for funding by the JFSP Governing Board. However, one board member suggested that we consider resubmitting the proposal to JFSP on an unsolicited basis. Thus, JFSP Project 09-S-03-1 was submitted and subsequently approved for funding by the JFSP Governing Board for three years starting with FY 2009-10; a 9-month extension was requested and approved in June/July 2012.

Study description and location

JFSP Project 09-S-03-1 principally constitutes a review and analysis of the literature dealing with certain features of crown fire behavior in conifer forests (e.g., the onset of crowning, type of crown fire and associated spread rate, fireline intensity and flame size, spotting, fire area and perimeter growth). In conifer forests at least, the onset of crowning, the type of crown fire and the associated spread rate and fireline intensity are integral to extreme fire behavior as they dictate the potential for other related phenomena (e.g., medium- and long-range spotting, the type of convection column development, various types of fire-induced vortices, and fire size in relation to elapsed time).

There is not a specific study area or areas for this project. The geographical emphasis though is primarily on the United States, and to a lesser extent Canada and Australia although relevant information from other regions of the world were also sought.

The Principal Investigator (PI) M.E. Alexander and Co-Principal Investigator (Co-PI) M.G. Cruz are quite familiar with the literature on crown fire behavior having both focused on crown fire phenomenology during post-graduate studies (Alexander 1998; Cruz 1999, 2004). The PI has also lectured on the subject of crown fires at the Fire Behaviour Modelling Short Courses held in Portugal in conjunction with the III, IV and V International Conferences on Forest Fire Research that took place in Portugal in 1998, 2002 and 2006 (Alexander 2006).

Information on crown fire behavior from several scientific peer-review journals is available, including Van Wagner's (1977, 1993) seminal articles on crown fires in the *Canadian Journal of Forest Research,* the special issue on the "International Crown Fire Modelling Experiment" (Butler *et al.* 2004a, 2004b; Stocks *et al.* 2004a, 2004b; Taylor *et al.* 2004), and recently developed and tested models for predicting passive and active crown fire rates of spread (Cruz *et al.* 2005; Alexander and Cruz 2006; Schaaf *et al.* 2007). Additional articles dealing with crown fire behavior can be found in *Forest Science* (Cruz *et al.* 2004), *International Journal of Wildland Fire* (Cruz *et al*. 2003b, 2006a, 2006b), *Forestry Chronicle* (Cruz *et al.* 2003a; Van Wagner 1998), and *Australian Forestry* (Cruz *et al.* 2008). The so-called "grey literature" is another source of valuable information on crown fire behavior (e.g., Alexander 1988; Rothermel 1991; Scott and Reinhardt 2001; Cruz *et al.* 2006c). In addition, the personal files of the project investigators, literature searches where made using conventional search engines such as *Google Scholar* as well as the resources of the Fire Research Institute Library (http://fireresearchinstitute.org/). The crown fire content within the NWCG S-190, S-290, S-390 and S-490 courses was also examined.

Another potential source of data-specific information on crown fire behavior is the documentation undertaken of wildfire behavior by the USDA Forest Service's Adaptive Management Services Enterprise Team (AMSET) since the 2003 fire season (http://www.fs.fed.us/adaptivemanagement/). The data collected by the AMSET Fire Behavior Assessment Team (Henson 2005) could prove useful in evaluating existing models for predicting the onset of crowning, type of crown fire and its associated spread rate as well as illustrating the various processes involved in crown fire behavior.

A number of activities were conducted in order to solicit input from both fire researchers and managers regarding the project:

- Publication of short notes or articles in user-oriented journals on the existence of the project.
- Establishment of a "neighborhood" regarding the project on the *MyFireCommunity.Net* website developed by the USDA Forest Service's Wildland Fire Lessons Learned Center.

- Creation of a unique website for the notifying and keeping the wildland fire community abreast of products produced by the project.
- Regular communication with the National Wildfire Coordinating Group's Fire Behavior Subcommittee starting in October 2010; this included in addition to email correspondence, one face-to-face meeting in April 2011 (Missoula, MT) and the delivery of progress reports on the project on the committee's January 2011, April 2012 and April 2013 teleconferences.
- Oral and poster presentations on the project and its products at selected conferences and workshops (Fig. 1a).
- A specific educational/training workshop on the project at a national or international level conference (Fig. 1b).

The four project investigators are situated in widely varying locations. Communication amongst project investigators thus relied upon conventional phone, the internet (e-mail, *Skype*), and project work meetings in April 2011 (Pack Forest/Seattle, WA), April 2012 (Edmonton, AB), and February 2013 (Raleigh, NC) (Fig. 1c).

In April 2011, project PI Alexander and Co-PI Cruz also spent two weeks together in Turkey based on the support of the Scientific and Technological Research Council of Turkey (Fig. 1d). This provided an opportunity to converse at length with our host, Dr. Ertugrul Bilgili and his Ph.D. Candidate, Bahar Dinc Durmaz of the Faculty of Forestry at the Karadeniz Technical University in Trabzon. The field work associated with Ms. Durmaz's thesis project involves some 100 high-intensity surface and crown fires in calabrian pine plantations (Bilgili *et al.* 2006, 2010; Durmaz *et al.* 2010). This also provided the opportunity to meet a former student of Dr. Bilgili's, Dr. Omer Kucuk, Faculty of Forestry, Kastamonu University, Kastamonu, Turkey, to discuss the crown fires he had documented in a Anatolian black pine plantation. This trip laid the foundation for the possibility of future collaborative research between Dr. Bilgili, Ms. Durmaz, and Dr. Kucuk with respect to analyzing the crown fire datasets assembled by the Turkish fire researchers.

In January 2011, project PI Alexander and Co-PI Cruz were approached by Paul A. Werth and Brian E. Potter (PI and Co-PI/Federal Cooperator, respectively, of JFSP Project 09-2-01-11) to take on the "crown fire development and spread" section of their synthesis of knowledge on extreme fire behavior. This opportunity came about as a result of the original Co-PI responsible for the review and analysis of crown fire behavior withdrawing from the project.

Figure 1. Joint Fire Science Program JFSP Project 09-S-03-1 related photographs. (**a**) Project PI Alexander standing at the presentation board for poster "Synthesizing Knowledge on Crown Fire Behavior in Conifer Forests: We Could Use Your Help!", International Association of Wildland Fire 4th Fire Behavior and Fuels Conference, Raleigh, North Carolina, February 19-22, 2013. Photo by Michelle Ekstrom, International Association of Wildland Fire; (**b**) Project Co-PI Cruz at the front of the room lecturing at the "Crown Fire Behavior in Conifer Forests" Workshop, International Association of Wildland Fire 4th Fire Behavior and Fuels Conference, Raleigh, North Carolina, February 18, 2013. Photo by Paula Nelson, International Association of Wildland Fire; (**c**) Project PI Alexander (left) and Co-PIs Vaillant (centre) and Cruz (right) at their final JFSP Project 09-S-03-1 meeting in Raleigh, North Carolina, February 15-17, 2013. Photo courtesy of Nicole Vaillant; and (**d**) Project Co-PI Cruz (left) and PI Alexander (right) at the photo memorial of the "faces" of fallen wildland firefighters located in the lobby of the national fire control centre of the Ministry of Environment and Forestry in Ankara, Turkey, April 14, 2011 (translation of the inscription at the bottom: "We remember with gratitude those who have lost their lives fighting forest fires"). Photo by Dr. Ertugrul Bilgili, Faculty of Forestry, Karadeniz Technical University, Trabzon, Turkey.

Key findings

The following is the summary of salient points taken from the "Crown Fire Dynamics in Conifer Forests" chapters contained in Werth *et al.* (2011, 2013):

Types of crown fires. Three kinds or classes of crown fire are recognized according to their degree of dependence on the surface phase of fire spread (i.e., passive, active and independent, although the latter is generally regarded as a rare and short-lived occurrence)[1].

Crown fire initiation. The amount of heat energy required in the form of convection and radiation to induce the onset of crowning is dictated by the canopy base height and foliar moisture content as manifested in the surface fire's intensity. A rather abrupt increase in fire activity should normally be expected as a fire transitions from the surface to crown fire phase.

Crown fire propagation. Whether a passive or active crown fire develops following the onset of crowning depends on the spread rate after initial crown combustion and is in turn related to canopy bulk density. A minimum value of about 0.1 kg/m^3 appears to represent a critical threshold for active crowning.

Crown fire rate of spread. At a minimum, a doubling or tripling in a fire's rate of advance follows the onset of crowning. Wind-driven crown fires have been documented to spread at up to 100 m/min for several hours and in excess of 200 m/min for up to an hour. Although the mechanical effect of slope steepness on increasing a fire's rate of spread is well known, fires in mountainous terrain generally do not spread nearly as far for a given period of time compared to those on flat topography.

Crown fire intensity and flame zone characteristics. As a result of the increase in spread rate and fuel available for combustion, a fire can easily quadruple its intensity in a matter of seconds when crowning takes place (e.g., from 3,000 kW/m to 12,000 kW/m). The resulting wall of flame, standing nearly erect, is on average up to two to three times the tree height and emits fierce levels of radiation. Flame fronts commonly exceed 30-45 m in depth.

Crown fire area and perimeter growth. The area burned by a crown fire is at least four to nine times greater that of a surface fire for the same period of time. Assuming unlimited horizontal fuel continuity, crown fires are capable of burning an area of upwards to 70,000 ha with a perimeter length of 160 km in a single burning period and have done so in the past.

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[1] The description of the independent crown fire in the S-190, S-290, S-390 and S-490 courses should accordingly be revised in future editions of these courses.

Crown fire spotting activity. Crown fires commonly display high-density, short-range spotting (<50 m). Spotting distances of up to about 2 km, although less common, are frequently seen on crown fires, resulting in normal barriers to fire spread being breached. Many spot fires are simply overrun by the main advancing flame front of a crown fire before they effectively contribute to an increase in the fire's overall rate of advance. Cases of long-distance spotting in excess of 10 km have been reported.

Models, systems, and other decision aids for predicting crown fire behavior. The current set of guides and decision-support system for assessing potential crown fire behavior used in the United States do require considerable adjustment on the part of trained and informed users (e.g., fire behavior analysts, long term fire analysts) for proper application. Alternative models and systems that have undergone far more extensive testing and requiring a minimum of inputs are available.

Implications for fire and fuel management. Operational fire management personnel can readily help themselves when it comes to being able to assess crown fire behavior by increasing the amount of wildfire monitoring and case study documentation.

Management implications

Classification of crown fires. The current NWCG (2012) glossary of wildland fire management terms does not match other proposed definitions related to crown fires (e.g., http://www.firewords.net/). This can lead to confusion within the wildland fire community. Scott and Reinhardt (2001) claimed that the possibility exists for a stand to support an active crown fire that would otherwise not initiate a crown fire. They referred to this situation as a "conditional surface fire." Later on Scott (2006) termed this a "conditional crown fire" which has led to some confusion. To our knowledge, no empirical proof has been produced before or since to substantiate the possible existence of such a situation, at least as a steady-state phenomenon. Yet, this is a popular concept amongst fire researchers involved in simulation studies of fuel treatment effectiveness (e.g., Honig and Fulé 2012)[2].

Flames don't have to extend into the lower canopy for crowning to occur. As first suggested by Alexander (1988), crown fire initiation can be expressed in terms of a surface fire's flame length instead of its fireline intensity, thereby permitting a ready comparison of canopy base height versus flame length and thus a rough guide to the likelihood of crowning (Anderson 1974).

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[2] The notion of the possible existence of a conditional crown fire or conditional surface fire in not mentioned in the S-190, S-290 and S-390 courses. It should accordingly be excluded from the S-490 course or an appropriate cautionary statement included.

Graphs and tables given in Alexander (1988) were subsequently presented in Rothermel (1983) and NWCG (1992).

Byram's (1959) flame length – fireline intensity relationship should not be reviewed as universal in nature; the same applies to Van Wagner's (1973) crown scorch height – fireline intensity relationship. As shown by Alexander and Cruz (2012a, 2012b), many other relationships exist. On the basis flame length – fireline relationships and Van Wagner's (1977) crown fire initiation model it has also been shown that the flames of a surface fire don't necessarily have to reach or extend into the lower tree crowns to initiate crowning (Alexander and Cruz 2012a).

Unsubstantiated coupling of crown fire behavior models. Beginning in the late 1990s and continuing until the present time, several U.S. fire behavior modelling systems (i.e., BehavePlus, FARSITE, NEXUS, FFE-FVS, FMA Plus, FlamMap) began to couple of Rothermel's (1972) surface fire model with his crown fire rate of spread model (Rothermel 1991) and the criteria for crown fire initiation and propagation in conifer forests as described by Van Wagner (1977, 1993). Cruz and Alexander (2010) very clearly demonstrated that these operational fire behavior modelling systems currently used to simulate the onset of crowning and active crown fire rate of spread in conifer forests of the western U.S. exhibit a significant underprediction bias.

The principal sources of this underprediction bias were shown to include: (1) incompatible model linkages, (2) use of surface and crown fire rate of spread models that have inherent underprediction biases themselves and (3) a reduction in crown fire rate of spread based on the use of unsubstantiated crown fraction burned functions. The use of uncalibrated custom fuel models to represent surface fuelbeds was considered as a fourth potential source of bias. The underprediction biases identified by Cruz and Alexander (2010) would also apply to the Fire Behavior Field Reference Guide currently under development via the leadership of the NWCG Fire Behavior Subcommittee.[3]

Defining canopy fuel stratum characteristics. Commensurate with the model coupling mentioned previously, there has in the U.S. been a deviation in the manner in which canopy base height, canopy fuel load, and canopy bulk density are defined with respect to Van Wagner's (1977, 1993) crown fire initiation and propagation models. For example, canopy bulk density has been defined as the maximum 3.0-m running mean of a vertical canopy fuel profile and canopy base height as the lowest point in the profile where canopy bulk density ≥ 0.012

[3] http://www.fbfrg.org/home

kg/m^3 (Scott and Reinhardt 2001; Reinhardt *et al.* 2006b). In contrast, Cruz *et al.* (2003b) for example defined canopy base height as the average height to the live crown base in a stand and the canopy bulk density as the canopy fuel load divided by the canopy depth (i.e., average stand height minus average height to live crown base).

Reinhardt *et al.* (2006b) considered the canopy fuel load to include, needle foliage, the 0.3 cm-diameter live roundwood, and the 0.6 cm-diameter dead roundwood, admitting that the latter two categories were not based on actual data but rather "guess-timates." Van Wagner (1977) on the other hand considered the canopy fuel load was limited to needle foliage.

In the implementation of Van Wagner's (1977) crown fire initiation model, some authors have applied or recommended unrealistically low foliar moisture content values (e.g., Cheyette *et al.* 2008). The latest version (5.0.5) of the BehavePlus fire behavior modelling system and the new NWCG Fire Behavior Field Reference Guide allows for the foliar moisture content down to 30 and 50%, respectively. One needs to bear in mind that Van Wagner's (1977) model has been parameterized on the basis of a single experimental crown fire with a foliar moisture content of 100%, although he did apply it to foliar moisture contents as low as 67% (Van Wagner 1993; Cruz and Alexander 2010).

Evaluating models to predict canopy fuel stratum characteristics. Cruz and Alexander (2012) subjected the regression equations of Cruz *et al.* (2003) to two evaluations. The first involved a random selection of 10 stands each from the four datasets used in original study by Cruz *et al.* (2003) that were also subjected to two simulated "low thinning" regimes. A second evaluation involved an independent dataset of 16 sampled ponderosa pine stands in the Black Hills of South Dakota by Keyser and Smith (2010). The results of both evaluations clearly showed that the stand-level models developed by Cruz *et al.* (2003b) are, considering their simplicity, quite robust. This should increase user confidence in the value of canopy fuel characteristics tables (Alexander and Cruz 2013e) as well as the software application that is also available for making calculations (Alexander and Cruz 2010; Cruz and Alexander 2013b).

It is worth noting that Reinhardt *et al.* (2006b) questioned the validity of the regression equations for estimating canopy base heights in coniferous forest fuel types developed by Cruz *et al.* (2003b) to produce logical results when applied to simulations involving low thinning. As it turned out, this was an error in interpretation with regard to the stand height input parameter (Cruz *et al.* 2010).

The myth of the "crown fire-proof" conifer forest. By linking Rothermel's (1972, 1991) models for predicting surface and crown fire rates of spread with Van Wagner's (1977, 1993) crown fire transition and propagation models, Scott and Reinhardt (2001) were able to develop two crown fire hazard indices -- the Torching index (TI) and the Crowning Index (CI). The TI and CI represent the threshold wind speeds required for the onset of crowning and active crown fire propagation in conifer forests, respectively. Each TI and CI value is tied to a unique set of surface fuelbed characteristics (expressed in terms of a stylized or custom fuel model), dead and live moisture contents of surface fuels, crown fuel properties (i.e., canopy base height and bulk density, foliar moisture content), and slope steepness. These two indices have proven to be very popular amongst both researchers and fire managers alike.

Cruz and Alexander (2010) found that many simulation studies that relied upon the TI and CI as a means of assessing crowning potential in relation to fuel treatment effectiveness, often produced unrealistic outcomes considering the associated environmental conditions and fuel characteristics. Quite often critically dry fuel moisture levels were specified (i.e., 1.5-3%) along with very low canopy base heights and relatively high canopy bulk densities and yet the simulations suggested that exceedingly strong winds were commonly required to initiate crowning and for fully developed or active crown fires to occur. In many cases, these simulation studies have reported TI and CI values for gale force wind conditions (i.e., sustained winds greater than about 100 km/h). Such winds seldom occur inland but when they do, they generally result in trees and whole forest stands being blown down over large areas. Scott (2006) suggested that these very high wind velocities simply indicated “a very low potential for initiating a crown fire” and that wind speeds at or in excess of 100 km/h “occur so rarely that crown fire can be considered nearly impossible to initiate”, there implying there is no need for any concern.

It could be argued that the outcomes of these simulation studies are realistic in that they simply reflect the fact that both strong winds and dry fuels are required to achieve any sort of torching or crowning activity. While this may be intuitively true for areas that have undergone some form of fuel treatment such as prescribed burning, for control or untreated areas the simulation results do not appear realistic based on general observation and experience. Simard *et al.* (2011), for example, indicated that TI levels above 700 km/h were necessary for passive crowning to occur in well-stocked, undisturbed lodgepole pine stands with an average canopy base height of 3.5 m.

It is clear that the burning conditions specified in these simulation studies are not necessarily representative of those associated with large, high-intensity wildfires that exhibit extensive crowning. For example, the crown fire run in lodgepole pine forests on the 1988 North Fork Fire that threaten the Old Faithful Inn complex in Yellowstone National Park occurred at a fine dead fuel moisture content of 6% with wind speeds of around 25 km/h (Thomas 1991).

Lack of physics-based model evaluation in predicting crown fire behavior. Operational fire behavior modelling systems were previously shown to possess a number of weaknesses that severely limited their use in assessing crown fire potential (Cruz and Alexander 2010). Had evaluations been undertaken as part of system development prior to implementation, more than a decade of misapplication might have been averted. A somewhat similar situation now appears to be unfolding with respect to the use of the present generation of physics-based models such as FIRETEC (Linn *et al.* 2002) and the Wildland-urban interface Fire Dynamics Simulator (WFDS) (Mell *et al.* 2007) in the simulation of potential crown fire behavior. In other words, applications of FIRETEC and WFDS (e.g., Parsons *et al.* 2010a, 1010b; Contreras and Chung 2013; Hoffman *et al.* 2013; Linn *et al.* 2013; Morvan et al. 2013) are now getting ahead of their evaluation (Alexander and Cruz 2013a), especially with respect to their use in assessing crown fire behavior.[4]

The lack of evaluation is exemplified by the WFDS simulations of fire behavior undertaken by Michaletz *et al.* (2012) for a 100 to 200 year closed white spruce stand (top height of 17.7 m) patterned after Site WS 04 in Ottmar and Vihnanek (1998). The fine dead fuel moisture specified for the simulations was 6% and the 10-m open wind speed was set at 36 km/h. All the surface fuel less than 1.0-cm in diameter was assumed to be available for combustion. Passive crown fires were predicted to occur with spread rates averaging 4.3 m/min and fireline intensities of 9,147 kW/m. This would equate to a fuel consumption of 7.1 kg/m^2 which in itself is an extraordinarily high value, even for a mature white spruce (cf. Stocks *et al.* 2004b). Michaletz et al. (2012) claimed that the simulations of fire behavior were in line with experimental fire observations obtained for much shorter, open black spruce stands which would be distinctly different from the mature white spruce stand modelled by Michaletz et al. (2012). From comparisons against empirical evidence obtained from active crowning wildfires (Alexander and Cruz 2006), the predicted fire spread rate should be at least 10 times greater than the value obtained by Michaletz et al. (2012) given the stated conditions.

Van Wagner's criteria for active crown fire spread is a robust concept. The robustness of the critical minimum spread rate for active crown fire relation as a function of canopy bulk density as deduced by Van Wagner (1977) is well substantiated (Cruz *et al.* 2005; Cruz and Alexander 2010). Albini (1993) viewed Van Wagner's (1977) criteria as a "lean flammability limit" whereas Agee (1996) termed it a "crown bulk density threshold". Considering that Van Wagner's (1977) concept for active crowning is the basis for a number of fire and fuel management oriented guidelines (e.g., Agee 1996; Graham 1999; Keyes and O'Hara 2002; Powell 2010) and models (e.g., Cruz *et al.* 2005, 2008) should increase their confidence in them.

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[4] JFSP is in fact supporting such endeavors (e.g., JFSP Project 12-1-03-30, "STANDFIRE: An IFT-DSS Module for Spatially Explicit, 3D Fuel Treatment Analysis").

Foliar moisture content has little or no effect on crown fire rate of spread. Contrary to conventional wisdom (Van Wagner 1998), an analysis of existing empirical data revealed that foliar or live moisture content has at best a very minor effect on the rate of spread of crowning fires in conifer forests (Alexander and Cruz 2013c); the same applies to shrublands. None of the present model functions used to adjust the spread rate for the relative effect of foliar or live fuel moisture are considered suitable, including their possible application to dead canopy foliage such as in the "red stage" of mountain pine beetle attacked stands as suggested by Moran and Cochrane (2012).

Surface fire versus crown fire rates of spread prediction. Some fire researchers have implied that the behavior of crown fires is more unpredictable than that of surface fires. A comprehensive survey of the error statistics associated with rate of fire spread model evaluation studies was undertaken in order to gauge their predictive ability of surface and crown fire rates of spread (Cruz and Alexander 2013a). This involved 49 fire spread model evaluation datasets consisting 1,278 observations in seven different fuel type groups. Examination of the error metrics obtained for surface and crown fires in this study, showed no differences in predictability. The highest mean absolute percent errors were in fact obtained for surface fires.

The predictability of the spread rate of crown fires is partially due to the fact that after a crown fire is established, its sustained propagation is to a large degree a function of the wind speed and fine dead fuel moisture content, and the heat release rates, while very high, occur over a relative narrow range (i.e., within an order of magnitude). For a surface fire spread model to be successful, it needs to be able to describe spread rates and fireline intensities spanning three or four orders of magnitude.

An example of linking surface and crown fire behavior to fire effects. In spite of a long standing appreciation for the influence of forest fire behavior on ecological effects, progress in the biophysical modelling of forest fires has been painfully slow and in some cases, unrealistic. Many conifer forest types are dependent on crown fire (e.g., Waldrop *et al.* 2003). In order to demonstrate that our existing knowledge of fire behavior can applied to the modelling of certain fire effects (e.g., Oosting 1944), the question of "What kind of fire behavior is required to open serotinous cones of jack pine and lodgepole pine?" was addressed (Alexander and Cruz 2013c).

It was determined that the manner in which the resinous bond that holds the tips of the scales of serotinous cones jack pine and lodgepole pine together is dictated by the type of fire. In surface fires it occurs as a result of convective and radiative heating of the live overstorey canopy and in crown fires by direct flame contact; seed mortality is associated with active crowning where flame front residence times at the ground surface exceed 50 seconds. The results obtained from the modelling exercise were in stark contrast to the previous work on the subject by Johnson and Gutsell (1993).

Model of elliptical crown fire length-to-breadth ratio underpredicts. The length-to-breadth ratio (L:B) model for crown fires put forth by Rothermel (1991) has in its basis very small fires carried out in a wind tunnel (Anderson 1983). A comparison of model predictions against L:B data obtained from wildfire observations (Alexander 1985; Forestry Canada Fire Danger Group 1992) indicates that the Rothermel (1991) L:B model consistently underpredicts at 10-m open winds greater than 20 km/h (Alexander and Cruz 2011, 2013d).

Maximum spotting distance model for active crown fires. A model for active crown fires to compliment the suite of existing models developed by the late Dr. Frank A. Albini for predicting the maximum firebrand spotting distance of single and group tree torching, burning piles of slash or 'jackpots' of heavy fuels, and wind-aided surface fires in non-tree canopied fuel complexes such as grass, shrubs and logging slash was formally documented (Albini *et al.* 2012). Although the active crown fire maximum spotting distance model has not undergone any specific evaluations to date, the estimates produced by the model appear realistic in light of existing documented observations.

Reviews on predicting crown fire and wildland fire behavior have proven valuable. According to the "pre-reviewers" obtained of the syntheses (Alexander and Cruz 2011, 2013d), journal review papers (Alexander and Cruz 2012a, 2013b) and book chapters (Alexander 2013) published as part of this project, both fire managers and fire researchers alike have indicated these publications are highly valued. Trevitt (1989) has articulated the value of promoting "studies that critically analyze and comprehensive synthesize our existing knowledge." A recent essay by Maier (2013) has also highlighted the important qualities of a literature review.

Alternative models for predicting the characteristics of crown fire behavior. A number of new, operational and physics-based models for crown fire initiation and rate of spread have been development (Alexander 2009) since the publication of Van Wagner (1977) and Rothermel (1991) and the modelling systems that have incorporated them like BehavePlus, NEXUS and FARSITE. This includes, for example, the Canadian Forest Fire Behavior Prediction (FBP) System (Forestry Canada Fire Danger Group 1992; Taylor *et al.* 1997; Wotton *et al.* 2009), Crown Fire Initiation and Spread (CFIS) system (Alexander *et al.* 2006)[5], and the Pine Plantation Pyrometrics (PPPY) (Cruz *et al.* 2008). For the most part, the models that form the basis of these

[5] The mechanical effects of slope steepness on crown fire initiation and spread have yet to be incorporated into the CFIS system.

system have received far more evaluation than the current crop of U.S. fire behavior modelling systems.

The Cruz *et al.* (2005) active crown fire rate of spread appears far superior to Rothermel (1991) in the context of the U.S. fire behavior modelling systems (Cruz and Alexander 2010). The same could be said for Nelson's (2003) flame front residence model with respect to Anderson's (1969) long-standing model for estimating surface fuel consumption.

Evaluation of fuel treatment effectiveness. Fuel treatments that aim to reduce crown fire behavior potential work by modifying the fuel complex structure in ways that limit certain fire processes. The effectiveness of these treatments can be quantified in different ways. We applied a typical fuel treatment effectiveness study framework to model surface and crown fire characteristics to a stand subjected to commercial thinning (Cruz and Alexander 2013d). Fire potential was analyzed through seven distinct scenarios involving different assumptions regarding fine dead fuel moisture contents and fire behavior models. Widely varying results were obtained depending on how the environmental inputs were handled and which fire behavior modeling system was employed.

Two main implications emerged from the study outcomes: (1) the decision as to which fire behavior characteristic should be used in evaluating the effects of fuel treatments has a strong bearing on calculated fire behavior potential and therefore warrants serious consideration on the part of analyst; and (2) our assessment of fire behavior potential considered the 97th percentile fire weather and fire danger conditions to define a worst case situation. One of the drawbacks of this approach is that the simulations capture a sole moment in the fire behavior potential spectrum. A fire manager might be more interested in assessing fire potential under more common and not so severe conditions (e.g., conditions where initial attack is more likely to be successful or where fuel treatments have a higher likelihood of being effective. To assess the fire potential of a stand over the full spectrum of fire behavior, the analysis should consider the cumulative distribution of days susceptible to a certain a level of fire behavior in lieu of adopting a "worst-case situation" approach.

Relationship to other recent findings and ongoing work on this topic

Crown fire potential in mountain pine beetle-attack lodgepole pine forests. Following the approval of JFSP Project 11-1-4-16 ("The Influence of Fuel Moisture and Flammable Monoterpenes on the Combustibility of Conifer Fuels"), in August 2011, Dr. Michael J. Jenkins (the project PI) invited Project PI Alexander to join the project team as a collaborator/contributor and to also serve as a full Adjunct Professor on Wesley G. Page's Ph.D. supervisory committee at Utah State University). This has led to several papers focusing on crown fire potential in the “red stage” of mountain beetle-attack lodgepole pine forests (Jenkins *et al.* 2012; Page *et al.* (2013a, 2013b, 2013c).

Physics-based fire behavior models. Michaletz *et al.* (2012) has stated that “WFDS is increasingly being used as a physics-based ‘laboratory’ for conducting experiments on fire spread through vegetation”. This kind of attitude is starting to create a fire research culture in the universities which encourages reliance upon computer modelling at the expense of creating new fire behavior field data (Parsons 2007; Contreras 2010; Hoffman 2011; Michaletz 2012). This needs to change for the long-term health of wildland fire behavior research.

Crown fire potential in other forest types. Kuljian (2010) tested the applicability of Van Wagner (1977) crown fire initiation model for crown fuels in a broadleaf evergreen tree species under a broad range of fuel moisture contents (dead foliage with moisture content of 5 and 9%; live foliage with moisture content of 70 and 80%). Although his experimental setup varied from a free-spreading fire configuration, his results for live crown fuels approached what would be predicted by Van Wagner model. For the dead crown fuel experiments he found his results more conservative then the Van Wagner’s (1977) model. Van Wagner’s (1977) model indicated that for a given fireline intensity, dead crown fuel ignition would occur at heights two to three times higher than observed experimentally. Kuljian (2010) suggested that Van Wagner (1977) formulation might be applicable to broadleaf species but the extrapolation of his crown fire initiation model to low fuel moisture content fuels, namely those characteristics of dead crown fuels, is questionable as the model will overpredict the likelihood of fuel ignition. Of note: Project PI Alexander and Co-PI Cruz advised M.Sc. Candidate Howard Kuljian on many occasions during his thesis project.

Experimental crown fires. The Canadian Forest Service, previously the leader in carrying out rapidly-spreading, high-intensity active crown fires in conifer forests on an experimental have not done so in more than a decade now and are unlikely to do so in the foreseeable future. The FPInnovations Wildfire Operations group has conducted several experimental crown fires in recent years (Schroeder 2007, 2010; Schroeder and Mooney 2009, 2012; Walkinshaw *et al.* 2012; Baxter *et al.* 2013; Mooney 2013) at the site of the former International Crown Fire Modelling Experiment (ICFME) in the Northwest Territories (Stocks *et al.* 2004a). Attempts at conducting similar experiments have been undertaken in Russian and the U.S. (e.g., McRae *et al.* 2005; Butler *et al.* 2013). However, the quality of the documentation (e.g., no data on fuel consumption or canopy bulk density, on-site weather measurements with respect to representativeness and sampling period) and experimental design (e.g., inadequate ignition device, short crown fire runs following ignition) is suspect from the standpoint of model evaluation and development purposes.

Future work needed

Systematic documentation of crowning wildfires for model evaluation purposes. A concerted program of model evaluation based on field observations and measurements of free-burning of experimental fires and operational prescribed fires as well as wildfires is urgently needed in lieu of a cultural that relies on model simulations for conducting wildland fire behavior research (Alexander and Cruz 2011, 2013d).

Development and testing of flame size model for crown fires. Existing suggestions (i.e., Byram 1959) and models (i.e., Thomas 1963 in Rothermel 1991; Butler *et al.* 2004b) for estimating flame lengths of crown fires have been shown to be inadequate (Alexander 1998; Alexander and Cruz 2011, 2013d).

Defining the threshold for vertical fire spread in terms of ladder/bridge fuels canopy bulk density is needed. The vast majority of simulation studies that have evaluated the effectiveness of fuel treatments on crown fire potential have relied on Scott and Reinhardt's (2001) definition for canopy base height (i.e., the lowest height above ground at which the canopy bulk density is ≥ 0.012 kg/m^3). They admitted that this was an arbitrary value and "not based on any kind of combustion physics" (Reinhardt *et al.* 2006a) yet this guideline has come to be an accepted standard with little or no questioning of its origin for some 15 years.

The quantitative study of vertical fire spread, including the role of bridge or ladder fuels, has been viewed as a continuing research need/knowledge gap for over 50 years (Lawson 1972; Sando and Wick 1972). Very little has been done about it. Other than a small study by Martin and Sapsis (1987), nothing has been done in this regard with respect to conifer forest fuel complexes.

Crown fuel consumption data collection and model evaluation. The model developed by Call and Albini (1997) has not been rigorously evaluated. Part of the problem is that the only published account of any empirical field data is that collected by Stocks *et al.* (2004b).

Application of ensemble or multiple simulation methods to the prediction of crown fire behavior. These simulation methods (Cruz 2010) are especially relevant for crown fires due to the large errors that can be introduced in the model predictions by the inaccurate classification of the fire as either a surface fire or crown fire.

Commensurate with this work is the examination of crown fire cessation. No such predictive model currently exists although Cruz and Alexander (2009) had initiated work earlier on this subject.

Deliverables

Deliverable	Description	Status
Book chapters	A state-of-knowledge synthesis on the characteristics and prediction of crown fire behavior in conifer forests (Alexander and Cruz 2011, 2013). Chapters on (i) fundamentals of wildland fire as a physical process, (ii) estimating free-burning wildland fire behavior, and (iii) the practical application of wildland fire behavior knowledge for the book *Fire on Earth: An Introduction* (Alexander 2013).	Completed. See citations below. Added deliverables.
FMT issue	Special issue of *Fire Management Today* (FMT) devoted to crown fire behavior based on the findings from the synthesis has been negotiated with the FMT Managing Editor (Appendix 1).	Manuscripts to be submitted July 30, 2013.
Journal articles	Publication of a number of scientific peer-reviewed journal articles or shorter notes to substantiate certain critical elements of the synthesis.	Completed. A total of 16 journal articles. See citations below.
Conference papers and technical journal notices	At least two conference papers highlighting the project; also extended this to notices in technical journals.	Completed. See citations below.
Software	Development of the *Cruz, Alexander and Wakimoto (2003) Canopy Fuel Stratum Characteristics Calculator*.	Added deliverable. See citation below.
Workshop	Developed and delivered a 6-hour Educational Workshop entitled "Crown Fire Behavior in Conifer Forests" on the JFSP Project 09-2-03-1 in conjunction with the International Association of Wildland Fire 4th Fire Behavior and Fuels Conference (Appendix 2).	Added deliverable. Course agenda and powerpoint presentations downloadable from project website.
Other contributions	Several additional papers written for short course, seminars and conferences with a particular emphasis on the application of crown fire behavior knowledge to firefighter safety and fire impacts.	Added deliverables. See citations below.
Project website	Creation and maintenance of project websites.	Added deliverable. See links below.

Book chapters

Alexander, M.E. 2013. Part 4: The science and art of wildland fire behaviour prediction. In: Scott, A.C.; Bowman, D.M.J.S.; Bond, W.J.; Pyne, S.J.; Alexander, M.E. Fire on Earth: An Introduction. Wiley-Blackwell, Chichester, England. *In press*.[6]

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See Appendix 1.

Journal articles

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See also Appendix 2.

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Appendix 1: Outline for Special Issue of *Fire Management Today*

(Volume 73, Number 4 – Winter 2013) on "The Behavior of Crowning Conifer Forest Fires"

The JFSP Sponsored Project to Synthesize Knowledge on Crown Fire Behavior in Conifer Forests: Martin E. Alexander, Miguel G. Cruz, Nicole M. Vaillant

Characteristics of Crown Fire-prone Conifer Forest Fuel Complexes: Miguel G. Cruz and Martin E. Alexander

Prediction of the Start and Spread of Crown Fires in Conifer Forests: Miguel G. Cruz and Martin E. Alexander

Predicting the Intensity, Flame Dimensions, Maximum Spotting Distances of Crown Fires in Conifer Forests: Martin E. Alexander and Miguel G. Cruz

Estimating the Elliptical Shape and Size of Wind-driven Crown Fires in Conifer Forests: Martin E. Alexander and Miguel G. Cruz

ArcFuels: An ArcMap toolbar for fuel treatment planning and wildfire risk assessment: Nicole M. Vaillant and Alan Ager

Capturing crown fire behavior on active wildland fires – the Fire Behavior Assessment Team: Nicole M. Vaillant, Carol Ewell, JoAnn Fites-Kaufman

Improving our Application and Understanding of Crown Fire Behavior Knowledge in Conifer Forests: Martin E. Alexander, Miguel G. Cruz and N.M. Vaillant

Appendix 2: Workshop Agenda

International Association of Wildland Fire 4th Fire Behavior and Fuels Conference

CROWN FIRE BEHAVIOR IN CONIFER FORESTS WORKSHOP

February 18, 2013 – Raleigh, NC

AGENDA

0800 – 0820 h Introduction – Marty Alexander

- JFSP Project Background and Websites
- Results To Date and Planned Products
- Workshop Objectives

0820 – 0930 Workshop Icebreaker – Nicole Vaillant

- Review & Discussion of Crown Fire Photos of Workshop Participants

0930 – 1000 General Background Information on Crown Fires – Marty Alexander/Miguel Cruz

- Significance
- Fire Behavior Fundamentals
- Nature, General Features and Classification
- Fire Environment Features

1000 – 1030 Break

1030 – 1100 Crown Fire Initiation and Sustained Propagation – Miguel Cruz/Marty Alexander

- Physical processes
- Existing models and theories

1100 – 1130 Crown Fire Characteristics – Marty Alexander/Miguel Cruz

- Crown Fire Rate of Spread and Intensity/Flame Size
- Crown Fire Spread Distance and Fire Size (Area and Perimeter)
- Other Crown Fire Phenomena

1130 – 1200 Operational Prediction of Crown Fire Behavior – Miguel Cruz/Marty Alexander

- Fire behavior prediction process, limitations and assumptions
- Canadian, American and Australia models, systems and modelling systems

1200 – 1300 Lunch

1300 – 1330 Applications of Crown Fire Behavior Knowledge – Miguel Cruz/Marty Alexander

- Assessing effectiveness of fuel treatments in reducing crown fire potential
- Modelling the impacts of fire behavior on serotinous cone opening

1330 – 1400 Future Outlook to the Understanding and Prediction of Crown Fire Behavior – Marty Alexander/Miguel Cruz

- Outstanding Research Needs/Knowledge Gaps
- The Solitudes to Model Development
- Conducting Experimental Fires and Operational Prescribed Fire Opportunities

1400 – 1445 Thoughts on Wildfire Behavior Observation and Documentation – Nicole Vaillant

- Adaptive Management Services Enterprise Team Experiences

1445 – 1500 Closing Comments – Marty Alexander

WORKSHOP OBJECTIVE & DESCRIPTION

The goal of this workshop is provide participants with a summary of the results emanating from the Joint Fire Science Program sponsored project "Crown Fire Behavior Characteristics and Prediction in Conifer Forests: A State of Knowledge Synthesis" (JFSP 09-S-03-1) that began in October 2009.

The current state-of-knowledge with respect to crown fire initiation and propagation in relation to fuel complex characteristics and surface weather conditions will be described with time for questions and discussion. Workshop participants will also have the opportunity to share their experiences and observations regarding crown fires, including thoughts on future research needs and knowledge gaps. Participants will be asked to submit a color photo of a crown fire to be projected during the workshop and be prepared to orally provide a short description of the image. The instructors will elicit input on fuels and fire behavior characteristics that are unique to the southern United States in regards to crown fire behavior in conifer forests.

WORKSHOP INSTRUCTORS

Dr. Marty Alexander is currently an adjunct professor of wildland fire science and management at the University of Alberta (and Utah State University) after having retired from a career in fire research with the Canadian Forest Service (1976-2010) in which he specialized in fire behavior with a particular emphasis on crown fires. Dr. Miguel Cruz is a senior bushfire research scientist with CSIRO in Canberra, Australia and has extensive field and modelling experience with crown fire behavior in both conifer forests and tall shrubland fuel complexes. Dr. Nicole Vaillant is a fire ecologist with the USDA Forest Service specializing in fuel treatment planning and fire behavior modelling.

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PROJECT WEBSITES

http://www.fs.fed.us/wwetac/projects/alexander.html

http://www.firescience.gov/JFSP_advanced_search.cfm (select "Alexander, Martin E." for Researcher Name, then select "Crown Fire Behavior Characteristics and Prediction in Conifer Forests: A State of Knowledge Synthesis")