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Assessing crown fire potential in coniferous forests of western North America: a critique of current approaches and recent simulation studies

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Abstract. To control and use wildland fires safely and effectively depends on creditable assessments of fire potential, including the propensity for crowning in conifer forests. Simulation studies that use certain fire modelling systems (i.e. NEXUS, FlamMap, FARSITE, FFE-FVS (Fire and Fuels Extension to the Forest Vegetation Simulator), Fuel Management Analyst (FMAPlus®), BehavePlus) based on separate implementations or direct integration of Rothermel's surface and crown rate of fire spread models with Van Wagner's crown fire transition and propagation models are shown to have a significant underprediction bias when used in assessing potential crown fire behaviour in conifer forests of western North America. The principal sources of this underprediction bias are shown to include: (i) incompatible model linkages; (ii) use of surface and crown fire rate of spread models that have an inherent underprediction bias; and (iii) 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 is a fourth potential source of bias. These sources are described and documented in detail based on comparisons with experimental fire and wildfire observations and on separate analyses of model components. The manner in which the two primary canopy fuel inputs influencing crown fire initiation (i.e. foliar moisture content and canopy base height) is handled in these simulation studies and the meaning of Scott and Reinhardt's two crown fire hazard indices are also critically examined.

Additional keywords: canopy base height, canopy bulk density, crown fire behaviour, crown fraction burned, crowning, Crowning Index, dead fuel moisture content, fire behaviour, fire behaviour modelling, fireline intensity, foliar moisture content, forest structure, rate of fire spread, Torching Index, wind speed.

Introduction

Crowning forest fires are exceedingly exciting to observe but like most natural phenomena, are dangerous as well. The safe and effective management of fire in most coniferous forest ecosystems is thus dependent to a very large extent on the ability to reliably assess or forecast crown fire potential based on predictive aids produced by research coupled with the skill and knowledge of the user.

Many advances have been made in crown fire behaviour research in recent years, including more intensively monitored experimental crown fires (Stocks *et al.* 2004) and physical-based modelling (Butler *et al.* 2004; Cruz *et al.* 2006*a*, 2006*b*). Nevertheless, crown fire behaviour is sometimes portrayed as a complex phenomenon for which we possess very limited knowledge and understanding of the exact physical processes involved (Cohen *et al.* 2006). Although this may very well be true, a substantial number of observations garnered from conducting outdoor experimental fires (Alexander and Quintilio 1990) and monitoring wildfires coupled with case study documentation (Cruz and Plucinski 2007) over the years have provided a solid foundation on several aspects of crown fire phenomenology as well as benchmark data on expected fire characteristics under certain environmental conditions, at least on an empirical basis.

Understanding the environmental conditions required for the onset or initiation and sustained propagation of crown fires is necessary to implement fuel management programs aimed at mitigating the likelihood of large, high-intensity crowning wildfires in the conifer-dominated forests found in western North America. Keyes and Varner (2006) have recently outlined just how complicated the processes involved are in using silvicultural methods to treat forest fuels in order to modify potential crown fire

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behaviour. The need for research into the effectiveness of fuel treatments in reducing crown fire potential has received considerable attention in recent years (Graham *et al.* 2004; Agee and Skinner 2005; Peterson *et al.* 2005). Roccaforte *et al.* (2008) classified research of this type into three categories: experimental, observational and simulation modelling.

Martinson and Omi (2008) have recently reported that more than half of the published studies aimed at quantifying fuel treatment effectiveness rely solely on modelling simulations. Commonly, these simulation studies characterise the fuel structure of distinct forest stands and through the use of fire modelling systems, coupled with specified fire weather, fuel moisture and slope conditions, attempt to integrate this information into a few fire behaviour descriptors in order to assess the relative 'flammability' of the fuel complex (McHugh 2006), and in turn, are able to gauge the effectiveness of fuel management strategies to mitigate the possibility of crown fires occurring (Graham *et al.* 1999; Keyes and O'Hara 2002).

Various fire modelling systems, such as NEXUS (Scott and Reinhardt 2001), Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS) (Reinhardt and Crookston 2003), FARSITE (Finney 2004), Fuel Management Analyst (FMAPlus®) (Carlton 2005), FlamMap (Finney 2006) and BehavePlus (Andrews *et al.* 2008), are extensively used in these simulation studies to assess potential crown fire behaviour in the western US (Keyes and Varner 2006; McHugh 2006; Varner and Keyes 2009) and to a lesser extent to date in western Canada (e.g. Bessie and Johnson 1995; Feller and Pollock 2006). The technical basis and intended uses of these modelling systems are contrasted elsewhere (McHugh 2006; Andrews 2007; Peterson *et al.* 2007).

All of the fire modelling systems referred to previously implement, link or integrate (or both) 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 in various ways, and provide an output of several fire behaviour characteristics (e.g. rate of fire spread, fireline intensity, type of fire, crown fraction burned). Some of the systems also output two crown fire hazard indices – the Torching index (TI) and the Crowning Index (CI) as per Scott and Reinhardt (2001). The TI and CI represent the threshold wind speeds required for the onset of crowning and active crown fire propagation in coniferous forests respectively. Each TI and CI value is tied to a unique set of surface fuelbed characteristics (expressed in terms of a stylised or custom fuel model), dead and live moisture contents of surface fuels, crown fuel properties (canopy base height and bulk density, foliar moisture content), and slope steepness. This approach of using fire modelling systems to assess potential crown fire behaviour has gained widespread popularity within the US wildland fire research community, as evident by the number of published simulation studies over the past 10 years or so (e.g. Scott 1998*a*; Stephens 1998; Raymond and Peterson 2005; Harrington *et al.* 2006; Graetz *et al.* 2007; Mason *et al.* 2007; Battaglia *et al.* 2008). Scott and Reinhardt's (2001) two crown fire hazard indices are now being recommended for use in Canada (Gray and Blackwell 2008).

Our cursory critique of these simulation studies has revealed that many of them have produced unrealistic outcomes in terms of crowning potential, as evident by the resulting TI and CI values, given the specified environmental conditions and fuel characteristics. Quite often, critically dry fuel moisture levels are specified along with very low canopy base heights and relatively high canopy bulk densities and yet the simulations suggest that exceedingly strong winds are commonly required to initiate crowning and for fully developed or active crown fires to occur.

We have subsequently discovered that the fire modelling systems used in assessing crown fire potential in these simulation studies have an inherent underprediction bias associated with them as a result of the underlying models or the manner in which they have been implemented (Cruz *et al.* 2003*a*). The primary purpose of the present paper is to accordingly document the unrealistic nature of the outputs from these simulation studies and the level of underprediction bias involved in the models or modelling systems (or both), and then to explain the reasons for such results. Finally, comments are made on the manner in which two of the canopy fuel characteristics (i.e. foliar moisture content and canopy base height) involved in these simulation modelling studies are handled as well the interpretation of the two crown fire hazard indices.

Wind speeds quoted in this article are in terms of the international 10-m open standard (Lawson and Armitage 2008) unless otherwise stated. For the convenience of the reader, a summary list of the variables, including their symbols and units, referred to in the equations and text is given at the end of this article.

Evidence for underprediction of crowning potential in relation to environmental conditions

The notion of an underprediction trend associated with the modelling systems used in various simulation studies has also been hinted at by others. Hall and Burke (2006) found in applying the NEXUS modelling system to prefire fuel complex data collected in the area burned by the 2002 Hayman Fire in north-central Colorado (Graham 2003) that the system failed to simulate the crowning activity actually observed under the weather and fuel moisture conditions that prevailed. Similarly, Agee and Lolley (2006) noted that the low torching potential found in their simulations was 'contradictory to local and regional experience on recent wildfires'. Fulé *et al.* (2001*a*) also recognised that simulation outputs from the NEXUS modelling system appeared contradictory to actual wildfire experience, noting that 'simulated fires using our fuel and weather conditions proved nearly impossible to crown using realistic data, even though real fires had crowned under similar or even less severe conditions'. Here, we specifically discuss and provide evidence for the underprediction bias in terms of wind speed and dead fuel moisture content.

Wind speed and dead fuel moisture combinations

The simulations produced in several studies examining fuel treatment effectiveness reveal a rather low potential for crown fire behaviour relative to the specified environmental conditions (e.g. Scott 1998*a*; Graves and Neuenschwander 2001; Fulé *et al.* 2002; Perry *et al.* 2004; Raymond and Peterson 2005; Agee and Lolley 2006; Hall and Burke 2006; Harrington *et al.* 2006; Page and Jenkins 2007; Roccaforte *et al.* 2008). This is reflected in the threshold wind speeds required for the onset of crowning as represented by the TI and for active crown fire spread as represented by the CI. Both values are generally quite high considering that the simulations are generally based on extremely dry fuel moisture conditions. In many cases, these simulation studies have reported TI and CI values associated with gale-force winds (i.e. sustained winds greater than $\sim$100 km h^{-1}). Such winds seldom occur inland, but when they do, they generally result in trees and whole forest stands being blown down over large areas (List 1951). Scott (2006) has indicated that these very high wind velocities simply indicate 'a very low potential for initiating a crown fire' and that wind speeds at or in excess of 100 km h^{-1} 'occur so rarely that crown fire can be considered nearly impossible to initiate'. Stephens *et al.* (2009) suggest that such levels of wind strength should be 'interpreted as a characteristic of a forest structure that is extremely resistant to passive crown fire'. Although these are possible explanations, they aren't the only ones.

It can 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. Although this may be intuitively true for areas that have undergone some form of fuel treatment, for control or untreated areas, the simulation results do not appear realistic based on general observation and experience (Fig. 1 and Table 1), thereby suggesting that the authors of these simulation studies have failed to compare their simulation outputs with empirical observation in order to gauge that their results are realistic (Alexander 2006). Empirical evidence from outdoor experimental crown fires (Stocks *et al.* 2004; Cruz *et al.* 2005) and from wildfire case study documentation (Alexander and Cruz 2006) provides a ready test of this assertion. Fig. 1*a* is a plot of the range in the fine dead fuel moisture (FDFM, %) as per Rothermel (1983) and 10-m open wind speed (U_{10}, km h^{-1}) associated with a dataset of 54 documented crowning wildfires from across North America as taken from a summary given in Alexander and Cruz (2006). FDFM is referred to as the 'estimated fine fuel moisture' in Cruz *et al.* (2004, 2005), Alexander and Cruz (2006), and Alexander *et al.* (2006).

Also plotted in Fig. 1*a* is the 1-h time-lag fuel moisture content (Fosberg and Deeming 1971; Deeming *et al.* 1977) – in lieu of the FDFM – and U_{10} pairs used in the control or no-treatment fuel complexes for a selected set of fuel treatment effectiveness simulation studies. It is apparent from Fig. 1*a* that the conditions used in these simulation studies are extremely severe and not representative of the conditions commonly encountered in large, high-intensity wildfire incidents that involve extensive crowning activity.

Fig. 1*b* illustrates the level of underprediction bias associated with crown fire rate of spread for nine simulation studies by comparing the resultant outputs with observed wildfire rates of spread in relation to U_{10}; some additional observations are given in Table 1. As a general trend, the simulation studies, even though they are relying on extremely dry fuel moisture conditions, require almost a doubling in the U_{10} to attain the level of fire spread rates contained within the wildfire dataset. It is evident from the plots of the TI and CI values (Fig. 1*c*) – the outputs sought by these studies in order to quantify stand or landscape 'flammability' – that the simulation results constitute a distinctly different population from the dataset compiled by Alexander and Cruz (2006) that is based largely, but not exclusively, on wildfires in the western and northern North American coniferous forests. The TI and CI values presented in Fig. 1*c* are applicable to stands with mostly low (i.e. $<$3 m) to moderately high (i.e. 3–8 m) canopy base heights. The various simulation studies generally indicate that exceptionally dry fuel conditions and very strong winds are required for passive and active crowning activity compared with the conditions associated with the documented wildfires.

Wind speed limits

Also noteworthy in Fig. 1*c* is the magnitude of simulated wind speeds, especially in respect to the TI, in several cases in excess of 100 km h^{-1}, given in some of these and other studies (e.g. Scott 1998*a*; Fiedler and Keegan 2003; Monleon *et al.* 2004; Perry *et al.* 2004; Fried *et al.* 2005; Ager *et al.* 2007; Moghaddas and Stephens 2007; Stephens *et al.* 2009). This is consentaneous with other studies aimed at quantifying the potential crown fire behaviour associated with specific fuel complex structures that have reported winds close to or in excess of 1000 km h^{-1} (e.g. Raymond and Peterson 2005; Hall and Burke 2006; Johnson 2008; Stephens *et al.* 2009; Vaillant *et al.* 2009*a*). Some authors have chosen to simply express their TI and CI (6.1-m open wind speeds) values as $\geq$40.2 km h^{-1} or the CI separately as $\geq$64.4 km h^{-1} (e.g. Skog *et al.* 2006; Huggett *et al.* 2008), thereby masking the possibility of very high speeds presumably required for crowning; $\geq$85 km h^{-1} has also recently appeared (Battaglia *et al.* 2008) and $>$145 km h^{-1} (Fiedler *et al.* 2010) have also recently appeared. More recently, some authors have elected to cite only the CI values (e.g. Ager *et al.* 2007; Brown *et al.* 2008; Finkral and Evans 2008).

In contrast to the winds reported in Fig. 1*c*, the 10-m open winds associated with the eight crown fire rate of spread observations used in the formulation of the Rothermel (1991) crown fire rate of spread model averaged 38 km h^{-1} and ranged from 20 to 83 km h^{-1}. The highest wind speed (i.e. 83 km h^{-1}) was associated with the later stages of the major run of the 1967 Sundance Fire in complex mountainous terrain in northern Idaho (Anderson 1968). If this one observation was removed, the winds would have averaged 32 km h^{-1}. Thus, based on all of the available evidence (i.e. Rothermel 1991; Alexander and Cruz 2006; Table 1), one can say with some degree of confidence that there has been no documented active crown fire of any size associated with sustained winds greater than $\sim$80 km h^{-1} reported to date.

Dead fuel moisture levels

In the development of his crown fire rate of spread model, Rothermel (1991) equated the FDFM of Rothermel (1983) to the 1-h time-lag fuel moisture content; this lack of distinction has undoubtedly led to some of the confusion now seen in several simulation studies. He then estimated the 10- and 100-h time-lag values by adding 1.0 and 2.0% to the FDFM value respectively. Some simulation studies (e.g. Cram *et al.* 2006), including many of those identified in Fig. 1*a* and 1*b*, have chosen to use the dead fuel moisture time-lags generated by the US National Fire Danger Rating System (NFDRS) (Deeming *et al.* 1977) rather than estimating the 1-h time-lag fuel moisture content from the FDFM or using the seasonal moisture condition scenarios (or both) presented in Rothermel (1991).

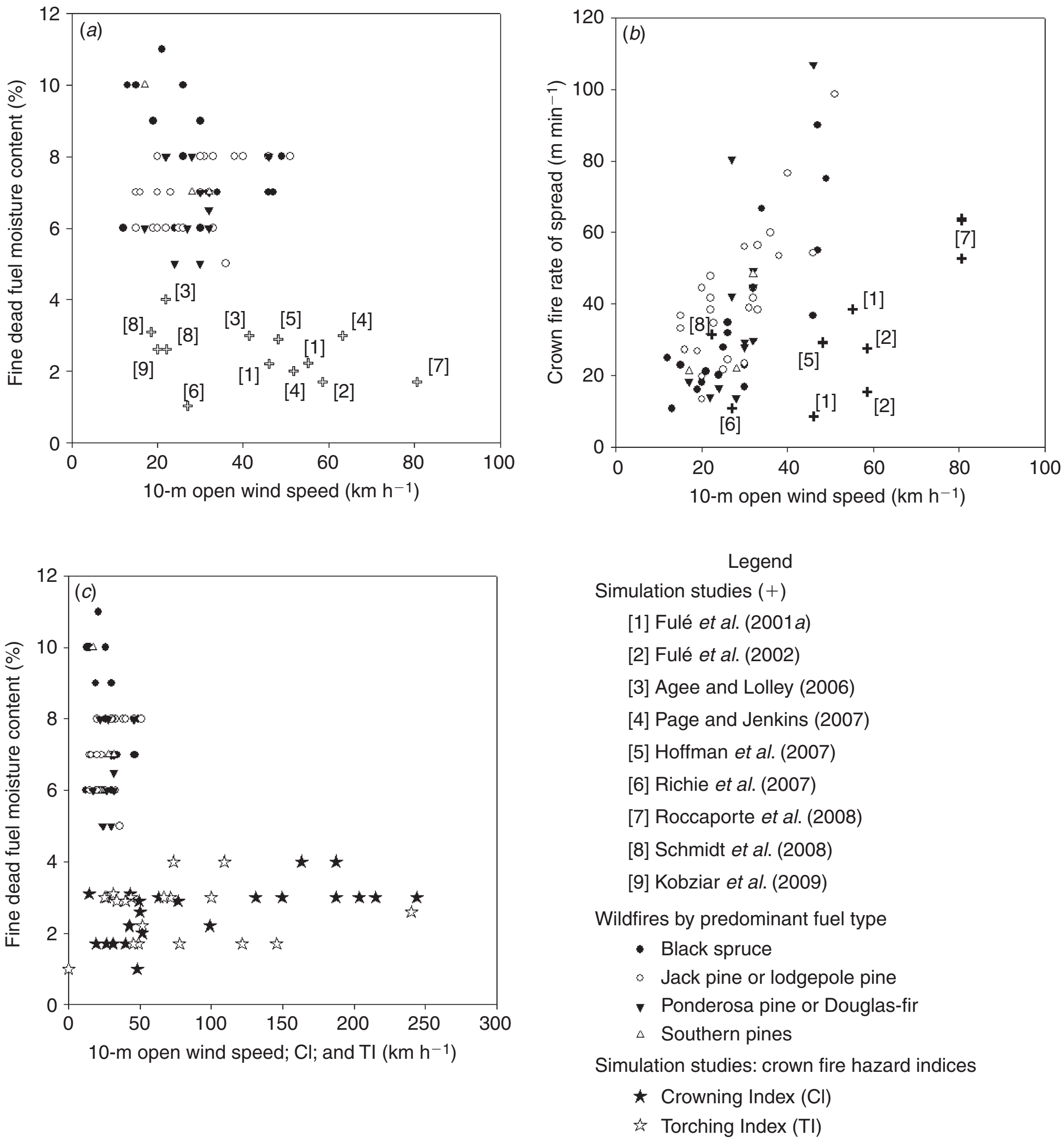

Fig. 1. Environmental conditions and associated crown fire rates of spread and indices of crown fire hazard for a dataset of actively crowning wildfires assembled by Alexander and Cruz (2006) and for a sample of selected simulation studies that have appeared in the scientific peer-reviewed literature: (*a*) fine dead fuel moisture *v.* 10-m open wind speed; (*b*) crown fire rate of spread *v.* 10-m open wind speed; and (*c*) fine dead fuel moisture *v.* 10-m open wind and Scott and Reinhardt's (2001) two crown fire hazard indices. Level terrain is assumed in all cases.

For the purpose of their simulations, Roccaforte *et al.* (2008) assumed 1-, 10- and 100-h time-lag fuel moisture contents of 1.7, 3.0 and 4.5% respectively, representing the 97th percentile level of fire weather severity based on 34 years of archived NFDRS calculations. DeRose and Long (2009) similarly applied values of 1.9, 2.1 and 3.2% respectively in their simulations. In calculating TI and CI values at the time that the 2002 Cone Fire in north-eastern California burned into their experimental fuel treatment plots, Ritchie *et al.* (2007) applied the NFDRS 1-h time-lag fuel moisture content of 1.0% as computed at a nearby fire weather station. The 10- and 100-h values both registered 2.0%. These three situations represent extremely low fuel moisture conditions for coniferous forests in all three categories.

Rothermel (1991) reported value ranges of 3–8, 4–9 and 5–9% respectively for the 1-h (i.e. FDFM was regarded as a surrogate), 10-h and 100-h time-lag fuel moisture contents associated with the wildfires used in the development of his crown fire rate of spread model. Even for his worst case 'late summer, severe drought' scenario, Rothermel (1991) only used 1-h (i.e. FDFM), 10-h and 100-h time-lag fuel moisture contents of 3.0, 4.0 and 6.0% respectively.

Table 1. Characteristics of some of the best-known or well documented (or both) crowning wildfires in conifer forests of North America and Australasia associated with exceptionally strong winds on level to gently undulating terrain not included in Fig. 1

Predominant fuel types are sand pine (*Pinus clausa*) and radiata pine (*P. radiata*). FDFM, fine dead fuel moisture; ROS, rate of spread; U_{10}, 10-m open wind speed. For U_{10}, the World Meteorological Organization standard to express wind speed at a height of 10 m in the open was followed here (Lawson and Armitage 2008). Winds measured at a height of 6.1 m in the open, as per the standard for fire danger rating and fire behaviour prediction used in the United States (Deeming *et al.* 1977; Rothermel 1983), were increased by 15% to approximate the U_{10} standard (Lawson and Armitage 2008)

Reference	Name of fire	Geographical location	Date (dd/mm/yy)	Predominant fuel type(s)	FDFM (%)	ROS ($m\,min^{-1}$)	U_{10} ($km\,h^{-1}$)	Type of crown fire
Stocks and Walker (1973)	Garden Lake	Ontario, CAN	02/06/30	Black spruce–jack pine–balsam fir	11	–[A]	48	Active
Folweiler (1937)	Big Henry	Florida, USA	12/03/35	Sand pine	–[B]	135–150	68	Active
Prior (1958)	Balmoral	New Zealand	26/11/55	Radiata pine	8	28	60	Passive and active
Schaefer (1957)	Dudley Lake	Arizona, USA	14/06/56	Ponderosa pine	6	–[C]	64	Active
Dieterich (1979)	Burnt	Arizona, USA	02/11/73	Ponderosa pine	9	30	74	Passive[D]
Geddes and Pfeiffer (1981)	Caroline	South Australia	02/02/79	Radiata pine	5	67	45	Active
Keeves and Douglas (1983)	Mount Muirhead	South Australia	16/02/83	Radiata pine	4	207	80	Active
NFPA (1992)	Spokane area	Washington, USA	16/10/91	Ponderosa pine	10[E]	30	66[E]	Passive and active[F]

[A]According to Stocks and Walker (1973), the extremely strong winds caused 'crowning and contributed greatly to the very fast spread of the fire' that saw two sustained runs of 24 and 64 km take place over a 26-h period on 1–2 June.
[B]According to Folweiler (1937), no measurements of relative humidity were available but it was 'probably low'.
[C]According to Schaefer (1957), the fire made a sustained run of 16 km. Dieterich (1976) estimated Byram's (1959) fireline intensity to have been 52 925 $kW\,m^{-1}$.
[D]According to Dieterich (1979), 'Damage from this fast-spreading fire was extremely variable ranging from complete destruction of crown material in patches of saplings and pole timber and an occasional mature tree, to large areas where the only evidence of fire was a blackened litter layer and slight scorch on the lowest portions of the crowns', and that much of the ponderosa pine was 'open grown, and tree crowns extended to within 4–5 feet [1.2–1.5 m] of the ground'. Alexander (1998) computed the fireline intensity at the head of the fire to be 5251 $kW\,m^{-1}$ using Eqn 4 and the critical surface fire intensity for initial crown combustion to be just 343 $kW\,m^{-1}$ using Eqn 1.
[E]Based on Alexander and Pearce (1992).
[F]According to the NFPA (1992) case study report, it was observed that: typically stands of ponderosa pine contain dead branches extending to the ground. In some cases, these 'ladder fuels' enabled the fire to reach the crowns of the 30- to 100-foot pine trees and would result in the fire spreading at extremely high rates. Unlike other severe wildland fires, however, this 'crowning' was fairly limited.

As illustrated in Fig. 1*a*, Alexander and Cruz (2006) found for a large database composed mainly of western and northern North American wildfires that the FDFM commonly varied between 6 and 10%. The moisture content of shaded needle litter in conifer forest stands very seldom is less than 2.5–3.0% (Countryman 1977; Harrington 1982; Rothermel *et al.* 1986; Hartford and Rothermel 1991; Wotton and Beverly 2007). The 1-h time-lag NFDRS fuel moisture content can easily be ~2.0% less than the shaded condition represented by the FDFM owing to the effects of solar radiation on fully exposed fuels. This is the reason for the very low fuel moisture conditions commonly associated with the simulation studies on fuel treatment effectiveness (Fig. 1*a*). Considering that the fine, dead fuels represented by the 1-h time-lag fuels are the principal carrier for surface fire spread, the use of the NFDRS computation in lieu of the FDFM represents a significant departure in the application of Rothermel's (1991) crown fire rate of spread model.

Reasons for underprediction of potential crown fire behaviour

The comparison of simulation results with actual observed data presented in Fig. 1 suggests there is a problem in the fundamental underlying models or the manner (or both) in which the models were implemented in the modelling systems. An in-depth analysis of the modelling system framework as dictated by the linkages between the Rothermel (1972, 1991) and Van Wagner (1977, 1993) models reveals that the underprediction bias in the assessment of potential crown fire behaviour arises from three principal sources: (1) incompatible model linkages; (2) use of surface and crown fire rate of spread models that have an inherent underprediction bias; and (3) the reduction in crown fire rate of spread based on the use of crown fraction burned functions. A further potential source of bias is the use of uncalibrated custom fuel models. All but one of these bias sources (i.e. the second one) arise from what we believe is unsubstantiated use of the cited models.

Rothermel (1972) surface fire–Van Wagner (1977) crown fire initiation model linkages

The implemented linkage between the outputs of the Rothermel (1972) surface fire model (i.e. rate of spread and intensity) and the Van Wagner (1977) crown fire initiation model overlooks an important assumption of the latter model. Through a combination of physical reasoning and empirical observation, Van Wagner (1977) defined quantitative criteria to predict the onset of crowning. He defined the critical surface fire intensity for initial crown combustion (I_o, kW m^{-1}) as a function of the canopy base height (CBH, m), and heat of ignition (h, kJ kg^{-1}):

$$I_o = (C \cdot \mathrm{CBH} \cdot h)^{1.5} \tag{1}$$

where h is in turn determined by the foliar moisture content (FMC, %) (Van Wagner 1989, 1993):

$$h = 460 + 25.9 \cdot \mathrm{FMC} \tag{2}$$

Van Wagner (1977) considered the quantity C in Eqn 1, the criterion for initial crown combustion, 'is best regarded as an empirical constant of complex dimensions whose value is to be found from field observations'. Van Wagner (1977) derived a value for the proportionality constant C using the following transformation of Eqn 1 on the basis of a blend of three experimental crown fires carried out in a red pine (*Pinus resinosa*) plantation:

$$C = \frac{I_o^{0.667}}{(\mathrm{CBH} \cdot h)} \tag{3}$$

The surface fire intensity at the onset of crowning was estimated to be ~2500 kW m^{-1} (Van Wagner 1968). Thus, for a CBH of 6.0 m and FMC of 100%, $C = 0.010$ (kW$^{2/3}$ kJ^{-1} kg m$^{-5/3}$).

Van Wagner (1977) equated I_o to Byram's (1959) fireline intensity (I_B, kW m^{-1}), which he calculated from measurements of fire spread rate and fuel consumption:

$$I_B = H \cdot w_a \cdot r \tag{4}$$

where H is the low heat of combustion (kJ kg^{-1}), w_a is the fuel consumed in the active flaming front (kg m^{-2}), and r is the rate of fire spread (m s^{-1}) (Alexander 1982). It is possible to express the requirements for the onset of crowning in terms of the surface fire spread rate by replacing I_o for I_B in Eqn 4 and working backwards (Van Wagner 1989, 1993; Forestry Canada Fire Danger Group 1992), giving the following result:

$$R_i = \frac{60 \cdot I_o}{H \cdot w_a} \tag{5}$$

where R_i is the critical surface fire rate of spread for crown fire initiation (m min^{-1}).

Modelling systems such as NEXUS, FlamMap, BehavePlus, FARSITE, FFE-FVS, and FMAPlus calculate fireline intensity from Rothermel's (1972) reaction intensity (I_R, kW m^{-2}) (Albini 1976):

$$I_B = I_R \cdot t_r \cdot r \tag{6}$$

where t_r is the flame-front residence time (s). Fireline intensities calculated in this manner are consistently lower than per the original Byram (1959) formulation (Cruz *et al.* 2003*a*, 2004). The extent of the differences is a function of the fuelbed characteristics. For the original 13 standard US fire behaviour fuel models as described by Anderson (1982), Byram's (1959) fireline intensity (Eqn 4) is larger than the Rothermel (1972) I_R-derived fireline intensity by a factor of 2 to 3 (Cruz *et al.* 2004).

The implication of these differences within a modelling system such as NEXUS is that higher simulated surface fire rates of spread, and consequently stronger wind speeds and hence larger TI values, are necessary to induce crowning than if the model linkages were to follow the original model assumptions. The end result is increasingly large TI values. Fig. 2 presents a graphical representation of the magnitude of this error for the Anderson (1982) Fuel Model 2 – Timber (grass and understorey) and Fuel Model 10 – Timber (litter and understorey) considering an I_o of 2935 kW m^{-1} per Eqns 1 and 2 based on a CBH of 5.0 m and an FMC of 140%; the output of Fuel Model 9 – Hardwood litter would be very similar to that of Fuel Model 10. The increase in mid-flame wind speed required for the onset of crowning is 72% (i.e. from 6.5 to 10.9 km h^{-1}) for Fuel Model 2 and 48% (i.e. from 8.2 to 12.1 km h^{-1}) for Fuel Model 10. The differences observed in this modelling exercise are considered as conservative in nature. The calculations of Byram's (1959) fireline intensity undertaken here assume that the fuels consumed in the flame front and thus contributing to the upward heat fluxes are the fine, dead and live fuels plus the 10-h time-lag fuels, whereas Van Wagner (1977) in his original formulation did not specifically differentiate between the fuels consumed during flaming as opposed to flaming and smouldering or glowing combustion. In other words, he assumed w_a was equivalent to the difference he obtained from pre- and post-burn fuel sampling – i.e. the fuel consumed in the active flaming front and by glowing or smouldering combustion following passage of the front (w, kg m^{-2}).

Conceptually, the two methods of computing Byram's (1959) fireline intensity should, in theory, yield nearly identical results. The main differences between these two arise from the use of the I_R and t_r models in the Rothermel (1972) model to calculate Byram's (1959) fireline intensity. I_R is estimated from an empirical model developed for homogeneous fuelbeds under no-wind/no-slope conditions in a laboratory setting. How well these assumptions hold for natural surface fuelbeds, with heterogeneous fuel particle and moisture content distributions is unknown, as the model has never been evaluated against field data to our knowledge other than the attempt by Brown (1972) involving simulated slash fuelbeds.

The use of Anderson's (1969) model to estimate t_r in Eqn 6 is the most likely source for the differences between the two methods of determining Byram's (1959) fireline intensity. Research on t_r in natural fuelbeds has identified fuel load, compactness, particle size and moisture as well as wind speed as the most influential variables (Cheney 1981; Nelson 2003). Anderson's (1969) model predicts t_r solely from the characteristic or average weighted size of individual fuel particles.

Nelson (2003) developed and evaluated a semi-physically based model to predict t_r that takes into account fuelbed structure and combustion zone properties. A comparison between the Anderson (1969) and Nelson (2003) t_r models reveals that the former model consistently yields lower t_r values when w_a exceeds $\sim$0.5 kg m^{-2} (Fig. 3). Evaluation data for simulated fuelbeds of slash pine (*Pinus elliottii*) needle litter (Nelson and Adkins 1988) and ponderosa pine (*P. ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*) slash (Brown 1972) reveal a marked underprediction of t_r by Anderson's (1969) model and general agreement with Nelson's (2003) model.

If Nelson's (2003) model is considered to provide an acceptable prediction of t_r, as supported by Fig. 3 and his own evaluation against an array of artificial fuelbeds, the Anderson (1969) model is underpredicting t_r in fuel beds with medium to high available fuel loads. This error is propagated within the modelling system and leads to low fireline intensities, and in turn, a low potential for crown fire initiation as illustrated in Fig. 2.

Underprediction bias in the Rothermel (1972) surface fire rate of spread model

In addition to the incompatibility between the various US fire modelling systems and Van Wagner's (1977) criteria for crown

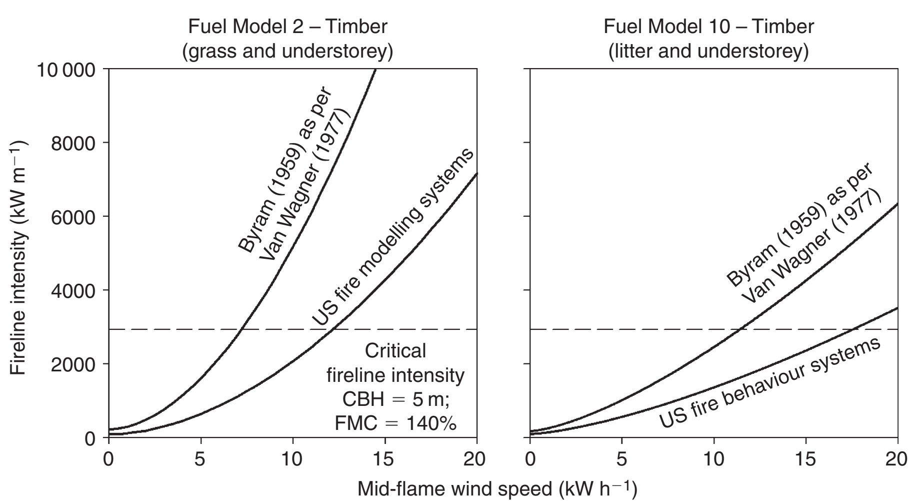

Fig. 2. Critical mid-flame wind speeds required for crown fire initiation as per Van Wagner's (1977) critical surface fire intensity criteria for two US fire behaviour fuel models (Anderson 1982) based on different methods of calculating fireline intensity (i.e. Byram (1959) as per Van Wagner (1977) *v.* US fire behaviour modelling systems) for a particular canopy base height (CBH) and foliar moisture content (FMC) equating to a critical surface fire intensity for initial crown combustion (I_o) of 2920 kW m^{-1}. The following environmental conditions were held constant: slope steepness, 0%; fine dead fuel moisture, 4%; 10- and 100-h time-lag dead fuel moisture contents, 5 and 6% respectively; live woody fuel moisture content, 75%; and live herbaceous fuel moisture content, 75%. The associated 10-m open winds would be a function of forest structure and can be approximated by multiplying the mid-flame wind speed by a factor varying between 2.5 (open stand) and 6.0 (dense stand with high crown ratio) (Albini and Baughman 1979).

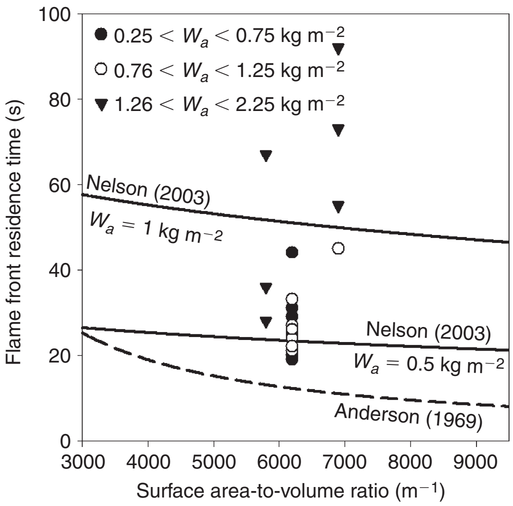

Fig. 3. Sensitivity of Anderson (1969) and Nelson (2003) flame front residence time models to surface area-to-volume ratio and fuel consumed in the active flaming front (w_a). For Nelson's (2003) model, the following environmental conditions were held constant: fuelbed depth, 0.1 m; fuel moisture content, 5%; and mid-flame wind speed, $5\,km\,h^{-1}$. Data points represent computed flame front residence times from experimental fires conducted in simulated fuelbeds of slash pine needle litter (Nelson and Adkins 1988) and ponderosa pine and Douglas-fir slash (Brown 1972), where it was implicitly assumed that w was $\sim w_a$.

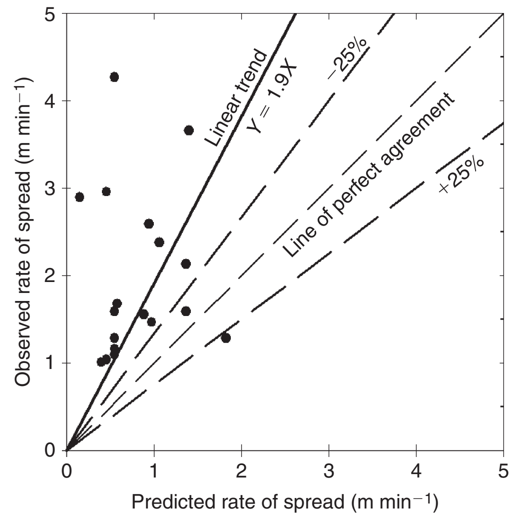

Fig. 4. Observed head fire rates of spread $>1\,m\,min^{-1}$ associated with prescribed burning experiments in ponderosa pine forests of Yosemite National Park, CA, *v.* predictions based on the Rothermel (1972) surface fire rate of spread model for Anderson (1982) Fuel Model 9 – Hardwood litter (adapted from van Wagtendonk and Botti 1984). The dashed lines around the line of perfect agreement indicate the ±25% error interval.

fire initiation with respect to determining w_a, a certain amount of uncertainty exists as to whether the Rothermel (1972) surface fire model can in fact reliably predict, in certain conifer forest stand types, the spread rate of moderate- and high-intensity surface fires that would lead to crowning. Studies that have evaluated Rothermel's (1972) fire spread model for any of the Anderson (1982) stylised 'timber' fuel models (numbers 2, 8, 9 and 10) have identified underprediction trends (Norum 1982; van Wagtendonk and Botti 1984; Grabner *et al.* 1997, 2001). This underprediction trend or bias arises from the sensitivity of the Rothermel (1972) fire spread model to the compactness of the horizontally oriented surface fuelbeds associated with these fuel models (Catchpole *et al.* 1993) and has been discussed in detail by Cruz and Fernandes (2008). Most investigators commonly develop an adjustment factor for rate of spread predictions on the basis of their performance testing (Rothermel and Reinhart 1983). Stephens (1998) for example used the adjustment factors derived by van Wagtendonk and Botti (1984) in his simulation study.

Modelling systems like NEXUS are widely applied to western US ponderosa pine forests (e.g. Johnson *et al.* 2007) and yet performance testing of Rothermel's (1972) model in such fuel complexes is limited to a single outdoor field study by van Wagtendonk and Botti (1984). The same underprediction bias seen in other studies is also evident in their study (Fig. 4 and Table 2). Considering that surface rate of fire spread is a factor in determining the onset of crowning in coniferous forests, the use of unadjusted predictions from stylised fuel models constitutes yet another source of underprediction bias in assessing crown fire potential.

Underprediction bias in the Rothermel (1991) crown fire rate of spread model

Until recently, the only comparison of observed crown fire spread *v.* predictions from Rothermel's (1991) model was that undertaken by Goens and Andrews (1998) on the 1990 Dude Fire that occurred in central Arizona. They found good agreement between predicted and observed spread distances. However, the Dude Fire was considered by Rothermel (1991) as a plume-dominated crown fire as opposed to a wind-driven crown fire, for which he considered his predictive methods were not applicable.

Several studies (Cruz *et al.* 2003*a*, 2005; Stocks *et al.* 2004; Alexander and Cruz 2006) have separately evaluated the Rothermel (1991) crown fire rate of spread model against outdoor experimental crown fire and wildfire datasets (Table 3). A composite summary of those evaluations is presented in Fig. 5. Rothermel's (1991) model underpredicted all 34 experimental observations, with a mean absolute error of 71% (Table 2).

A distinct underprediction bias was also evident in the wildfire observations (Fig. 5*b*). All 54 observations were underpredicted with a mean absolute error of 61%; 63 and 58% for the US and Canadian wildfires respectively (Table 2). The Rothermel (1991) model consistently underpredicted the four observed spread rates in ponderosa pine forests extracted from the 2002 Hayman Fire in north-central Colorado (Finney *et al.* 2003; Graham 2003) by a factor of 2.8 (Alexander and Cruz 2006).

Scott (2006) has acknowledged the underprediction trends evident in Fig. 5 and suggested the use of a correction or adjustment factor (1.7) to obtain what Rothermel (1991) defined as the near-maximum crown fire rate of spread derived on the basis of five 'chance' observations of temporary escalations in

Table 2. Model performance statistics for the Rothermel (1972), Rothermel (1991) and Schaaf *et al.* (2007) rate of fire spread models evaluated against different types of data sources

Statistic	Rothermel (1972)	Rothermel (1991)		Schaaf *et al.* (2007)
	Prescribed fires	Experimental fires	Wildfires	Wildfires
Number of observations	18	34	54	15
Root mean square error	1.54	27	30.7	22.2
Mean absolute error	1.23	22.2	26.0	15.2
Mean absolute percentage error	57	70.8	60.7	41.6
Mean bias error	−1.16	−22.2	−25.9	−15.7
Percentage within ±25% error	6	3	4	20
Over and under predictions	1, 17	0, 34	0, 54	1, 14

Table 3. Basic descriptive statistics associated with the experimental fire and wildfire datasets used in the evaluation of the Rothermel (1991) crown fire rate of spread model as shown in Fig. 5

For Experimental fires, refer to Table 1 in Cruz *et al.* (2005) and to Stocks *et al.* (2004) for the specific details on data sources. For Wildfires, refer to Alexander and Cruz (2006) for the specific details on data sources

Variable	Experimental fires ($n = 34$)				Wildfires ($n = 54$)			
	Mean	s.d.	Min.	Max.	Mean	s.d.	Min.	Max.
10-m open wind speed (km h^{-1})	15.6	5.9	5	35	28.2	9.92	12	51
Air temperature (°C)	25.7	3.9	18.5	31.4	26.6	4.2	20	36
Relative humidity (%)	36.1	7.5	23	52	28	10.6	5	56
Fine dead fuel moisture (%)	7.8	1.9	4	12	7.2	1.37	5	11
Rate of fire spread (m min^{-1})	29.2	16.9	10.7	69.8	39.8	22.1	10.7	107

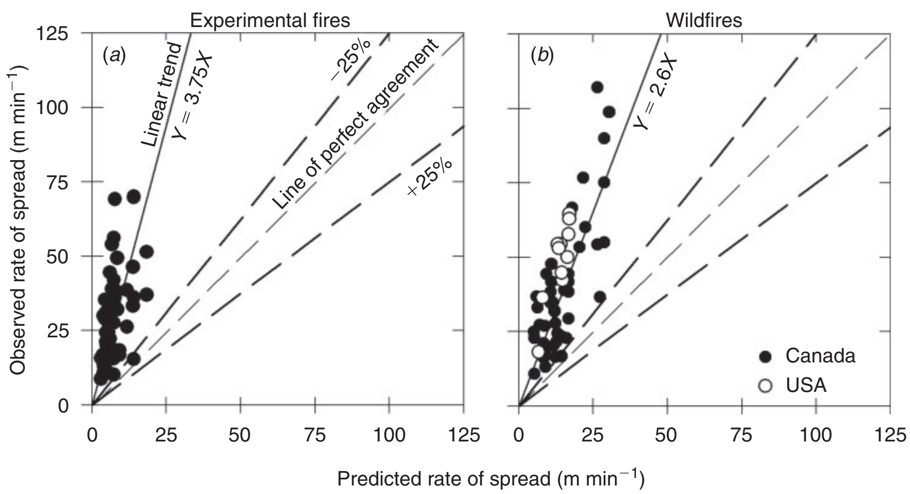

Fig. 5. Observed rates of spread of (*a*) experimental active crown fires; and (*b*) wildfires that exhibited extensive active crowning *v.* predictions based on the Rothermel (1991) crown fire rate of spread model. The dashed lines around the line of perfect agreement indicate the ±25% error interval.

crown fire spread but without any corresponding wind speed measurements. However, according to Rothermel (1991, p. 25), the near-maximum crown fire rate of spread adjustment was intended solely for predicting short bursts in crown fire spread that could be expected to occur during upslope runs and not as a general adjustment factor.

Why is the Rothermel (1991) model consistently under-predicting by a factor of ∼2.5–3.0 and why does it also appear to be relatively insensitive to burning conditions? It is likely due to a multitude of interacting factors (Alexander 2006).

The Rothermel (1991) model is a simple relationship consisting of a correlation derived between the observed average crown fire rate of spread based on eight observations involving seven western US wildfires and the output of the Rothermel (1972) surface fire spread model using Fuel Model 10 and a wind-reduction factor of 0.4 (R_{10}, m min^{-1}) in order to adjust the 6.1-m open wind speed to a mid-flame height value (Albini and Baughman 1979). The Rothermel (1991) model for predicting active crown fire rate of spread (R_a, m min^{-1}) is as follows:

$$R_a = 3.34 \cdot R_{10} \quad (7)$$

Only four of the eight observations used in the model development involved level terrain, so the difficulty of obtaining representative winds in complex terrain relative to observed spread rate can be called into question. Furthermore, the overall average observed rate of spread for five of the eight observations used in the model development was 43 m min^{-1}, which seems reasonable for active or fully developed crown fires in light of the wildfire database compiled by Alexander and Cruz (2006). However, three of eight observations had spread rates of only 14 m min^{-1}. Without knowing what the associated canopy bulk density (CBD) values were for these three observations, such spread rates are low for active crown fires (Cruz *et al.* 2005; Alexander and Cruz 2006). This raises the issue as to the stage of development or degree of crown fire activity (i.e. passive crowning *v.* active crowning) associated with these three crown fire observations and their relative magnitude in the derivation of the Rothermel (1991) model.

From a conceptual perspective, it can be argued that the underlying relationships in the Rothermel (1972) model (i.e. developed from shallow surface fuelbeds in a laboratory setting) do not apply to crown fire phenomena, where the dimension of the fuelbed sustaining fire propagation and the heat flux generated are orders of magnitude higher. Rothermel (1972) readily acknowledged this point and clearly stated in the preface of his publication that the nature and mechanisms of heat transfer in a crown fire are considerably different than those for a surface fire and therefore stated that 'the model developed in this paper is not applicable to crown fires'. Thus, using R_{10} as a correlative or independent variable in what amounts to a statistical model is questionable. The underprediction tendency associated with Rothermel's (1991) model shown in Fig. 5 has also been found to occur with the crown fire rate of spread model developed recently by Schaaf *et al.* (2007) as part of the Fuel Characteristic Classification System (Ottmar *et al.* 2007). The Schaaf *et al.* (2007) model, based on a reformulation of the Rothermel (1972) model by Sandberg *et al.* (2007), is specifically designed to predict the rate of spread of crown fires in coniferous forests. Schaaf *et al.* (2007) undertook to test model performance on the basis of data extracted from Alexander and Cruz (2006) for 15 actively crowning wildfires in black spruce (*Picea mariana*) forests of Canada (Fig. 6 and Table 2). Cronan and Jandt (2008) observed the same underprediction bias evident in Fig. 6 with the experimental fires they conducted in Alaskan black spruce forests.

Another possible reason for the underprediction trend in the Rothermel (1991) model is its low sensitivity to changes in wind speed. As noted, the Rothermel (1991) crown fire spread model is a direct function of Fuel Model 10. Considering that heat

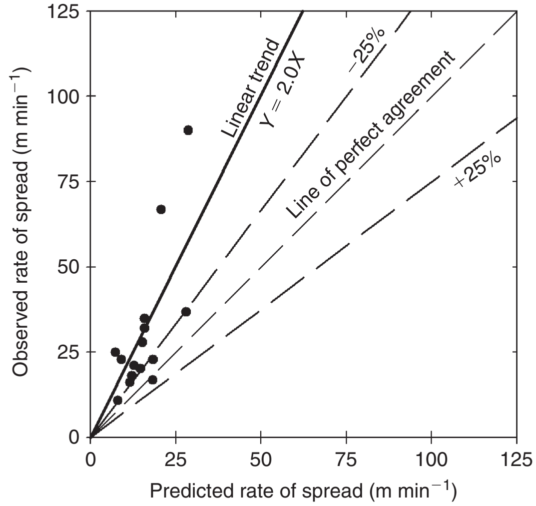

Fig. 6. Observed rates of spread of actively crowning wildfires in black spruce forests *v.* predictions based on the Schaaf *et al.* (2007) crown fire rate of spread model. The dashed lines around the line of perfect agreement indicate the ±25% error interval.

transfer is optimised for vertically oriented, high-porosity fuelbeds (Rothermel 1972), the wind speed–rate of spread relationship of a litter and understorey fuelbed may not be representative of phenomena occurring in deep, low-packing-ratio fuel layers such as canopy fuels in a conifer forest stand. Cohen *et al.* (2006) have described in some detail the inadequacies of the Rothermel (1972) model framework to represent the processes determining crown fire propagation in conifer forests.

The seven wildfires used in the development of the Rothermel (1991) crown fire rate of spread model encompass a wide range in fuel complex structure and composition, although it is difficult to critically assess this factor because formal case study documentation is only available for two of the seven wildfires (Anderson 1968; NFPA 1990) that Rothermel (1991) used in his model development. The Rothermel (1991) crown fire rate of spread model does not explicitly take into account any stand or canopy fuel structure variables as inputs (e.g. CBH, CBD). Hence, crown fire behaviour in the Rothermel (1991) model is independent of the physical fuel characteristics associated with conifer forest stands (Finney 2004).

Rothermel (1991) indicated that the correlation he obtained between the observed crown fire rate of spread and the prediction of surface fire rate of spread from Fuel Model 10 did 'give reasonable results'. However, he was also quick to point out that 'It is readily apparent that more research is needed to strengthen this analysis', and emphasised that his guide represented 'first-order approximations of crown fire behavior' designed to aid operational decision-making.

All 34 experimental fires and 39 of the 54 wildfire observations presented in Fig. 5 involve boreal or boreal-like forest fuel complexes. Thus, it could be argued that the fires selected for evaluation are not 'applicable to the Northern Rocky Mountains or mountainous areas with similar fuels and climate' as per one of Rothermel's (1991) assumptions. Strictly speaking, this is a valid comment.

However, the Rothermel (1991) model has been directly and also indirectly applied through the application of fire modelling systems like NEXUS, FlamMap, FARSITE, FFE-FVS, FMAPlus and BehavePlus, to other distinctly different forest stand types and in other regions of the western US, including for example, the Sierra Nevada (Stephens and Moghaddas 2005*a*, 2005*b*; Dicus *et al.* 2009), north-central (Kobziar *et al.* 2009) and north-eastern (Ritchie *et al.* 2007) regions of California as well as the whole state (Vaillant *et al.* 2009*a*, 2009*b*), south-central (Hummel and Agee 2003), north-eastern (Graves and Neuenschwander 2001) and western Washington (Agee and Lolley 2006), north-eastern (Williamson 1999; Ager *et al.* 2007), central (Fitzgerald *et al.* 2005) and western Oregon (Raymond and Peterson 2005), south-western Utah (Stratton 2004), central Arizona (Goens and Andrews 1998), northern Arizona (Fulé *et al.* 2001*a*, 2001*b*, 2002, 2004), south-central New Mexico (Mason *et al.* 2007), northern Arizona–north-central New Mexico (Clifford *et al.* 2008), and even the north-eastern US (Duveneck and Patterson 2007). In defence of the datasets incorporated in Fig. 5, the fuel characteristics associated with montane and subalpine forests in the Northern Rocky Mountains – namely, ponderosa pine, lodgepole pine (*Pinus contorta*), Englemann spruce (*Picea engelmannii*) and subalpine fir (*Abies lasiocarpa*) are not that dissimilar structurally from forests composed of pure and mixed stands of red pine, jack pine (*Pinus banksiana*), black spruce, white spruce (*Picea glauca*) and balsam fir (*Abies balsamea*).

Reduction of crown fire rate of spread due to use of crown fraction burned functions

All of the fire modelling systems mentioned here (i.e. NEXUS, FlamMap FARSITE, FFE-FVS and FMAPlus), with the exception of BehavePlus, that integrate or link the Rothermel (1972, 1991) and Van Wagner (1977, 1993) models to predict the full range of fire behaviour apply a reduction factor to the predicted crown fire rate of spread based on a crown fraction burned (CFB) function (Table 4) as used for example in the Canadian Forest Fire Behaviour Prediction (FBP) System (Van Wagner 1989; Forestry Canada Fire Danger Group 1992).

The CFB, which indicates the proportion of tree crowns involved in the spread of the fire, varies from 0.0 (surface fire with no crown fuel involvement) to 1.0 (fully developed crown fire). In the FBP System, passive crown fire spread or intermittent crowning and continuous crowning or active crown fire spread is judged to occur at CFB values ranging from 0.1 to 0.89 and $\geq$0.9 respectively (Forestry Canada Fire Danger Group 1992).

The final rate of fire spread (R, m min^{-1}), whether surface or crown, is computed as follows:

$$R = R_s + \text{CFB} \cdot (R_a - R_s) \tag{8}$$

where R_s is the predicted surface fire rate of spread (m min^{-1}) per Rothermel's (1972) model and R_a by Rothermel (1991) per Eqn 7.

The CFB adjustment scheme devised by Van Wagner (1993) provides for a gradual transition in a fire's spread rate from the initial onset of crowning (i.e. passive crown fire spread), as defined by Eqn 5, to the point of active crown fire development

Table 4. Description of computation procedures involved in predicting passive and active crown fire rate of spread in terms of crown fraction burned (CFB) within the various US fire modelling systems

FMAPlus performs the same crown fire computations as FARSITE and NEXUS

Spread regime	BehavePlus	NEXUS and FFE-FVS	FARSITE and FlamMap
Passive crown fire	Does not calculate a CFB for use in computations. Does not provide a spread rate output specifically associated with passive crown fires but does identify passive crown fires as a distinct type of fire.	Calculates CFB between 0.0 and 1.0 using a simple linear transition function between surface and active crown fire rates of spread (Scott and Reinhardt 2001). CFB values are higher than those produced by the CFB function used in FARSITE or FlamMap. Spread rate for passive crown fires is determined to be intermediate between the active crown fire and surface fire rates of spread based on the calculated CFB value.	Calculates CFB between 0.0 and 1.0 based on an exponential transition function between surface and active crown fire rates of spread developed by Van Wagner (1993). CFB values are lower than those produced by the CFB function used in NEXUS or FFE-FVS. Spread rate for passive crown fires assumed to be the same as the surface fire rate of spread.
Active crown fire	Uses Rothermel's (1991) model to predict the average active crown fire rate of spread.	Uses Rothermel's (1991) model to predict the average active crown fire rate of spread. There is also the option to apply the near-maximum crown fire rate of spread multiplier (i.e. 1.7).	Uses Rothermel's (1991) model to predict a reference active crown fire rate of spread that is then adjusted on the basis of the CFB. Because calculated CFB values are lower than those produced by the CFB function used in NEXUS and FFE-FVS, active crown fire spread rates remain less than that predicted by Rothermel's (1991) model even after an active crown fire is judged to have occurred.

based on Van Wagner's (1977) concept of a critical minimum spread rate for active crowning (R_o, m min^{-1}):

$$R_o = \frac{S_o}{\text{CBD}} \quad (9)$$

where S_o is the critical mass flow rate for solid crown flame (kg m^{-2} min^{-1}) and CBD is the canopy bulk density (kg m^{-3}). Van Wagner (1977) provided one estimate of S_o, namely 3.0 kg m^{-2} min^{-1} (Alexander 1988), based largely on a single experimental crown fire in a red pine plantation plot exhibiting a CBD of 0.23 kg m^{-3} (Van Wagner 1964). Cruz *et al.* (2005) have since confirmed the robustness of this estimate based on an examination of a relative large ($n = 37$) dataset of experimental crown fires carried out in several different conifer forest fuel complexes (Fig. 7*a*).

Dickinson *et al.* (2009) claim to have recalibrated Van Wagner's (1977) model represented by Eqn 9 on the basis of the foliar biomass per unit area or available canopy fuel load (CFL, kg m^{-2}) rather than the CBD:

$$R_o = \frac{23.4}{\text{CFL}} \quad (10)$$

This formulation implies that the propagation of active crown fire is not dependent in any way on the stand structure (i.e. height or crown depth) or, in other words, the vertical distribution of the available canopy fuel. It appears from the available experimental evidence that the Dickinson *et al.* (2009) modification of Van Wagner's (1977) R_o model is not as reliable at distinguishing active crown fires from passive crown fires as originally envisioned (Fig. 7*b*).

In deriving his estimate of S_o, Van Wagner (1977) computed the CBD as the available canopy fuel load divided by the canopy depth (Cruz *et al.* 2003*c*) and assumed that all the fuel was uniformly distributed. Admittedly, this is not always the case, for example, in multistoried stands (Reinhardt *et al.* 2006*b*) and even to a certain extent in red pine plantations (Sando and Wick 1972, pp. 6–7) such as Van Wagner (1964, 1968, 1977) worked in. Nevertheless, Alexander *et al.* (1991*b*) found that Van Wagner's (1977) simple model represented by Eqn 9 worked well at distinguishing between surface and crown fires in a black spruce–lichen woodland fuel complex that exhibited large gaps between clumps of trees and crowns that extended down to the ground surface. In their implementation of Eqn 9 in NEXUS, Scott and Reinhardt (2001) initially defined CBD as the maximum 4.5-m vertical running mean bulk density; this was later changed to a 3.0-m interval, although no reason was given (Peterson *et al.* 2005; Scott and Reinhardt 2005, 2007; Scott 2006). This represents a distinct departure from the manner in which Van Wagner (1977) calculated CBD and undoubtedly leads to higher CBD values and hence lower R_o values required for active crowning to occur. As such, it constitutes a violation of one of the fundamental assumptions of Van Wagner's (1977) active crown fire propagation model represented by Eqn 9.

The form of the CFB function varies among the fire modelling systems. FARSITE uses the original exponential form presented by Van Wagner (1993). NEXUS, however, assumes a linear adjustment when the rate of fire spread is between R_i and R_o (Scott and Reinhardt 2001). This gives distinctly different results even if the core models are the same (Fig. 8). Scott and Reinhardt (2001) explored the impact of Van Wagner's (1993) CFB function in FARSITE and found that even under extreme burning conditions, the crown fire rate of spread predicted by the Rothermel (1991) model was reduced by approximately one-third. Regardless of which CFB function is used, the result is a further increase in the underprediction bias (Stocks *et al.* 2004).

The BehavePlus modelling system (Andrews *et al.* 2008) has separately implemented the Rothermel (1972, 1991) surface and crown fire rate of spread and Van Wagner (1977) crown fire initiation and propagation models rather than attempt to directly link them using a CFB function. Thus, BehavePlus doesn't

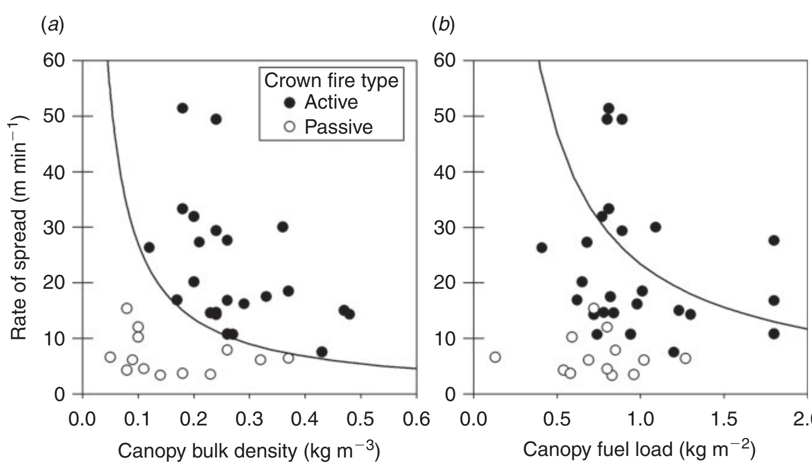

Fig. 7. Scatterplots of experimental crown fire rates of spread by type of spread regime *v.* two canopy fuel properties (adapted from Cruz *et al.* 2005). The curve in (*a*) represents Van Wagner's (1977) criterion for active crowning represented by Eqn 9, assuming an S_o value of 3.0 kg m^{-2} min^{-1}. The curve in (*b*) represents the Dickinson *et al.* (2009) recalibration of the Van Wagner (1977) criterion using canopy fuel load rather than canopy bulk density as represented by Eqn 10.

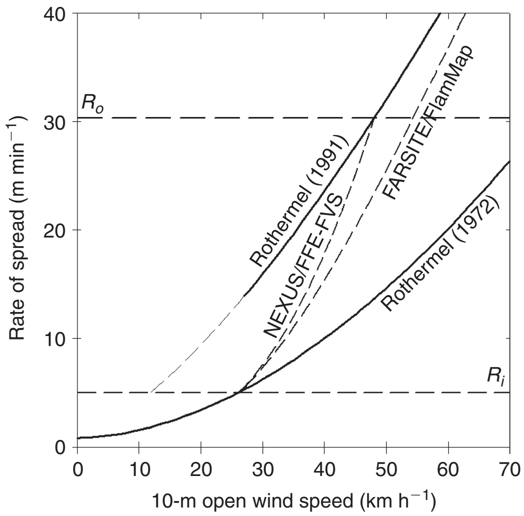

Fig. 8. Comparison of the effect of crown fraction burned functions on rate of fire spread used in the NEXUS and FFE-FVS (Scott and Reinhardt 2001; Reinhardt and Crookston 2003) *v.* FARSITE and FlamMap (Finney 2004, 2006) modelling systems in relation to the Rothermel (1972, 1991) surface and crown fire rate of spread models and Van Wagner's (1977) criteria for the critical minimum spread rates for crown fire initiation (R_i) and active crowning (R_o) for the Anderson (1982) Fuel Model 2 – Timber 2 (grass and understorey) with a canopy bulk density of 0.1 kg m^{-3}, canopy base height of 1.5 m, and a wind reduction factor of 0.2 (Albini and Baughman 1979). The following environmental conditions were held constant: slope steepness, 0%; fine dead fuel moisture, 6%; 10- and 100-h time-lag dead fuel moisture contents, 7 and 8% respectively; live woody fuel moisture content, 75%; live herbaceous fuel moisture content, 75%; and foliar moisture content, 140%. The dashed portion of the Rothermel (1991) curve represents output below the original dataset bounds for rate of spread.

provide a spread rate for passive or intermittent crowning but rather provides a transition to crowning ratio and an active crown fire spread ratio based on the values generated by Eqns 4 *v.* 1 and Eqns 7 *v.* 9 respectively in a manner analogous to Anderson's (1974) index of crowning potential as dictated by the ratio of predicted flame height *v.* an observed or measured CBH.

There is no experimental or sound theoretical evidence for a CFB effect on crown fire rate of spread. Furthermore, general observations of wildfires (e.g. Alexander *et al.* 1991*a*; Cohen *et al.* 2006) and documentation of experimental crown fires (e.g. Van Wagner 1964; Bruner and Klebenow 1979; Burrows *et al.* 1988; Fernandes *et al.* 2004; Stocks *et al.* 2004) indicate that a rather abrupt transition between surface and crown fire regimes is far more commonplace than a gradual transition as implied by a CFB function (Alexander 1998) and as illustrated in Fig. 8.

Use of uncalibrated custom fuel models

Understandably, the use of standard, stylised fuel models (Anderson 1982) in simulation studies examining fuel treatment effectiveness on potential crown fire behaviour limits the extent to which one can gauge the influence of surface fuelbed characteristics on the start and spread of crown fires. Furthermore, there is no empirical proof produced to date to substantiate that by simply increasing the number of fuel models (Scott and Burgan 2005) or reformulating Rothermel's (1972) surface fire rate of spread model (Sandberg *et al.* 2007) would greatly improve matters.

The use of calibrated custom fuel models to represent surface fuelbeds is thus seen by some as a more realistic alternative. However, the use of uncalibrated custom models (e.g. Bessie and Johnson 1995; Battaglia *et al.* 2008; Cheyette *et al.* 2008) can constitute another potential source of underprediction bias. Custom fuel models (Burgan and Rothermel 1984; Burgan 1987) are likely to be unsuccessful when developed without calibrating the predictions or tuning the parameters against field observations of fire behaviour (e.g. Hough and Albini 1978; Cruz and Fernandes 2008).

Studies that have evaluated custom fuel models in horizontally oriented fuels, such as found in conifer litter surface fuelbeds, have identified strong underprediction trends (e.g. Lawson 1972; McAlpine and Xanthopoulos 1989; Hély *et al.* 2001) and in other forest fuel complexes as well (e.g. Burrows 1994; Grabner *et al.* 1997). The effect of this underprediction trend or bias is noticeable in the studies of potential crown fire behaviour that rely on uncalibrated custom fuel models based on field sampling using methods such as those of Brown *et al.* (1982).

Agee and Lolley (2006), for example, predicted a flame height of 1.4 m for their control or untreated ponderosa pine–Douglas-fir fuel complex for simulations based on a 1-h time-lag fuel moisture content of 3% and 6.1-m open wind speeds of 36 km h^{-1}. Comparatively, the Hayman Fire in north-central Colorado (Finney *et al.* 2003; Graham 2003) went from ~5000 to 25 000 ha over a period of 12 h on 9 June 2002 under more moist fuel conditions (FDFM 6–7%) than that of the Agee and Lolley (2006) simulated situation and with a maximum U_{10} of 30–40 km h^{-1} at its peak (Alexander and Cruz 2006).

Similar unrealistic predictions of potential fire behaviour have been reported by others, for example by Page and Jenkins (2007) for lodgepole pine stands infested with mountain pine beetle (*Dendroctonus ponderosae*) in northern and north-eastern Utah and central Idaho (e.g. rates of spread of ~2.0 m min^{-1} for FDFM of 6% and 6.1-m open winds of 50 km h^{-1}) and by Stephens and Moghaddas (2005*a*, 2005*b*) for California mixed-conifer forests (rate of spread of 1.9 m min^{-1} for a 1-h time-lag fuel moisture content of 3.9% and 6.1-m open winds of 22 km h^{-1}). The low spread potential of these custom fuel model predictions explains the need for very dry fuels and high wind speeds in order to induce crown fire activity, as illustrated in Fig. 1*c*.

Other simulation modelling and interpretation issues

Selection of foliar moisture content levels

Van Wagner's (1977) crown fire initiation model is sensitive to FMC (Fuglem and Murphy 1980; Alexander 1988). Changing the FMC from 80 to 140% will almost double the surface fire intensity required for the onset of crowning (Alexander 1988). Within the simulation framework of the fire behaviour modelling systems like NEXUS, this will lead to a large increase in the critical surface fire rate of spread required for crown fire initiation and hence wind speed or fuel dryness (or both) necessary to initiate crown fire activity. Varner and Keyes (2009) recently pointed out that some modellers have assigned FMC 'values without justification or use values that lie on the extremes of published data'.

Scott and Reinhardt (2001) suggested using a constant or default FMC value of 100% as 'a reasonable approach' until better data exist. They also suggested that future research should be directed at compiling existing FMC data and then conducting field research to fill in data gaps. Keyes (2006) concluded on the basis of a review of FMC studies that a single FMC default value 'ignores established differences amongst tree species'. However, he also stated that 'For species lacking published FMC data, a low default value of 90 or 100% remains a prudently conservative assignment'. As a general rule of thumb, an FMC of 90% seems unduly low based on existing information. Chandler *et al.* (1983) regarded crown fire potential as 'high' when the FMC fell below 100%. Some authors have used an FMC of 100% in their simulation studies (e.g. Brown *et al.* 2008; Vaillant *et al.* 2009*b*), whereas others have elected to use much lower values.

Roccaforte *et al.* (2008) used an FMC of 80% in their simulations for ponderosa pine fuel complexes in north-western Arizona without any justification. Although this value might be appropriate for ponderosa pine forests in the south-western US, which typically experience their fire season much earlier in the year, it would be unduly low for other areas in the western US given the seasonal dynamics in FMC found to date in ponderosa pine. Several studies conducted in the western US indicate that the FMC typically ranges from 100 to 120% for 1-year-old ponderosa pine needles between July and September (Philpot and Mutch 1971; Agee *et al.* 2002; Finney *et al.* 2003; Faiella and Bailey 2007), the traditional peak burning period in the western US. Agee *et al.* (2002) and Faiella and Bailey (2007) in turn report FMC in the range of 250–335% and 180–220% respectively for new needle growth. Simulations should consider an aggregate or composite FMC taking into account the differences in moisture contents between new and old needles and the relative proportions of each as well as seasonal changes (cf. Van Wagner 1974). The proportion of new and 1-year and older needle growth is dependent on species, canopy position and site characteristics (Reich *et al.* 1995). Needle longevity for ponderosa pine has been reported to vary between 2 and 4 years in low to moderate elevation sites, but reaching 6 to 9 years in high-stress environments such as arid and alpine habitats (Ewers and Schmid 1981; Richardson and Rundel 1998). Assuming that new needle foliage makes up approximately one-third of the foliage biomass (Van Wagner 1967, 1974) and taking into account the midpoint of Faiella and Bailey's (2007) foliar moisture content ranges for 1-year and older needle foliage (i.e. 110%) and for new growth (i.e. 200%), a nominal FMC value for summertime conditions in ponderosa pine would be ~140%.

It appears the use of low FMC values is becoming commonplace in simulation studies examining potential crown fire behaviour. Stephens and Moghaddas (2005*a*, 2005*b*) used 75% for mixed conifers and Page and Jenkins (2007) used 70% for lodgepole pine. Neither study sampled FMC directly, referenced any previous studies of FMC or otherwise rationalised their FMC selection. Similarly, Stephens *et al.* (2009) used an FMC of 75% without any justification. In their study in ponderosa pine, Ritchie *et al.* (2007) indicated the FMC 'was estimated to be 75% since the Cone Fire burned under dry, north wind conditions following the long, dry summer'. Certainly FMC values this low have occasionally been observed (Keyes 2006). Van Wagner (1993) in fact computed FMC values that average 67% based on a weighting of the moisture contents of old needle foliage and fine, dead woody crown material relative to their separate fuel loadings (Van Wagner 1977). However, such low FMC levels have typically been reported in boreal coniferous tree species just before needle flushing in the spring (Van Wagner 1967, 1974; Fuglem and Murphy 1980).

The National Wildfire Coordinating Group (2008) recently recommended that in the absence of specific information on FMC, one should assume that the FMC is equal to the live woody fuel moisture content input given in BehavePlus, which presently allows for the FMC to vary from 30 to 300%. The moisture content of understorey shrub vegetation can reach 30% (Rothermel 1983) or less and thereby be treated as dead fuel. Existing information on the moisture contents of conifer trees and shrubs sampled at the same time and at the same location does not support this recommendation (e.g. Philpot 1963; Agee *et al.* 2002).

Some authors have selected FMC values below 30% in their application of fire behaviour modelling systems like NEXUS to insect-killed conifer forest stands (e.g. Cheyette *et al.* 2008). Given the empirical nature of Van Wagner's (1977) crown fire initiation model with respect to FMC, applying FMC values any lower than ~70% is not recommended, even if the computer software associated with modelling systems such as NEXUS or BehavePlus allow for it. What is needed is the derivation of a *C* value for use in Eqn 1 based on a carefully documented outdoor experimental fire(s) carried out at very low FMC levels in order to determine crown fire potential in canopy fuel layers comprised largely of fine, dead fuels (e.g. Kuljian and Varner 2010).

Canopy base height criteria

Another input in Van Wagner's (1977) crown fire initiation model, and one that readily favours the occurrence of crowning activity is the CBH. In fact, the natural variation in CBH would allow for a much greater effect on crowning potential than would the observed variation in FMC (Fuglem and Murphy 1980; Alexander 1988).

Van Wagner's (1977) crown fire initiation model has an empirical basis and was parameterised using the mean crown base height of the trees within a red pine plantation experimental plot (Van Wagner 1968). In their simulation studies, Ritchie *et al.* (2007) and Roccaforte *et al.* (2008) used the lowest quartile CBH value. We do not dispute the fact that the lowest quartile could possibly be a better descriptor of a fuel complex's vertical continuity than the average value when applying a physical-based model. Nonetheless, the use of the lowest quartile in the context of Van Wagner's (1977) crown fire initiation model, as represented by Eqn 1, violates one of the fundamental assumptions of this semi-empirical-based model.

Defining what constitutes an effective CBH can admittedly be difficult at times (Williamson 1999; Scott and Reinhardt 2001; Cruz *et al.* 2004; Menning and Stephens 2007; Mitsopoulos and Dimitrakopoulos 2007), especially in forest stands with highly complex vertical fuel distributions. Muraro (1971) was the first to suggest a threshold CBD value (i.e. 0.320 $kg\,m^{-3}$) as a means of quantitatively defining the CBH. Sando and Wick (1972) indicated that 'little is known about the amount of fuel required to support combustion vertically'; they ended up selecting an arbitrary threshold value as well (i.e. 0.037 $kg\,m^{-3}$), which

Williams (1977) simply doubled for his application (i.e. 0.074 kg m^{-3}). Roussopoulos (1978) arbitrarily defined CBH as the height separating the lower 5.0% of the total needle foliage load from the upper 95%.

In determining CBH, the majority of simulation studies examining potential crown fire behaviour have followed Scott and Reinhardt's (2001) definition – i.e. 'the lowest height above ground at which there is a sufficient amount of canopy fuel to propagate fire vertically into the canopy'. Scott and Reinhardt (2001) also selected an arbitrary CBD value (0.011 kg m^{-3}) as the basis for determining CBH. In the intervening years, this approach has come to be an accepted standard with little or no questioning of its origin. Reinhardt *et al.* (2006*a*) readily admit that this threshold value is 'not based on any kind of combustion physics, but it seems to perform well', although they offer no details regarding their performance testing. Thus, the lack of an objectively defined threshold CBD value for determining CBH remains a continuing research need (Alexander 2006).

Meaning of the two crown fire hazard indices

TI and CI values are outputs of NEXUS, FFE-FVS and FMA-Plus but not of the BehavePlus, FARSITE or FlamMap modelling systems. The TI and CI concept were initially introduced by Scott (1998*b*) and later elaborated on by Scott and Reinhardt (2001) for the purpose of assessing crown fire hazard in coniferous forests. Scott (2008) has also extended the methodology to shrubland and open forest woodland fuel complexes. The TI might have been more appropriately termed the 'passive or intermittent crowning index' as torching is more commonly associated with calm to light winds (e.g. Lawson 1972; Dyrness and Norum 1983) and a single tree torching does not make for even a passive crown fire (Forestry Canada Fire Danger Group 1992). Similarly, the CI could have been labelled the 'active or continuous crowning index'.

Although the TI and CI are to be regarded as relative numerical values (Fulé *et al.* 2004; Roccaforte *et al.* 2008; Stephens *et al.* 2009), Scott and Reinhardt (2001) chose to express both indices in terms of the wind speed (in either km h^{-1} or miles h^{-1}) as taken at a height of 6.1 m (20 feet) above open ground per the standard for fire danger rating and fire behaviour prediction used in the US (Deeming *et al.* 1977; Rothermel 1983). Later on, Scott (2006) expressed TI and CI in terms of the 10-m open wind standard used for fire danger rating and fire behaviour prediction in Canada (Lawson and Armitage 2008) and elsewhere (e.g. Australia and New Zealand).

The present practice of calculating TI and CI values by various authors does not readily allow for direct comparison between different studies or assessments. For example, the fuel moisture contents selected are based on one of the various scenarios presented by Rothermel (1991) or on percentile values derived from a fire weather database, each of which has value. Added to this is the fact that both the FDFM (Rothermel 1983) and the NFDRS 1-h time-lag fuel moisture content (Fosberg and Deeming 1971; Deeming *et al.* 1977) are used in computing the two crown-fire hazard indices and they do not result in the same numerical value for a given set of weather conditions. Some authors have failed to specify the associated environmental conditions (e.g. Graves and Neuenschwander 2001; Fiedler *et al.* 2004; Monleon *et al.* 2004; Mason *et al.* 2007) or the description remains vague (e.g. Moghaddas and Craggs 2007). Furthermore, some authors have failed to explicitly specify the FMC applied in their simulations (e.g. Stephens 1998; Monleon *et al.* 2004; Johnson *et al.* 2007; DeRose and Long 2009). The situation is further complicated by the lack of standardisation of the index scale as dictated by the use of two different units of measure (i.e. km h^{-1} and miles h^{-1}) and to a much lesser extent, two different open wind-speed exposure heights (i.e. 6.1 and 10 m). To make matters worse, some authors have now chosen to express TI and CI outputs in m s^{-1} (e.g. Ritchie *et al.* 2007; Finkral and Evans 2008). The basic premise of any index is that it has a consistent scale.

Summary and concluding remarks

The ready availability of a multitude of fire modelling systems in the US in recent years has led to their widespread use in numerous simulation studies aimed at assessing various fire behaviour characteristics associated with specific fuel complex structures, including the propensity for crown fire initiation and spread (McHugh 2006). The results of these simulations, often aimed at evaluating fuel treatment effectiveness, are in turn utilised in a whole host of applications (e.g. Scott 2003; Fiedler *et al.* 2004; Skog *et al.* 2006; Johnson *et al.* 2007; Finkral and Evans 2008; Huggett *et al.* 2008; Johnson 2008; Reinhardt *et al.* 2010) and thus have significant implications for public and wildland firefighter safety, community fire protection, fire management policy-making, and forest management practices. As Cheney (1981) has noted, 'The reality of fire behaviour predictions is that overestimates can be easily readjusted without serious consequences; underestimates of behaviour can be disastrous both to the operations of the fire controller and the credibility of the person making the predictions'.

A critical review of several of these simulation studies, as documented here, has found that the results are often unrealistic for a variety of reasons. It's recognised that the authors of these studies commonly point out the limitations of the models and modelling systems being used through a customary disclaimer concerning the unknowns regarding crown fire behaviour (e.g. Stephens *et al.* 2009). Nevertheless, the fact that the fuel treatment evaluation studies referenced here are based on modelling systems that utilised model linkages for gauging potential crown fire behaviour that have not previously undergone any form of performance evaluation against independent datasets or any empirical observations should be of concern. There appears, however, to be an aversion within an element of the fire research community to do so (e.g. Scott and Reinhardt 2001; Scott 2006; Stephens *et al.* 2009). Nevertheless, such testing is now generally regarded as a basic tenet of modern-day model development and evaluation (Jakeman *et al.* 2006).

Fire modelling systems like NEXUS (Scott and Reinhardt 2001), FFE-FVS (Reinhardt and Crookston 2003), FARSITE (Finney 2004), FMAPlus (Carlton 2005), FlamMap (Finney 2006), and BehavePlus (Andrews *et al.* 2008) that are based on separate implementations or linkages between Rothermel's (1972, 1991) rate of fire spread models and Van Wagner's (1977, 1993) crown fire transition and propagation models have been shown to have a marked underprediction bias when used to assess potential crown fire behaviour. What has been allowed to evolve is a family of modelling systems composed of independently developed, linked models that were never intended to work together, are sometimes based on very limited data, and may propagate errors beyond acceptable limits.

We have documented here the sources of the bias based on empirical evidence in the form of published experimental fire and wildfire datasets. By analysing model linkages and components, we have described the primary sources of such bias, namely: (1) incompatible model linkages; (2) use of surface and crown fire rate of spread models that have an inherent underprediction bias; and (3) reduction in crown fire rate of spread based on use of unsubstantiated CFB functions. The use of uncalibrated, custom fuel models to represent surface fuelbeds is considered another potential source of bias.

Our analysis has also shown that the crown fire initiation underprediction bias inherent in all of these fire modelling systems could possibly be rectified by modifying the method used to calculate the surface fireline intensity for the purposes of assessing crown fire initiation potential, namely using Nelson's (2003) model to estimate t_r in place of Anderson's model (1969). Other modelling systems exist for predicting the likelihood of crown fire initiation and other aspects of crown fire behaviour (Alexander *et al.* 2006; Cruz *et al.* 2006*b*, 2008). Mitsopoulos and Dimitrakopoulos (2007) have, for example, made extensive use of this suite of models in their assessment of crown fire potential in Aleppo pine (*Pinus halepensis*) forests in Greece. These systems are based on models that have undergone performance evaluations against independent datasets and been shown to be reasonably reliable (Cruz *et al.* 2003*b*, 2004, 2006*b*; Cronan and Jandt 2008). Resolving the underprediction bias associated with predicting active crown fire rate of spread inherent in the Rothermel (1991) model would require substantial changes, including a reassessment of the use of a CFB function, if not complete replacement with a more robust empirically developed model (Cruz *et al.* 2005) that has been extensively tested (Alexander and Cruz 2006) or a physically based one that has undergone limited testing (Butler *et al.* 2004).

Alexander (2007) has emphasised that assessments of wildland fire potential involving simulation modelling must be complemented with fire behaviour case study knowledge and by experienced judgment. This review has revealed an overwhelming need for the research users of fire modelling systems to be grounded in the theory and proper application of such tools, including a solid understanding of the assumptions, limitations and accuracy of the underlying models as well as practical knowledge of the subject phenomena (Brown and Davis 1973; Albini 1976; Alexander 2009*a*, 2009*b*).

List of symbols, quantities and units used in equations and text

C, criterion for initial crown combustion ($\mathrm{kW^{2/3}\,kJ^{-1}\,kg\,m^{-5/3}}$)
CBD, canopy bulk density ($\mathrm{kg\,m^{-3}}$)
CBH, canopy base height (m)
CFL, canopy fuel load ($\mathrm{kg\,m^{-2}}$)
CFB, crown fraction burned
CI, crowning index ($\mathrm{km\,h^{-1}}$)
FDFM, fine dead fuel moisture (%)
FMC, foliar moisture content (%)
h, heat of ignition ($\mathrm{kJ\,kg^{-1}}$)
H, low heat of combustion ($\mathrm{kJ\,kg^{-1}}$)
I_B, fireline intensity ($\mathrm{kW\,m^{-1}}$)
I_o, critical surface fire intensity for initial crown combustion ($\mathrm{kW\,m^{-1}}$)
I_R, reaction intensity ($\mathrm{kW\,m^{-2}}$)
r, rate of fire spread ($\mathrm{m\,s^{-1}}$)
R, final rate of fire spread, surface or crown ($\mathrm{m\,min^{-1}}$)
R_a, active crown fire rate of spread ($\mathrm{m\,min^{-1}}$)
R_i, critical surface fire rate of spread for crown fire initiation ($\mathrm{m\,min^{-1}}$)
R_s, surface fire rate of spread ($\mathrm{m\,min^{-1}}$)
R_o, critical minimum spread rate for active crowning ($\mathrm{m\,min^{-1}}$)
R_{10}, predicted surface fire rate of spread for Fuel Model 10 using a 0.4 wind reduction factor ($\mathrm{m\,min^{-1}}$)
S_o, critical mass flow rate for solid crown flame ($\mathrm{kg\,m^{-2}\,min^{-1}}$)
t_r, flame front residence time (s)
TI, torching index ($\mathrm{km\,h^{-1}}$)
U_{10}, 10-m open wind speed ($\mathrm{km\,h^{-1}}$)
w, fuel consumed in the active flaming front and by glowing or smouldering combustion following passage of the front ($\mathrm{kg\,m^{-2}}$)
w_a, fuel consumed in the active flaming front ($\mathrm{kg\,m^{-2}}$)

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