A conceptual framework for ranking crown fire potential in wildland fuelbeds[1]

Mark D. Schaaf, David V. Sandberg, Maarten D. Schreuder, and Cynthia L. Riccardi

Abstract: This paper presents a conceptual framework for ranking the crown fire potential of wildland fuelbeds with forest canopies. This approach extends the work by Van Wagner and Rothermel, and introduces several new physical concepts to the modeling of crown fire behaviour derived from the reformulated Rothermel surface fire modeling concepts proposed by Sandberg et al. (this issue). This framework forms the basis for calculating the crown fire potentials of Fuel Characteristic Classification System (FCCS) fuelbeds (Ottmar et al., this issue). Two new crown fire potentials are proposed (*i*) the torching potential (TP) and (*ii*) the active crown potential (AP). A systematic comparison of TP and AP against field observations and Crown Fire Initiation and Spread (CFIS) model outputs produced encouraging results, suggesting that the FCCS framework might be a useful tool for fire managers to consider when ranking the potential for crown fires or evaluating the relative behaviour of crown fires in forest canopies.

Résumé : Cet article présente un cadre conceptuel pour classer le potentiel de feu de cimes des couches de combustibles en milieu naturel où il y a des canopées forestières. Cette approche pousse plus loin les travaux de Van Wagner et de Rothermel et introduit plusieurs concepts physiques nouveaux dans la modélisation du comportement des feux de cimes dérivés des concepts reformulés de Rothermel pour la modélisation des feux de surface proposés par Sandburg et al. (ce numéro). Ce cadre forme la base pour calculer les potentiels de feu de cimes des couches de combustibles du système de classification des caractéristiques des combustibles (SCCC) (Ottmar et al., ce numéro). Deux nouvelles possibilités de feux de cimes sont proposées : (*i*) la possibilité de flambée en chandelle et (*ii*) la possibilité de feu de cime dépendant. Une comparaison systématique de ces deux types de feux de cimes avec des observations sur le terrain et les prévisions du modèle de l'École canadienne d'enquêtes sur les incendies a donné des résultats encourageants. Ces résultats indiquent que le cadre du SCCC pourrait s'avérer un outil utile que les responsables de la gestion des incendies devraient considérer pour classer le potentiel de feu de cimes ou pour évaluer le comportement relatif des feux de cimes dans les canopées forestières.

[Traduit par la Rédaction]

Introduction

The Fuel Characteristic Classification System (FCCS; Ottmar et al. 2007) offers the capacity to describe the physical characteristics of any wildland fuelbed no matter how complex, and the capacity to compare one fuelbed with another. FCCS enables the user to assess the absolute and relative effects of fuelbed differences due to natural events, fuel management practices, or the passage of time. The differences can be expressed as native physical differences, such as changes in loadings and arrangements of fuelbed components, or as changes in the potential fire behaviour and effects, such as fire behaviour or fuel consumption (Sandberg et al. 2007*b*). Comparing the potential for crown fire initiation and spread among the various FCCS fuelbeds is problematic because there is no broadly applicable and physics-based crown fire model available that accounts for these fuelbed differences. FCCS does not require specific prediction of crown fire behaviour across the full range of fire environments, but does require a relative ranking of crown fire potential over the full range of wildland fuelbed characteristics.

The past 40 years or so of fire research and observations have produced a significant body of literature on crown fires. Van Wagner's (1964, 1968) papers on experimental crown fires in red pine (*Pinus resinosa* Ait.) plantations may be considered the start of the modern era of crown fire research. Subsequent studies ranged from observations of the characteristics of intense, rapidly moving wildfires, to descriptions of fire types (e.g., Van Wagner 1977, Rothermel 1991), to a heuristic key for rating crown fire potential (e.g., Fahnestock 1970), to the development of various mathematical models for predicting crown fire behaviour (e.g., Kilgore and Sando 1975; Scott and Reinhardt 2001; Van Wagner 1977, 1989, 1993). The identification of dependent crown fire thresholds by Scott and Reinhardt (2001) based on stylized fuelbeds and Rothermel's (1972)

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surface flame length predictions have proven useful to managers within the limitations of current knowledge. A series of observational experiments was completed during the International Crown Fire Modeling Experiment (ICFME) in Canada (Stocks et al. 2004 *a*, 2004*b*). Additional refinements and conjectures into crown fire modeling have been advanced by Butler et al. (2004*b*), Cruz et al. (2003*a*, 2003*b*, 2004, 2006*a*, 2006*b*, 2006*c*), Alexander et al. (2006), and Alexander and Cruz (2006).

Collectively, these studies have shown that the potential for crown fire occurrence does not depend on any single element of the fuel complex or on any single element in the fire weather environment. Rather, crown fires result from various combinations of factors in the fuel, weather, and topography of the fuelbed. Important factors include: surface fire intensity, canopy closure, crown density, the presence of ladder fuels, height to base of the combustible crown, crown foliar moisture content, and wind speed. This is the foundation for the FCCS crown fire equations. FCCS crown fire potentials (Sandberg et al. 2001, 2007*a*) are based on an updated semiempirical model that describes crown fire initiation and propagation in vegetative canopies. It is based on the work by Van Wagner (1977) and Rothermel (1991), but contains additional physical concepts for modeling crown fire behaviour derived from the reformulated Rothermel (1972) surface fire modeling concepts proposed by Sandberg et al. (2007*b*). This modeling framework is conceptual in nature. It has not yet been comprehensively tested against independent data sets. Its use is currently limited to assessing the crown fire potential of the FCCS fuelbeds. Additional refinement and verification are needed before the FCCS crown fire model can be considered for wider application.

The FCCS crown fire modeling framework ranks the relative potential for crown fire initiation and spread of natural fuelbeds based on a set of actual and inferred characteristics. It draws upon published model results from crown fire experiments by others, personal observations of crown fires, and conversations with fire managers. This model is intended to objectively assess, on a relative scale, the probability of experiencing torching or active crown fire spread in any FCCS fuelbed. Currently applied crown fire models (Van Wagner 1977; Scott and Reinhardt 2001; Cruz et al. 2006*a*–2006*c*; Alexander et al. 2006; Alexander and Cruz 2006) are largely empirically based and appropriate only when applied to the range of stand structures and fire behaviours observed. While they can be very useful in those cases, they do not provide the broad conceptual framework or applicability necessary to compare the crown fire potential within families of dissimilar fuelbeds.

This paper makes extensive use of symbols in the various equations that are presented. A comprehensive List of symbols is presented at the end of the reference list.

Background

Wildland fires are categorized generally in terms of three types: ground, surface, and crown fires (Peterson et al. 2005). Ground fires are fires that burn fuels in the ground only; for example, duff, roots, and buried decomposing material. Ground fires are characterized by low spread rates but can nevertheless cause considerable injury to live trees and shrubs (Scott and Reinhardt 2001). Surface fires are those that burn in the layer immediately above the surface and consume fuels such as needles, grass, shrubs, and dead-and-down woody debris (Scott and Reinhardt 2001; Peterson et al. 2005). Crown fires occur in forested ecosystems and may involve the entire fuel complex from just above the mineral soil to the tops of the trees. These fires are of special interest to managers because they represent the upper end of observed wildland fire intensities and are characterized by high rates of spread, long flame lengths, and high energy release rates (Butler et al. 2004*a*).

Some of the earliest published work on crown fire models focused on indices of crown fire behaviour. Fahnestock (1970) developed a heuristic key of crown fire potential that incorporated various stand characteristics such as canopy closure, crown density, and the presence or absence of ladder fuels. Similarly, Kilgore and Sando (1975) expressed crown fire potential in giant sequoia (*Sequoiadendron giganteum* (Lindl.) Buchh.) as a function of the mean height to the canopy base, crown fuel weight, presence or absence of ladder fuels, crown volume ratio, and the vertical profile of the canopy fuel packing ratio. Neither approach modeled the physical mechanisms that control crown fire initiation and spread.

Van Wagner (1977) advanced the physical understanding of crown fires by presenting theory and observations on the factors that govern the start and spread of crown fires. He hypothesized that crown fires are initiated when the convective heating from a surface fire drives off the moisture in the crown fuels, raising the fuel elements to ignition temperature. Van Wagner (1977) defined the *critical fireline intensity* (that is, the minimum fireline intensity) required for crowning by rearranging a relationship developed by Thomas (1963) that linked fire intensity (as defined by Byram 1959) with the maximum temperature in the convective plume above the fire. The resulting equation expressed the critical fireline intensity as a function of the canopy base height, the foliar moisture content of canopy fuels, and a proportionality constant defined by Van Wagner (1977) as "an empirical constant of complex dimensions." The value of the proportionality constant was estimated to be 0.01 based on several assumptions appropriate for red pine plantation stands in the lake region of southern Canada and the northern United States, including an estimated minimum surface intensity of 2500 $kW \cdot m^{-1}$, a 6 m crown base height, and a foliar moisture content of 100%.

The Van Wagner (1977) model has several limitations (outlined in Cruz et al. 2004): (1) the original formulation by Yih (1953) relates the heat transfer to the maximum temperature in the heat plume and not, more appropriately, to the total heat production found by integrating the time–temperature profile; (2) the model relies exclusively on convection theory, ignoring the contribution of upward radiant heat fluxes in heating the fuel elements to ignition temperature; (3) the model does not properly reflect the influence of wind flow in tilting the heat plume and entraining air into the plume (Mercer and Weber 1994); and (4) the proportionality constant is not universal and should vary with changes in the structural characteristics of different fuelbed complexes (e.g., Alexander 1998; Mercer and Weber 2001; Cruz et al. 2004). Despite these limitations, the Van Wagner (1977) model is used in whole or in part in several North American systems used to predict crown fire initiation (Forestry Canada Fire Danger Group 1992; Finney 2004; Scott and Reinhardt 2001).

Scott and Reinhardt (2001) provided an example of a new modeling approach based on earlier work by Rothermel and Van Wagner. They combined the Rothermel (1972, 1991) equations) and the Van Wagner (1977) equations into two crown fire initiation indices: a *torching index* and a *crowning index*. The torching index is the 6.1 m wind speed at which crown fire is expected to initiate based on Rothermel's (1972) surface fire model and Van Wagner's (1977) crown fire initiation criteria. The crowning index is the 6.1 m wind speed at which active crowning is possible based on Rothermel's (1991) crown fire spread rate model and Van Wagner's (1977) criterion for active crown fire spread. Both indices are used to ordinate different forest stands by their relative susceptibility to crown fire and to compare the effectiveness of crown fire mitigation treatments.

Combining and refining the Van Wagner (1977) and Xanthopoulos (1990) approaches, Alexander (1998) developed an algorithm to predict the onset of crown fire. His approach used an estimate of the convective plume angle based on the Taylor (1961) and Thomas (1964) relationship between plume angle and fireline intensity and wind speed, and an estimate of the temperature increase above the ambient temperature at the base of the crown using a modification of Byram's (1959) fireline intensity equation. This approach had several limitations that are common to other models, including the use of Byram's (1959) fireline intensity, which is not necessarily a good descriptor of the surface heat fluxes reaching the base of the crown; the inadequacy of current methods for predicting residence times as a function of fuelbed properties and fuel availability for flaming; and the need to parameterize the several constants for different fuelbed complexes with different structural characteristics.

Building on earlier work by Cruz (1999), Cruz et al. (2003*b*, 2004) developed a probabilistic model, based on logistic regression techniques, for the prediction of crown fire occurrence (i.e., initiation) based on several fire environment and fire behaviour variables normally available to support fire-management decisions. These variables included 10 m open wind speed, fuel strata gap, surface fuel consumption (a surrogate for fireline intensity), and estimated fine-fuel moisture content. The strength of this model is that it predicts the *probability* of a crown fire rather than the dichotomous "crown / no crown" results from Van Wagner (1977) and Alexander (1998). Its greatest limitation is a lack of physical reasoning. For example, the model does not directly account for the heat energy released by a surface fire, but instead uses surface fuel consumption as a surrogate. Other limitations include bias in the data set used to condition the model (e.g., in 60% of the situations the fuel strata gaps were <3 m), inability to consider the influence of crown bulk density on crown fire spread beyond the fuel strata gap, and inability to account for point-source fires or prescribed-fire ignition patterns (e.g., perimeter mass ignitions) that do not approximate those of free-burning wildfires. These models are most applicable to live conifer forests on level terrain. Moreover, the majority of fuelbeds used to develop the model were conifer stands in Canada and the northern United States. It is not known whether this model can be accurately applied to other forest types and regions.

Cruz et al. (2006*a*–2006*c*) described the development and testing of a semiphysical model for predicting the temperature and ignition of canopy fuels above a spreading surface fire, titled the Crown Fuel Ignition Model (CFIM). CFIM uses a set of physical equations, along with empirically based submodels, to define the heat source, buoyant plume dynamics, and radiative and convective energy transfer to the fuel elements at the base of the canopy layer. Simulation testing showed that the fuel strata gap and moisture content of fine dead surface fuels were the dominant variables controlling the fuel-particle temperature rise and subsequent crown fuel ignition. Flame-available fuel loading and 10 m open wind speed were of lesser importance. Foliar moisture content and canopy surface-area-to-volume ratio showed the least effect. The authors make no claims about the efficacy or performance of the models. All that is said is the test results were considered to be "within the range of predictions" produced by Van Wagner (1977), Alexander (1998), and Cruz et al. (2004).

Alexander et al. (2006) reported on the development and testing of the Crown Fire Initiation and Spread (CFIS) model, a crown fire modeling system that incorporates elements of CFIM (Cruz et al. 2006*a*–2006*c*) in addition to several other models designed to simulate various aspects of crown fire behaviour. In determining whether a crown fire is active or passive, CFIS uses the criterion for active crowning (suggested by Van Wagner 1977), which is a function of the canopy bulk density and the predicted active crown fire rate of spread. The active crown fire rate of spread was represented by a nonlinear regression equation with independent variables of 10 m open wind speed, estimated fine-fuel moisture content of dead surface fuels, and canopy bulk density. CFIS provides the user with a means of evaluating the impacts of proposed fuel treatments on the potential crown fire initiation and spread. It is not known whether CFIS is superior to other models for predicting the initiation and spread of crown fires. CFIS is considered most appropriate for free-burning fires that have reached pseudo steady state in live boreal or boreal-like conifer forests on level terrain.

Alexander and Cruz (2006) evaluated the predictive capacity of the Cruz et al. (2005) crown fire spread rate models against an independent set of wildfire observations from the United States and Canada. The Cruz et al. (2005) model integrates the effects of 10 m open wind speed, canopy bulk density, and estimated fine-fuel moisture content to yield estimates of the crown rate of spread for both passive and active crown fires after the fire type has been determined using Van Wagner's (1977, 1993) criterion for active crowning. The model performed reasonably well against a large sample set of 57 North American wildfires, producing fewer *under predictions* than the Rothermel (1991) spread model, which was included in the evaluation. However, critical information on canopy bulk density was missing on all but two of the 43 Canadian wildfires, and 5 of the 14 American wildfires. Instead, the missing values were assigned to one of several broad classes based on forest type. Canopy bulk density is an important variable in determining the crown fire rate of spread, and the use of inferred values diminishes the value of this evaluation.

Scott (2006) compared the relative behaviour of the surface and crown fire rates of spread contained in three fire management applications: FlamMap (Stratton 2004), NEXUS (Scott 1999), and CFIS (Alexander et al. 2006). FlamMap and NEXUS are largely based on Rothermel (1991) and Van Wagner (1993), although they differ in their implementation. Scott (2006) found that the three models predicted considerably different crown fire rates of spread, especially in the transitions from surface to passive and from passive to active crown fire (Scott 2006). However, the relative, ordinal ranking of crown fire behaviour was similar for the three systems (Scott 2006). FCCS provides the same kind of relative ranking of potential crown fire behaviour for all of the 216 FCCS fuelbeds (Ottmar et al. 2007).

All of these methods used to assess crown fire potential have limitations. Most of these methods are semiphysical (or semiempirical) in nature, combining physical equations of heat generation and transfer and fuelbed characteristics with one or more empirically based calibration constants. Many of the physical characteristics of the fuelbed, of fuel consumption, and of fire conditions are difficult to obtain or missing from previously reported studies. This makes it challenging to populate the physical and semiempirical models with appropriate parameters. In most cases, model development has been based on a limited set of actual fires or in a limited geographic area.

The conceptual framework offered in this paper provides decision makers with a tool for objectively assessing, on a relative scale, the probability of experiencing torching or active crown fire spread in any FCCS fuelbed. Although it suffers from some of the same limitations as earlier models, its strength is in providing a comprehensive consideration of the factors that are commonly used by fire behaviour analysts to assess crown fire potential. Some factors that are considered in the FCCS conceptual framework, such as canopy continuity and ladder fuel abundance, are found in few or none of the other models. By advancing this transparent quantitative framework, which includes several heuristic algorithms, we provide a more robust consideration of factors that can be evaluated against future observations and experience by users.

Framework description

The FCCS crown fire potential equations are based on a two-layer system consisting of a surface layer and a canopy layer. The surface layer is composed of fuel elements in the woody, nonwoody (e.g., grasses and forbs), shrub, and litter–lichen–moss fuelbed strata. The canopy layer, in turn divided into three sublayers (understory, midstory, overstory), is composed of woody and nonwoody (e.g., foliage) fuel components. A vertical gap separates the combustible fuels in the canopy layer from those in the surface layer. For purposes of estimating the propagating flux ratio, the canopy is assumed to be composed of uniformly distributed, thermally thin, short, cylindrical fuel elements. We have assumed that the unburned fuels ahead of the canopy fire are heated by a combination of radiant heat transfer and forced convection under laminar flow conditions over the canopy elements (Reynolds number (Re) 50–400). In this simplified formulation, terrain effects are ignored (i.e., flat terrain) and wind speed does not explicitly aid in heat transfer other than by changing the crown-to-crown flame transmissivity within canopies with <100% cover.

General equation

The general form of the FCCS crown fire potential (CFP) equation is

$$\text{CFP} = \max(\text{TP}, \text{AP}) \quad [1]$$

where TP is the torching potential and AP is the active crown fire potential. Both are dimensionless, ranging in value from 0 to 10. TP is the potential for a surface fire to spread into the canopy as single- or multiple-tree torching. If TP > 1, then torching is possible. TP is defined as the scaled crown fire initiation term, I_C (dimensionless, range 0 to 10).

$$\text{TP} = c_{TP} I_C \quad [2]$$

Here, c_{TP} is a scaling function to limit TP within the range of 0 to 10. Fuelbeds with I_C values >10 are assigned a TP of 10. Fuelbeds with I_C values <10 are scaled from 0 to 10.

AP is the potential for a surface fire to spread into the canopy as an active crown fire. If AP is >0, then active crown fire spread is possible. AP is computed as the scaled product of four terms.

$$\text{AP} = c_{AP} I_C F_C R_C \quad [3]$$

Here, F_C is the crown-to-crown flame transmissivity term (dimensionless, range 0 to 1) and R_C is the crown fire spread-rate term (m·min^{-1}, range 1 to >100 m·min^{-1}). c_{AP} is a scaling function that limits AP to a range of 0 to 10 (dimensionless). Fuelbeds with a product of $I_C F_C R_C > 10$ are assigned an AP of 10, and fuelbeds with a product of $I_C F_C R_C < 10$ are scaled from 0 to 10.

The I_C, F_C, and R_C terms are developed in the following section.

Crown fire initiation term (I_C)

The crown fire initiation term originates from an early definition of fire intensity, I_B (kJ·m^{-1}·s^{-1} or kW·m^{-1}), from Byram (1959)

$$I_B = \frac{H W_f R}{60} \quad [4]$$

where H is the heat yield of the fuel (kJ·kg^{-1}), W_f is the mass of the fuel consumed in the flaming front (kg·m^{-2}), R is the forward rate of spread of the fire (m·min^{-1}), and 60 is a conversion factor that reduces I_B from units of kJ·m^{-1}·min^{-1} to units of kJ·m^{-1}·s^{-1} (kW·m^{-1}). Andrews and Rothermel (1982) defined heat per unit area, H' (kJ·m^{-2}), equivalent to HW_f in eq. 4

$$H' = HW_f = I_R t_R \quad [5]$$

where I_R is reaction intensity (kJ·m^{-2}·min^{-1}) and t_R is the residence time in minutes. Combining eqs. 4 and 5 yields

$$I_B = \frac{I_R t_R R}{60} \quad [6]$$

To define the concept of a critical fireline intensity, Van Wagner (1977) rearranged a relationship (developed by

Thomas 1963) linking fire intensity as defined by Byram (1959) (see eq. 4) with the maximum temperature in the convection plume above the fire. The critical fireline intensity, I' (kJ·m^{-1}·s^{-1} or kW·m^{-1}), is the minimum fireline intensity at which crowning is initiated (after Van Wagner 1977, 1989)

$$[7] \quad I' = \left[\frac{\mathrm{CBH}(460 + 25.9\mathrm{FMC})}{100}\right]^{3/2}$$

where CBH is the canopy base height (m), FMC is the foliar moisture content of canopy fuels (%), and 100 is an empirical constant. One aspect of crown fire modeling that would greatly benefit from additional field research is the critical bulk density or minimum fuel load required to define the CBH.

As noted earlier, the basis for Van Wagner's (1977) model is that a crown fire occurs when the convective heat supplied by a surface fire drives off the moisture in the crown fuels and raises them to ignition temperature. However, recent studies using statistically based models have shown that the fine-fuel moisture content of dead woody fuels on the surface has a much greater effect on the ignition of crown fuels than the canopy FMC (Cruz 1999; Cruz et al. 2004; Cruz et al. 2006*c*). The explanation given in Cruz et al. (2006*c*) is that the heating of canopy fuel elements is continuous and prolonged, and that the heat energy required to evaporate the FMC is small compared with the total heat energy released from high intensity surface fires. Foliar moisture content could still be an important variable under conditions of low surface fireline intensity and high FMC, or in cases where the heating of the canopy fuel elements is less effective owing to a high stand density or large fuel strata gap. Several recent papers have acknowledged the importance of FMC in determining crown fire behaviour (Xanthopoulos and Wakimoto 1993; Butler et al. 2004*b*).

Following Van Wagner (1977), crown fire initiation is expected whenever the surface fireline intensity exceeds the critical fireline intensity; that is, when $I_B/I' > 1$. The ratio of eqs. 6 and 7 yields

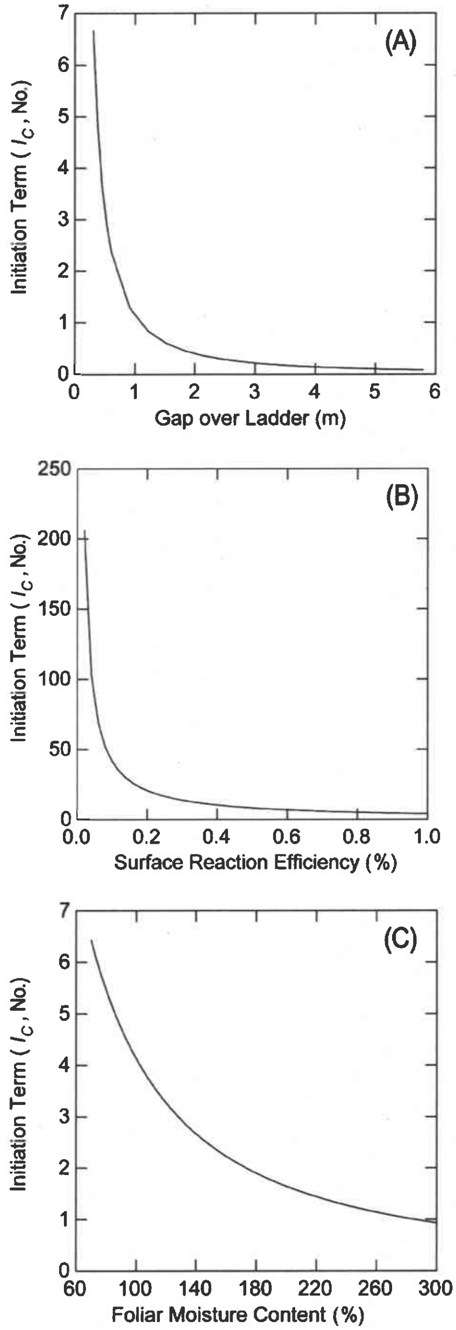
$$[8] \quad \frac{I_B}{I'} = \frac{16.667 I_R t_R R}{[\mathrm{CBH}(460 + 25.9\mathrm{FMC})]^{3/2}}$$

Equation 8, expressed in terms of FCCS variables with the residence time set proportional to the inverse of the surface potential reaction velocity, defines I_C as

$$[9] \quad I_C = \frac{16.667 I_{R.\mathrm{FCCS}}(1/\Gamma')R_{\mathrm{FCCS.S}}}{[(\mathrm{gap/ladder})(460 + 25.9\mathrm{FMC})]^{3/2}}$$

where Γ' is the potential reaction velocity (min^{-1}) of surface fuels from Rothermel (1972), $R_{\mathrm{FCCS.S}}$ is the surface fire spread rate from FCCS (m·min^{-1}), gap is the physical separation distance (m) between the top of the surface fuel layer and the bottom of the combustible canopy layer, and ladder is a heuristically assigned value representing the presence and type of ladder fuels sufficient to act as a vertical carrier of fire to the canopy base (default, ladder = 1, meaning no ladder fuel). These terms are as defined in Sandberg et al. (2007*b*). While the traditional Van Wagner (1977) equation bases the calculation of I' on CBH (see numerator of eq. 7), the FCCS I' uses the vertical gap between the top of the surface fuelbed layer and the bottom of the combustible canopy layer, which

Fig. 1. (A) Reduction in crown fire initiation with increasing gap over ladder distance (introduced in the denominator of eq. 9 for Fuel Characteristic Classification System (FCCS) fuelbed 52 (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii* – *Pinus ponderosa* Dougl. ex P. & C. Laws.). (B) Reduction in crown fire initiation potential with increasing surface reaction efficiency for FCCS fuelbed 52. A higher reaction efficiency translates to a higher reaction velocity and a shorter residence time, hence less time for the heating of canopy fuels. (C) Reduction in crown fire initiation with increasing foliar moisture content (%) for FCCS fuelbed 52.



may be adjusted by a factor related to the abundance of combustible ladder fuels. The validity of this modification will be evaluated in future model validation efforts. Note that Cruz (1999) and Cruz et al. (2004, 2006*a*) use the same measure of fuel layer separation (which they term *fuel strata gap*), which can also be modified for ladder fuels.

I_C is evaluated along a continuum ranging from 0 to ∞. The higher the I_C value, the greater the potential for initiating a crown fire. This is the same equation set used in Scott and Reinhardt (2001) except that they structured the equations in a manner that established midflame wind speed as the principal variable, whereas we have structured the equations to evaluate the initiation potential across a range of fuelbeds with different surface reaction intensities and rates of spread at a variable benchmark wind speed (default midflame wind speed is 107 $m \cdot min^{-1}$ or ~6.4 $km \cdot h^{-1}$).

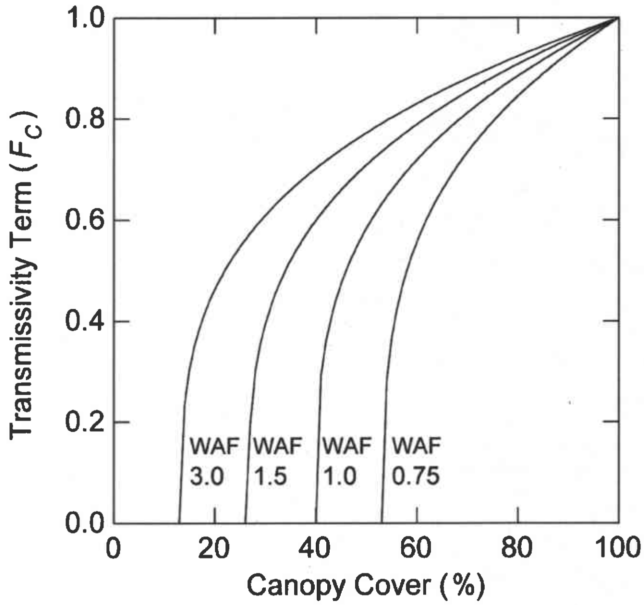
The influences of reaction efficiency, gap/ladder distance, and foliar moisture content on I_C are displayed in Figs. 1*a*–*c*. These formulations are all based on the assumption that energy from the surface fire that initiates crowning is attributable to the propagating surface flame, although it is well accepted that torching and active crown fire initiation may also occur after flame front passage from heat supplied by residual surface flames or from radiating smoldering fires. We expect to present a more complete description of surface-to-canopy heat transfer in the future.

Crown-to-crown flame transmissivity term (F_C)

F_C is a dimensionless measure of the capacity of the canopy to transfer flames through the canopy based on leaf area index (LAI), wind speed, and horizontal continuity of tree crowns. The higher the wind speed, the higher the *effective* horizontal continuity of tree crowns and the higher the crown-to-crown transmissivity. And the higher the transmissivity, the greater the potential to sustain an active crown fire. Torching is not affected by the horizontal continuity of tree crowns.

This new conceptual term is proposed as a replacement for the model originally proposed by Van Wagner (1977), which determines whether an active crown fire will occur by comparing the estimated crown fire spread rate with a critical spread rate required to sustain an active crown fire. Although practical and widely used, Van Wagner's (1977) model assumes that the canopy is horizontally uniform and continuous. It does not explicitly account for spacing between tree crowns nor does it consider the effect of increasing midcanopy wind speed in reducing effective spacing. Moreover, application of the Van Wagner (1977) model relies on an estimate of crown fire spread rate based on a limited correlation developed by Rothermel (1991). However, this new, more physically intuitive F_C term is less supported by observations than the approach developed by Van Wagner (1977) and Rothermel (1991). Additional testing of this modeling concept is planned.

Fig. 2. Effect of canopy cover and wind speed adjustment factor (WAF) on crown-to-crown transmission of fire (eq. 10). Values of WAF > 1 decrease the threshold canopy cover (default, 40%) required for crown-to-crown transmission, and values of WAF < 1 increase the threshold canopy cover required for crown-to-crown transmission. At any single canopy cover, higher WAF values yield higher rates of crown-to-crown transmission. The greatest effect of wind speed occurs at low canopy covers.



F_C is defined as follows

$$[10] \qquad F_C = \left(\begin{array}{ll} 0, & \text{for LAI} < \text{TLAI} \\ \dfrac{\max\{0, [(\text{COV} \times \text{WAF}) - \text{TCOV}]^{0.3}\}}{[(100 \times \text{WAF}) - \text{TCOV}]^{0.3}}, & \text{for LAI} \geq \text{TLAI} \end{array} \right)$$

where LAI is the leaf area index ($m^2 \cdot m^{-2}$), TLAI is the threshold LAI for active crowning ($m^2 \cdot m^{-2}$), COV is the total percent cover of tree crowns (i.e., percentage of ground area covered by tree crowns, dimensionless), WAF is the canopy wind speed adjustment factor (dimensionless), and TCOV is the threshold percent canopy cover (dimensionless) required to propagate an active crown fire when WAF = 1 (TCOV = 40). This formulation assumes that a relatively continuous canopy is required for efficient crown-to-crown heat transfer. Whether this is true or not could be the subject of additional field research. In the interim, we propose that the influence of cover and wind speed on TC is as described by eq. 10 and illustrated in Fig. 2.

Threshold leaf area index (TLAI)

TLAI may be estimated using Van Wagner's (1977) empirical relationship that describes the interaction between canopy bulk density (CBD, $kg \cdot m^{-3}$) and minimum spread rate needed to sustain an active crown fire (RAC, $m \cdot min^{-1}$).

$$[11a] \qquad \text{CBD} = \frac{0.05}{\text{RAC}}$$

The numerator in this equation is an empirically derived critical mass flow rate (units of $kg \cdot m^{-2} \cdot s^{-1}$). Alexander (1988) used a critical mass flow rate of 3.0 $kg \cdot m^{-2} \cdot min^{-1}$ to express the RAC in units of $m \cdot min^{-1}$.

$$[11b] \quad CBD = \frac{3.0}{RAC}$$

Rothermel (1991) derived the following empirical relationship for the active-crowning rate of spread, R_{active} (m·min^{-1})

$$[12] \quad R_{active} = 3.34(R_{10})_{40\%WRF}$$

where $(R_{10})_{40\%WRF}$ is the spread rate (m·min^{-1}) predicted by Rothermel (1972) using fuel characteristics for Fire Behaviour Prediction System model 10 and a midflame wind speed set at 40% of the 6.1 m wind speed. Rothermel (1991) did not address the application of his crown fire spread model other than to say that it would be used under "severe burning conditions" conducive to crown fire. Replacing the critical rate of spread in eq. 11*b* with the active-crowning rate of spread in eq. 12 allows us to fit a relationship between the critical CBD and surface rate of spread for model 10.

$$[13] \quad CBD_{critical} = \frac{3.0}{3.34(R_{10})_{40\%WRF}}$$

The TLAI required to propagate an active crown fire may be defined in terms of $CBD_{critical}$, surface-area-to-volume ratio of foliage elements (σ, m^2·m^{-3}), and particle density (ρ_p, kg·m^{-3})

$$[14a] \quad CBD = \frac{\text{Mass of canopy fuel elements}}{\text{Volume of canopy}}$$

$$[14b] \quad CBD = \frac{(\text{Volume of canopy fuel elements})\rho_p}{(\text{Area of ground})D_C}$$

$$[14c] \quad CBD = \frac{(\text{Surface area of canopy fuel elements})\rho_p}{(\text{Area of ground})D_C\sigma}$$

$$[14d] \quad CBD = \frac{LAI\,\rho_p}{D_C\sigma}$$

where D_C is the mean canopy depth (m). The TLAI is the LAI that is required to produce the critical CBD. Thus,

$$[14e] \quad CBD_{critical} = \frac{TLAI\,\rho_p}{D_C\sigma}$$

Substituting eq. 13 into eq. 14*e* yields the following for the TLAI required to sustain an active crown fire.

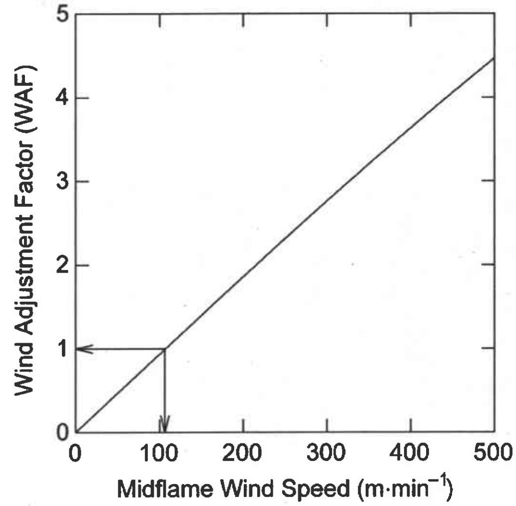
$$[15] \quad TLAI = \frac{3\sigma D_C}{3.34(R_{10})_{40\%WRF}\rho_p}$$

The BEHAVE algorithm (Andrews 1986) was used to compute $(R_{10})_{40\%\ WFR}$ as a function of the 6.1 m open wind speed ($U_{6.1}$, m·min^{-1}) for a 1 h surface fuel moisture content of 9%. Equation 15 was then used to compute TLAI/D_C, assuming a foliage ρ_p = 400 kg·m^{-3}, and σ = 6562 and σ = 8202 m^2·m^{-3} (FCCS default values) for coniferous trees and broadleaf shrub species, respectively. The resulting general equation is

$$[16] \quad \frac{TLAI}{D_C} = Ae^{-2.6\times10^{-3}U_{6.1}}$$

where A is 10.8 and 8.6 for coniferous trees and flammable broad-leaved shrub species, respectively.

Fig. 3. Effect of midflame wind speed on wind speed adjustment factor (WAF) from eq. 17. WAF is the multiplier used to adjust the canopy cover (%) when computing the crown-to-crown flame transmission term, F_C.



Canopy wind speed adjustment factor (WAF)

The wind speed adjustment factor increases (decreases) the effective canopy cover for wind speeds that are higher (lower) than the FCCS benchmark wind speed of 107 m·min^{-1}. The effective canopy cover is the product of COV and WAF. WAF is given by

$$[17] \quad WAF = \frac{U/\sqrt{U^2 + W^2}}{U_B/\sqrt{U_B + W^2}}$$

where U is the horizontal midflame wind speed (m·min^{-1}), W is an assumed vertical, convectively driven wind speed of 1590 m·min^{-1} (95.4 km·h^{-1}), and U_B is the FCCS benchmark horizontal midflame wind speed of 107 m·min^{-1} (6.4 km·h^{-1}). W was based on the mean maximum vertical wind speed in the air above 16 experimental crown fires in black spruce reported by Clark et al. (1999; see Table 2). If the midflame wind speed is higher (lower) than the benchmark wind speed, then effective canopy cover will be higher (lower) by the WAF shown in Fig. 3.

The use of F_C (eq. 10) to assess the potential for propagating an active crown fire departs from the conventional approach that compares the actual crown rate of spread with RAC (eqs. 11 and 12). Unlike the combined Van Wagner (1977) and Rothermel (1991) approach, F_C takes into account the horizontal continuity of tree crowns as well as threshold density (as measured by threshold LAI) when assessing the potential for propagating an active crown fire.

Crown fire rate of spread term (R_C)

This section presents a new physically based mathematical approach for estimating the crown fire spread rate using the reformulated Rothermel's (1972) surface fire spread rate adapted to vegetative canopies. Sandberg et al. (2007*b*) proposed the following reformulation of Rothermel's (1972) spread rate (m·min^{-1}) for surface fires

$$[18] \quad R_{\mathrm{FCCS}} = \frac{I_{\mathrm{R.FCCS}}\xi(1+\phi_{\mathrm{W.FCCS}})}{(\mathrm{FAI}\zeta_{\mathrm{I}}\rho_{\mathrm{p}}Q_{\mathrm{ig}}/\delta)_{\mathrm{woody}} + (\theta\rho_{\mathrm{b}}Q_{\mathrm{ig}})_{\mathrm{nonwoody}} + (\theta\rho_{\mathrm{b}}Q_{\mathrm{ig}})_{\mathrm{shrub}} + (\theta\rho_{\mathrm{b}}Q_{\mathrm{ig}}\eta_{\Delta'.\mathrm{llm}})_{\mathrm{llm}}}$$

where ξ is the propagating flux ratio (the proportion of $I_{\mathrm{R.FCCS}}$ transferred ahead of the surface fire to the unburned fuels; dimensionless), $1 + \phi_{\mathrm{W.FCCS}}$ is the acceleration factor for wind (dimensionless), FAI is the fuel-area index of surface fuelbed categories ($\mathrm{m^2 \cdot m^{-2}}$), ζ_{I} is the ignition thickness heated on the surfaces of thermally thick fuel elements (m), ρ_{b} is the bulk density of the fuels ($\mathrm{kg \cdot m^{-3}}$), Q_{ig} is the heat of preignition (i.e., the amount of energy required to raise the fuel temperature to ignition, a function of fuel moisture content; $\mathrm{kJ \cdot kg^{-1}}$), δ is the depth of the woody fuelbed stratum (m), θ is the planform area proportional to the coverage for the individual nonwoody, shrub, and litter–lichen–moss strata ($\mathrm{m^2 \cdot m^{-2}}$), and $\eta_{\Delta'.\mathrm{llm}}$ is the absorption efficiency of the litter–lichen–moss stratum (assumed equal to the reaction efficiency; dimensionless). The numerator of this equation represents the surface-fuel heat source acting to accelerate the fire spread. The denominator contains the individual heat sinks acting to retard the fire spread. These terms are all as defined in Sandberg et al. (2007*b*).

For active crown fires, the combined reaction intensity from the flaming combustion of the surface and canopy fuels should result in greater forward heating of the fuels and greater spread rates. In equation form, this is expressed as

$$[19] \quad I_{\mathrm{R.FCCS}} = I_{\mathrm{R.FCCS.S}} + I_{\mathrm{R.FCCS.C}}$$

where $I_{\mathrm{R.FCCS.S}}$ is the reaction intensity of surface fuels (defined in Sandberg et al. (2007*b*)) and $I_{\mathrm{R.FCCS.C}}$ is the reaction intensity of canopy fuels. Equation 18 may be further adapted to crown fires (designated by subscript C) by eliminating the shrub and litter–lichen–moss sink terms in the denominator, by replacing the FAI for the nonwoody fuels with LAI, by replacing ξ with a relationship appropriate for canopies, by replacing δ with the mean crown depth (D_{C}, m), and by replacing Rothermel's (1972) wind speed coefficient, $1 + \phi_{\mathrm{W.FCCS}}$, with the dimensionless wind speed coefficient, U/U_{B}, introduced in eq. 17. The result is a spread rate equation for canopies that is influenced by both the surface and canopy heat sources and heat sinks.

$$[20] \quad R_{\mathrm{FCCS.C}} = \frac{(I_{\mathrm{R.FCCS.S}} + I_{\mathrm{R.FCCS.C}})\xi_{\mathrm{C}}(U/U_{\mathrm{B}})}{\sum_{i=1}^{2}(\mathrm{FAI}\zeta_{\mathrm{I}}\rho_{\mathrm{p}}Q_{\mathrm{ig}}/D_{\mathrm{C}})_{\mathrm{canopy,\ woody}} + \sum_{i=1}^{2}(\theta\mathrm{LAI}\zeta_{\mathrm{I}}\rho_{\mathrm{p}}Q_{\mathrm{ig}}/D_{\mathrm{C}})_{\mathrm{canopy,\ nonwoody}} + \text{surface sink terms from eq. 18}}$$

This spread rate equation is designed to accommodate a variety of vegetative canopies. The index i represents the overstory and understory canopy subcategories. The $I_{\mathrm{R.FCC.C}}$, ξ_{C}, and D_{C} terms are described in more detail in the following sections. The calculation of ζ_{I}, ρ_{b}, Q_{ig}, and θ terms are as described in Sandberg et al. (2007*b*).

Canopy reaction intensity

The reformulated Rothermel (1972) reaction intensity, $I_{\mathrm{R.FCCS.S}}$, for the surface fuelbed is Sandberg et al. (2007*b*)

$$[21] \quad I_{\mathrm{R.FCCS.S}} = \eta_{\Delta'.\mathrm{S}}\sum_{i=1}^{3}(\Gamma'_{\mathrm{max.FCCS}}\Upsilon_{\mathrm{R}}\rho_{\mathrm{p}}h\eta_{\mathrm{M.FCCS}}\eta_{\mathrm{K}})_i + (\eta_{\Delta'.\mathrm{llm}}\Gamma'_{\mathrm{max.FCCS}}\Upsilon_{\mathrm{R}}\rho_{\mathrm{p}}h\eta_{\mathrm{M.FCCS}}\eta_{\mathrm{K}})_{\mathrm{llm}}$$

where $\eta_{\Delta'.\mathrm{S}}$ is the surface-fuel reaction efficiency (dimensionless), $\Gamma'_{\mathrm{max.FCCS}}$ is the maximum surface reaction velocity for fuels of mean surface-area-to-volume ratio at the optimum packing ratio ($\mathrm{min^{-1}}$), γ_{R} is the reaction volume of fuels involved in the reaction zone ($\mathrm{m^3 \cdot m^{-2}}$, volume density of fuels that contribute energy forward to unburned fuels), ρ_{p} is the oven-dry particle density ($\mathrm{kg \cdot m^{-3}}$), h is the fuel low heat content ($\mathrm{kJ \cdot kg^{-1}}$), $\eta_{\mathrm{M.FCCS}}$ is the moisture damping coefficient (dimensionless, acts to reduce the reaction velocity), η_{K} is the mineral damping coefficient (dimensionless, assumed to be 0.42, consistent with 1% silica-free ash content), and $\eta_{\Delta'.\mathrm{llm}}$ is the reaction efficiency for the litter–lichen–moss stratum (dimensionless).

This equation may be adapted to crown fires by replacing $\eta_{\Delta'.S}$ with the canopy reaction efficiency, $\eta_{\Delta'.\mathrm{C}}$, and by eliminating the litter–lichen–moss term.

$$[22] \quad I_{\mathrm{R.FCCS.C}} = \eta_{\Delta'.\mathrm{C}}\sum_{i=1}^{2}(\Gamma'_{\mathrm{max.FCCS}}\Upsilon_{\mathrm{R}}\rho_{\mathrm{p}}h\eta_{\mathrm{M.FCCS.C}}\eta_{\mathrm{K}})_i$$

The $\eta_{\Delta'.\mathrm{C}}$ and $\eta_{\mathrm{M.FCCS.C}}$ terms are described in greater detail in the following sections.

Canopy reaction efficiency

Because of differing crown morphologies and densities, among other factors, not all tree canopies burn with the same efficiency. Fahnestock (1970) attempted to capture this in a heuristic equation that reduced crown fire potential by as much as 40% based on crown density. Although Rothermel (1972) did not examine tree canopies when he developed his surface fire spread model, we have applied his concept of an efficiency term based on the relative packing ratio to the rating of the crown fire hazard. Rothermel (1972) observed that the optimum packing ratio in surface fuels shifted to a lower value in the presence of wind, and we have assumed that the same will occur in canopies. Rothermel's estimate of optimum density, corrected for convective flow in the canopy, provides a basis for estimating the reaction efficiency in the canopy.

$\eta_{\Delta'.\mathrm{C}}$ is the ratio of the *reaction velocity* over the *poten-*

Fig. 4. Effect of increasing relative canopy depth (a measure of foliage density) on the canopy reaction efficiency, $\eta_{\Delta'.C}$, from eq. 23. This curve reflects the relatively weak influence of less than optimum foliage density (relative canopy depths > 1) on canopy flammability.

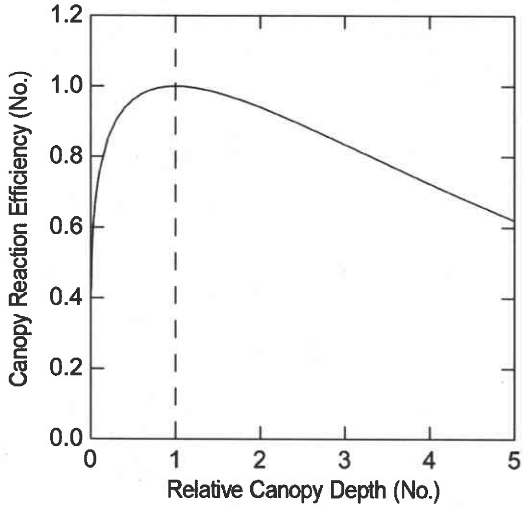
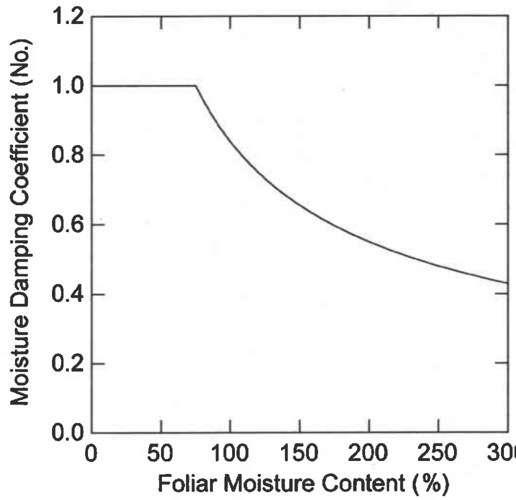


Fig. 5. Effect of canopy foliar moisture content (%) on the moisture damping coefficient and canopy flammability (eq. 25). The shape of this curve approximates the influence of foliar moisture content on canopy flammability in Van Wagner (1977).



tial reaction velocity of canopy fuels (range 0 to 1). Reaction velocity is a dynamic variable that quantifies the completeness and rate of the fuel consumption. It is strongly influenced by fuelbed density, particle size, moisture content, and mineral content (Rothermel 1972), as expressed by the $\eta_{\Delta'.C}$, ρ_p, $\eta_{M.FCCS.C}$, and η_K terms in eq. 22.

For canopy layers, $\eta_{\Delta'.C}$ is defined as

$$[23] \qquad \eta_{\Delta'.C} = [\Delta'_C \exp(1 - \Delta'_C)]^{0.2}$$

where Δ'_C is the *relative depth* of the canopy (dimensionless) (Fig. 4) and the exponent 0.2 expresses the response of the reaction efficiency to changes in relative crown depth. The canopy reaction efficiency is analogous to $\eta_{\Delta'.S}$ (Sandberg et al. 2007*b*), but less sensitive to deviations from the optimum air-to-fuel particle ratio. The concept of relative depth, Δ'_C, replaces Rothermel's (1972) *relative packing ratio*, as described in Sandberg et al. (2007*b*). The two would be numerically identical except for changes made in estimating the effective heating number, ε. The relative canopy depth is defined as the optimum canopy depth, δop_C (m), divided by D_C (m).

$$[24] \qquad \Delta'_C = \frac{\delta op_C}{D_C}$$

D_C is the difference between the mean total canopy height and the mean height to the base of the combustible crowns, or the canopy base height, CBH.

Moisture damping coefficient

The canopy foliar moisture content damping term in the FCCS, $\eta_{M.FCCS}$, is based on Van Wagner's (1977) relationship of foliar moisture to canopy ignition (dimensionless) (Fig. 5)

$$[25] \qquad \eta_{M.FCCS} = \left[\frac{m}{\max(m, \text{FMC})}\right]^{0.61}$$

where m is the reference foliar moisture content at maximum foliar flammability (dimensionless) and FMC is the mean live foliar moisture content of the canopy layer in question (upper story and mid- and under-story). The exponent 0.61 approximates Van Wagner's (1977) influence of foliar moisture on canopy flammability (dimensionless).

Flammability is assumed to be constant below some reference (minimum) foliar moisture content m. For canopies, the default value of m is 75%.

Propagating flux ratio

The propagating flux ratio represents the proportion of reaction intensity transferred to the unburned fuel by radiative and convective processes. The total propagating flux ratio in eq. 20 is the sum of the propagating flux ratios for radiation and convection.

$$[26] \qquad \xi_C = \xi_{\text{radiation}} + \xi_{\text{convection}}$$

In some instances, radiant energy transfer dominates the process of transferring heat energy from the fire to the unburned crown fuels ahead of the fire; for example, when fires spread in still air or against the wind (Butler et al. 2004*a*). Other times, convective energy transfer clearly dominates when fires burn upslope or under very high winds, both of which reduce the flame angle relative to the fuel surface. Both mechanisms are important for evaluating the rate of forward heating in fires.

The fraction of radiant energy transferred to the unburned crown fuels may be approximated using a modification of Beer's Law, which expresses the amount of radiant energy absorbed ahead of the fire by the unburned fuel elements

$$[27] \qquad \xi_{\text{radiation}} = 1 - \left(\frac{I_{\text{rad}}}{I_0}\right) = 1 - e^{-kx}$$

where $\xi_{\text{radiation}}$ is the propagating flux ratio at distance x (m) from the radiant source, I_{rad} is the transmitted radiant intensity passing through a spheroid (kJ·m^{-2} s^{-1}), I_0 is the initial radiant intensity (kJ·m^{-2} s^{-1}), and k is the rate of attenuation through the canopy media, also termed *optical depth* or *opacity* (m^{-1}).

The rate of attenuation of radiant energy from fires in vegetative canopies was given by Butler et al. (2004*b*) as

$$[28] \quad k = \frac{\sigma W_{\text{mass}}}{4\delta_k \rho_p}$$

where σ is the fuel surface area-to-volume ratio ($m^2 \cdot m^{-3}$), W_{mass} is the dry mass of fuel per unit planar area ($kg \cdot m^{-2}$), and δ_k is the fuel array depth (this is the same as D_C in canopies; m), Expressed in terms of LAI and D_C, eq. 28 becomes

$$[29] \quad k = \frac{\text{LAI}}{4D_C}$$

Substituting eq. 29 into eq. 27 and replacing distance x with some characteristic distance $\tilde{x}$ for radiative transfer in canopies yields

$$[30] \quad \xi_{\text{radiation}} = 1 - e^{-\left(\frac{\text{LAI}}{4D_C}\right)\tilde{x}}$$

The denser the canopy (higher LAI) for a given canopy depth, the greater the absorption of the radiant energy by the unburned fuel elements and the greater the propagating flux ratio. Conversely, the greater the canopy depth for a given LAI, the lower the density of the stand and the lower the propagating flux ratio.

Butler et al. (2004*a*) found that radiant energy transfer between the flame and fuels can occur over distances as great as 60 m in the upper canopy and 20 m in the portion of canopy with the highest bulk density. A characteristic $\tilde{x}$ of 1 m was chosen, yielding a radiation propagating flux ratio of 0.56% for FCCS fuelbed 52 (*Pseudotsuga menzeisii* (Mirb.) Franco var. *menziesii – Pinus ponderosa* Dougl ex P. & C. Laws.).

The propagation flux ratio based on convective heating of canopy fuels, $\xi_{\text{convection}}$ (dimensionless), is defined as the ratio of the convective heat flux (heat energy per unit time) absorbed by the canopy fuels, specifically the foliage, divided by the total heat flux in the corresponding air volume

$$[31] \quad \xi_{\text{convection}} = \frac{C_{\text{forced}}\text{LAI}}{E}$$

where C_{forced} is the forced-convection heat flux absorbed per unit area of foliage ($W \cdot m^{-2}$ foliage; by definition, 1 W = 1 $J \cdot s^{-1}$) and E is the total heat flux in the canopy air per unit of ground area ($W \cdot m^{-2}$ ground). C_{forced} is defined as (Monteith and Unsworth 1990, pg. 122)

$$[32] \quad C_{\text{forced}} = \frac{k_C(T_{\text{air}} - T_{\text{foliage}})\text{Nu}}{d}$$

where k_C is the thermal conductivity of air ($W \cdot m^{-1} \cdot K^{-1}$), T_{air} and T_{foliage} are the temperatures of the heated air and foliage surface (K), respectively, Nu is the Nusselt number (dimensionless), and d is a characteristic dimension of the fuel element. The Nusselt number is a function of the Re. Based on a relationship reported for forced flow in arrays of pine needles (Cruz et al. 2006*b*), the Nusselt number was defined as

$$[33] \quad \text{Nu} \approx 0.1417\text{Re}^{0.6503}$$

E is calculated from physical principles

$$[34] \quad E = \frac{h_{\text{air}}\rho_{\text{air}}D_C\Gamma'}{60}$$

where h_{air} is the heat content of air ($J \cdot kg^{-1}$), ρ_{air} is the density of air ($kg \cdot m^{-3}$), D_C is the canopy depth (m), Γ' is the potential reaction velocity (min^{-1}), and 60 is a conversion factor for min^{-1} to s^{-1}. The potential reaction velocity is the reaction velocity (defined as the ratio of the reaction zone efficiency to the reaction time) times the mineral and moisture damping coefficients (Rothermel 1972; Burgen 1987). The potential reaction velocity may also be considered a measure of the fraction of canopy fuels consumed (i.e., the fraction of fuel consumed scaled by the inverse product of the reaction time and the mineral and moisture damping coefficients). The greater the fraction of canopy fuels consumed, the greater the heat flux within the air column.

Convection propagating flux ratios ranged from 0.1 to 0.35 for Re values of 50–400, respectively, for FCCS fuelbed 52.

Evaluation of FCCS crown fire potentials

Sensitivity analysis

The FCCS crown fire potentials were evaluated using three approaches: a sensitivity analysis, a comparison of predicted crown fire rates of spread with observed data, and a comparison of the FCCS crown fire potentials with results obtained from the CFIS model (Alexander et al. 2006). The sensitivity analysis examined the relationship between TP and AP and two important environmental variables, estimated fine-fuel moisture content (EFFM) and wind speed. FCCS results for a range of representative EFFM values (3%, 6%, 9%, and 12%) were obtained by translating the effects of EFFM on the parameters that drive the FCCS surface fire potentials (described in Sandberg et al. 2007*b*). These effects include the nonwoody and shrub moisture damping coefficients. Each of these moisture scenarios resulted in different surface fire characteristics, and through the formulations presented in this paper, resulted in different crown fire characteristics. In FCCS, TP was influenced by EFFM even though EFFM is not a normal input to the model. The sensitivity analysis based on the FCCS conifer fuelbeds ($N = 86$) showed that TP decreased with increasing EFFM (Fig. 6), as evidenced by a shift in the frequency of high TP values to lower TP values with increasing EFFM (Fig. 6). Similarly, AP decreased with increasing EFFM (Fig. 7).

The sensitivity of AP to variations in the wind speed was tested for 21 natural FCCS conifer fuelbeds in Alaska and the northeastern United States. The 10 m open wind speeds ranged from 5 to 50 $km \cdot h^{-1}$. AP increased with increasing wind speed (Fig. 8). At a wind speed < 5 $km \cdot h^{-1}$, AP = 0 for all 21 fuelbeds (i.e., no crowning). At 10 $km \cdot h^{-1}$, half of the fuelbeds had AP values >0 and above 50 $km \cdot h^{-1}$, more than 90% of the models were predicted to crown (Fig. 8).

Comparison with field observations

The FCCS-predicted crown fire rates of spread, R_C, were compared with the rates of spread observed in 15 black spruce (*Picea mariana* (P. Mill.) B.S.P.) stands reported by Alexander et al. (2006, Table A1). These field observations were compared with the fire potential results for FCCS

Fig. 6. Distribution of torching potential (TP) as a function of estimated fine-fuel moisture (EFFM) based on 86 Fuel Characteristic Classification System (FCCS) conifer fuelbeds. Classes shown are 0 (black), 0–1 (dark gray), 1–6 (open), and 6–10 (light gray).

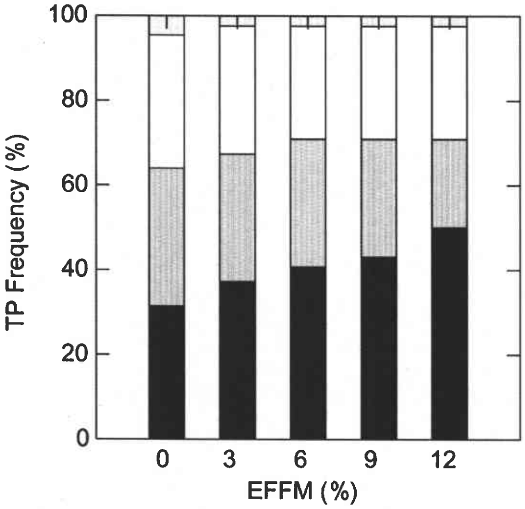
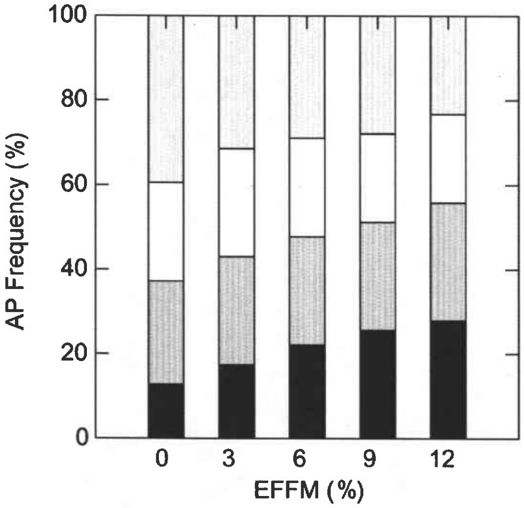
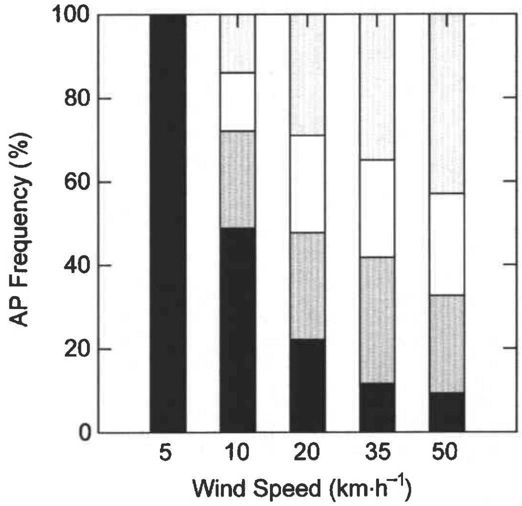


Fig. 7. Distribution of active crowning potential (AP) as a function of estimated fine-fuel moisture (EFFM) based on 86 Fuel Characteristic Classification System (FCCS) conifer fuelbeds. Classes shown are 0 (black), 0–1 (dark gray), 1–6 (open), and 6–10 (light gray).



fuelbed 87, a black spruce – feather moss (Hedw.) Schimp. in B.S.G. stand. Black spruce – feather moss was chosen from among the 216 available FCCS fuelbeds because it yielded the closest agreement with the CBD reported in Alexander et al. (2006), 0.27 kg·m^{-3} for the FCCS and 0.20 kg·m^{-3} for the observations. Input parameters to the FCCS consisted of the moisture content, set to the value rounded to the observed EFFM, and wind speed, set to the actual observed value. Linear regression of $\log_{10}$-transformed R_C values (needed to adjust for high leverage points) produced a coefficient of determination (R^2) of 0.48 (Fig. 9). This comparison also indicates that the FCCS-predicted rates of spread are typically lower than observed values. This is consistent with other comparative studies showing

Fig. 8. Distribution of active crowning potential (AP) as a function of 10 m open wind speed based on 21 Fuel Characteristic Classification System (FCCS) conifer fuelbeds in Alaska and the northeastern United States. Classes shown are 0 (black), 0–1 (dark gray), 1–6 (open), and 6–10 (light gray).



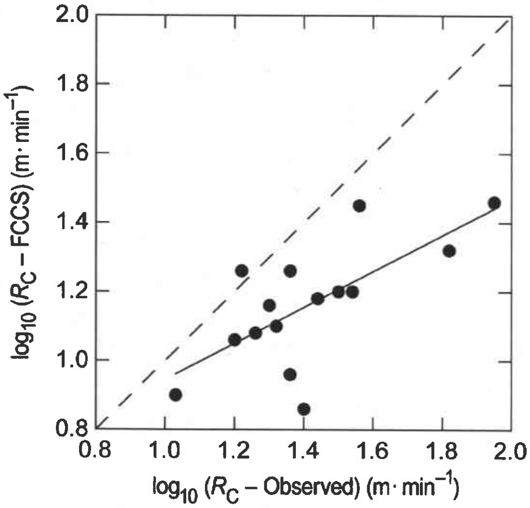
that the crown fire models that utilize the Rothermel (1991, 1972) equations in some form tend to produce relatively low predicted crown fire rates of spread (i.e., Cruz et al. 2005; Scott 2006). However, since FCCS is intended to provide relative crown fire potentials, an additional regression was performed based on the relative ranks of the R_C values. This comparison showed that higher observed R_C values tended to coincide with higher predicted R_C values (R^2 = 0.44; EF = 0.33). EF is defined as the *modeling efficiency*, which is similar to R^2 except that the latter provides an indication of the fit to a 1:1 line, whereas the former provides an indication of the fit to a linear regression line (Mayer and Butler 1993; Alexander et al. 2006). These results suggest that the predicted rates of spread by FCCS track the observed values quite well, especially when based on their relative ranking.

Comparison with CFIS-predicted fire behaviour

The FCCS crown fire potentials were then compared with the CFIS model (Cruz et al. 2006*b*, 2006*c*). In FCCS, the potential for a surface fire to crown is expressed as TP, and in CFIS, as the "probability of crowning." These parameters were regressed against each other using 21 FCCS conifer fuelbeds in Alaska and the northeastern United States, at a wind speed of 15 km·h^{-1} (10 m open wind speed) and over EFFM values ranging from 0% to 12% (N = 105). As described in the previous section, the comparison was based on the relative ranks of the TP and CFIS crown fire probabilities, not the actual values. The linear regression of the ranked values indicated that TP tracks well with the CFIS-based crown fire probabilities, yielding an R^2 value of 0.43 and an EF value of 0.35 (data not shown).

Finally, the FCCS-predicted TP, AP, and R_C values were summarized as a function of the fire type predicted by the CFIS model. The CFIS fire types consist of: surface fire, torching fire, or active crown fire (Cruz et al. 2006*b*, 2006*c*; Alexander et al. 2006). All of the FCCS conifer

Fig. 9. Predicted versus observed crown fire rate of spread, $\log_{10}$-transformed ($\log_{10}(R_C)$). Observations are based on 15 crown fires in black spruce stands reported by Alexander et al. (2006). Predictions were obtained based on Fuel Characteristic Classification System (FCCS) fuelbed 87, a black spruce – feather moss stand, using the reported estimated fine-fuel moisture content (EFFM) and wind speed values (R^2 = 0.48).

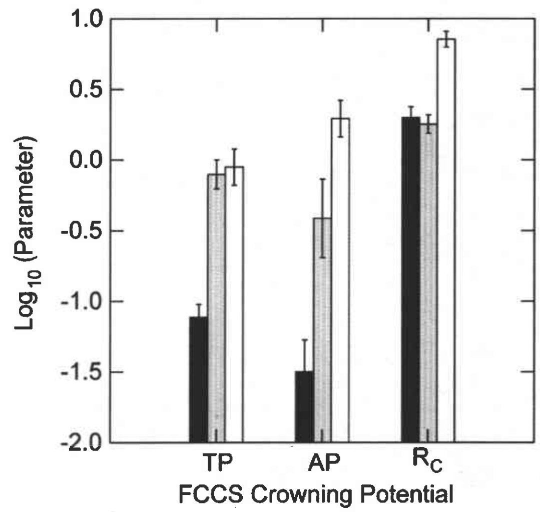


models were used to test for differences in TP (EFFM ranging from 0% to 12%, wind speed fixed at 15 km·h^{-1}) and a subset of 21 conifer stands (see previous discussion) was used to test for differences in AP and R_C (EFFM fixed at 9%, wind speed 5–60 km·h^{-1}). The underlying question of this test was if one considers CFIS as an independent determination of the potential fire type (a discrete classification: surface, torching, and active crowning), then how well do the FCCS crown fire potentials (continuous variables) reflect these distinct fire types? The results indicate that statistically significant differences in TP, AP, and R_C exist among these different fire types, consistent with the expected trends (Fig. 10). Surface fires are characterized by low TP, AP, and R_C values. Torching fires are characterized by high, intermediate, and low values for TP, AP, and R_C, respectively, reflecting the limited ability of the canopy to carry an active crown fire (Fig. 10). Finally, active crown fires were characterized by high TP, AP, and R_C values (Fig. 10). Differences between these fire types in terms of the FCCS crown fire potentials (Fig. 10) were statistically significant based on analysis of variance (using $\log_{10}$-transformed values to obtain an approximately normal data distribution with a Bonferroni posthoc test): for TP, $F_{2,427}$ = 78.6, P < 0.001, and surface < both torching and active; for AP, $F_{2,249}$ = 63.8, P < 0.001, and surface < torching < active; for R_C, $F_{2,249}$ = 115.5, P < 0.001, and both surface and torching < active.

Summary

Anticipating the occurrence of crown fires in natural fuelbeds is critical for effective fire management and planning. This paper presents a conceptual framework for ranking the crown fire potential of different wildland fuelbeds with vegetative canopies. We have extended the work by Van Wagner (1977) and Rothermel (1991) and introduced several

Fig. 10. Fuel Characteristic Classification System (FCCS) crown fire potentials (torching potential, TP, and active crowning potential, AP) and crown fire rate of spread, R_C, by fire type. The TP comparison is based on 86 FCCS conifer fuelbeds. The AP and R_C comparisons are based on 21 FCCS conifer fuelbeds in Alaska and the northeastern United States. Input parameters included estimated fine-fuel moisture content (EFFM) for TP comparisons (N = 430) and wind speed for AP and R_C comparisons (N = 252). Fire type was calculated from the Crown Fire Initiation and Spread (CFIS) model (Cruz et al. 2006*b* and 2006*c*; Alexander et al. 2006) using the FCCS fuelbed characteristics and environmental inputs, EFFM, and wind speed. Fire types consisted of surface (black bar), torching (gray bar), and active crown fire (open bar). Differences between fire types were statistically different for each of the potentials (P < 0.001; zero values were set to a value of 10^{-2} or $\log_{10}$ = –2). Error bars represent the 95% confidence interval.



new physical concepts to the modeling of crown fire behaviour derived from the reformulated Rothermel (1972) surface fire behaviour equations described in Sandberg et al. (2007*b*). The FCCS framework for computing the crown fire potential of wildland fuelbeds systematically and objectively considers the many variables that are commonly used by fire behaviour analysts to assess crown fire potential. Some key parameters, such as canopy continuity and ladder fuel abundance, are ignored in most other fire management systems. By advancing a transparent quantitative framework, even one containing heuristic knowledge-based algorithms, we hope to provide a robust framework to evaluate crown fire behaviour against future models and field observations.

Evaluation of the FCCS crown fire potentials shows that TP and AP respond in a consistent manner with changes in key environmental parameters such as fine-fuel moisture content and wind speed, and that the relative ranking of the predicted R_C values track quite well with observations. Moreover, the predicted FCCS crown fire potentials accurately reflect the differences in fire type that were predicted by an independent crown fire model, CFIS (Alexander et al. 2006). These results are encouraging and suggest that the FCCS crown fire potentials can serve as a useful tool for fire managers to consider when evaluating the potential for crown fires or the relative behaviour of active crown fires in forest canopies.

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List of symbols

AP	FCCS active crown fire potential (dimensionless, scale 0–10)
c_{AP}	scaling function to limit AP within the range of 0–10
c_{TP}	scaling function to limit TP within the range of 0–10
C_{forced}	forced-convection heat flux absorbed by foliage ($W{\cdot}m^{-2}$)
CBD	canopy bulk density ($kg{\cdot}m^{-3}$)
$CBD_{critical}$	critical canopy bulk density required for active crown fire spread ($kg{\cdot}m^{-3}$)
CBH	canopy base height (m)
CFP	FCCS crown fire potential (dimensionless, scale 0–10)
COV	total cover of tree crowns (percent of ground area covered by tree crowns)
d	characteristic spatial dimension of a fuel element (m)
D_C	mean canopy depth or mean difference between stand height and canopy base (m)
gap	physical separation between the top of the surface fuel layer and the bottom of the canopy fuel layer (m)
E	total heat flux in the canopy air space per unit of ground area ($W{\cdot}m^{-2}$ ground)
F_C	FCCS crown-to-crown flame transmissivity term (dimensionless)
FAI	fuel area index of surface fuelbed categories ($m^2{\cdot}m^{-2}$)
FCCS	Fuel Characteristic Classification System
FMC	foliar moisture content of canopy fuels (%)
h	fuel low-heat content ($kJ{\cdot}kg^{-1}$)
h_{air}	heat content of air ($J{\cdot}kg^{-1}$)
H	fuel heat yield ($kJ{\cdot}kg^{-1}$)
H'	fuel heat yield per unit area ($kJ{\cdot}m^{-2}$)
I_B	Byram's fireline intensity ($kJ{\cdot}m^{-1}{\cdot}s^{-1}$ or $kW{\cdot}m^{-1}$)
I'	critical fireline intensity defined by Van Wagner (1977) ($kJ{\cdot}m^{-1}$ s^{-1} or $kW{\cdot}m^{-1}$)
I_C	FCCS crown fire initiation term (units)
I_R	Rothermel's (1972) reaction intensity ($kJ{\cdot}m^{-2}{\cdot}min^{-1}$)
I_{rad}	transmitted radiant intensity passing through a spheroid ($kJ{\cdot}m^{-2}{\cdot}s^{-1}$)
$I_{R.FCCS}$	FCCS combined reaction intensity of surface and crown fuels ($kJ{\cdot}m^{-2}{\cdot}min^{-1}$)
$I_{R.FCCS.C}$	FCCS reaction intensity of canopy fuels ($kJ{\cdot}m^{-2}{\cdot}min^{-1}$)
$I_{R.FCCS.S}$	FCCS reaction intensity of surface fuels ($kJ{\cdot}m^{-2}{\cdot}min^{-1}$)
I_0	initial radiant intensity ($kJ{\cdot}m^{-2}{\cdot}s^{-1}$)
k	opacity or optical depth (m^{-1})
k_C	thermal conductivity of air ($W{\cdot}m^{-1}{\cdot}K^{-1}$)
ladder	FCCS heuristically assigned value representing abundance of canopy ladder fuels (default = 1, representing no ladder fuel)
LAI	Leaf area index ($m^2{\cdot}m^{-2}$)
m	reference foliar moisture content (dimensionless)
Nu	Nusselt number (dimensionless)
Q_{ig}	heat of preignition ($J{\cdot}kg^{-1}$)
R	fire rate of surface fire spread ($m{\cdot}min^{-1}$)
R_{active}	active crowning rate of spread ($m{\cdot}min^{-1}$)
R_C	FCCS crown fire spread rate term ($m{\cdot}min^{-1}$)
$R_{FCCS.S}$	FCCS surface fire rate of spread ($m{\cdot}min^{-1}$)
$(R_{10})_{40\%\text{-}WRF}$	surface rate of fire spread ($m{\cdot}min^{-1}$) predicted by Rothermel (1972) using fuel characteristics for Fire Behaviour Prediction System model 10 and a midflame wind speed set at 40% of the 6.1 m wind speed
RAC	minimum spread rate required to sustain an active crown fire ($m{\cdot}min^{-1}$)
Re	Reynolds number (dimensionlesss)
t_R	residence time of flaming fire front (min)
T_{air}	temperature of the heated air (K)
$T_{foliage}$	temperature of the foliage surface (K)
TCOV	FCCS threshold percent canopy cover required for active crown fire (dimensionless)
TLAI	FCCS threshold LAI required for efficient crown-to-crown flame transfer ($m^2{\cdot}m^{-2}$)
TP	FCCS torching potential (dimensionless, scale 0–10)
U	horizontal midflame wind speed ($m{\cdot}min^{-1}$)
U_B	FCCS benchmark horizontal midflame wind speed ($m{\cdot}min^{-1}$; set to 107)
$U_{6.1}$	wind speed measured in the open at a 6.1 m height ($m{\cdot}min^{-1}$)
W	FCCS vertical, convectively driven wind speed ($m{\cdot}min^{-1}$; assumed to be 268)
W_f	mass of fuel consumed in the flaming fire front ($kg{\cdot}m^{-2}$)
W_{mass}	dry mass of fuel per unit of planar area ($kg{\cdot}m^{-2}$)
WAF	FCCS canopy wind speed adjustment factor (dimensionless)
δ	depth of the woody fuelbed stratum (m)

δ_k fuel array depth used in calculating radiant propagating flux term (equivalent to D_C in canopies; m)
δop_C FCCS optimum canopy depth (m)
Δ'_C FCCS relative canopy fuelbed depth (defined as δop_C divided by D_C) (dimensionless)
η_K Mineral damping coefficient (dimensionless, assumed to be 0.42 based on 1% silica-free ash)
$\eta_{M.FCCS}$ FCCS moisture damping coefficient (dimensionless)
$\eta_{\Delta'.llm}$ FCCS absorption efficiency of the litter–lichen–moss stratum (dimensionless)
$\eta_{\Delta'.C}$ FCCS canopy reaction efficiency (dimensionless)
$\eta_{\Delta'.S}$ FCCS surface-fuel reaction efficiency (dimensionless)
γ_R reaction volume of fuels involved in the reaction zone ($m^3 \cdot m^{-2}$)
Γ' potential reaction velocity (min^{-1})
$\Gamma'_{max.FCCS}$ FCCS maximum reaction velocity at the optimum packing ratio (min^{-1})
ρ_{air} density of air ($kg \cdot m^{-3}$)
ρ_b bulk density of fuel elements ($kg \cdot m^{-3}$)
ρ_p oven-dry mass density of the fuel particles ($kg \cdot m^{-3}$; assumed to be 400 $kg \cdot m^{-3}$)
σ surface-area-to-volume ratio of fuel elements ($m^2 \cdot m^{-3}$)
θ planform area ($m^2 \cdot m^{-2}$; nonwoody, shrub, and litter–lichen–moss)
ξ propagating flux ratio for surface fuelbed (dimensionless)
ξ_C FCCS combined propagating flux ratio in the canopy (dimensionless)
$\xi_{convection}$ FCCS propagating flux ratio for convective heat transfer in the canopy (dimensionless)
$\xi_{radiation}$ FCCS propagating flux ratio for radiant heat transfer in the canopy (dimensionless)
ζ_I FCCS ignition thickness heated on surfaces of thermally thick fuel elements (m)
$1+$ acceleration factor for wind (dimensionless)
$\varphi_{W.FCCS}$