

Interdependencies between flame length and fireline intensity in predicting crown fire initiation and crown scorch height

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Abstract. This state-of-knowledge review examines some of the underlying assumptions and limitations associated with the inter-relationships among four widely used descriptors of surface fire behaviour and post-fire impacts in wildland fire science and management, namely Byram's fireline intensity, flame length, stem-bark char height and crown scorch height. More specifically, the following topical areas are critically examined based on a comprehensive review of the pertinent literature: (i) estimating fireline intensity from flame length; (ii) substituting flame length for fireline intensity in Van Wagner's crown fire initiation model; (iii) the validity of linkages between the Rothermel surface fire behaviour and Van Wagner's crown scorch height models; (iv) estimating flame height from post-fire observations of stem-bark char height; and (v) estimating fireline intensity from post-fire observations of crown scorch height. There has been an overwhelming tendency within the wildland fire community to regard Byram's flame length–fireline intensity and Van Wagner's crown scorch height–fireline intensity models as universal in nature. However, research has subsequently shown that such linkages among fire behaviour and post-fire impact characteristics are in fact strongly influenced by fuelbed structure, thereby necessitating consideration of fuel complex specific-type models of such relationships.

Additional keywords: fire behaviour, fire impacts, fire modelling, first-order fire effects, flame angle, flame depth, flame-front residence time, ignition pattern, stem-bark char height, surface fire.

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Introduction

Fire models or modelling systems are commonly used for simulating fire behaviour characteristics and post-fire impacts or primary fire effects in several wildland fire and fuel management applications (Burrows 1994; Reinhardt *et al.* 2001). In this regard, a recent review on assessing crown fire potential by Cruz and Alexander (2010a) revealed an overwhelming need for the 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.

The purpose of the present communication is to review commonly overlooked assumptions and limitations associated with the inter-relationships among four widely used descriptors of surface fire behaviour and post-fire impacts in wildland fire science and management, namely fireline intensity, flame length, stem-bark char height and crown scorch height (Fig. 1). The motivation behind the development of the relationships depicted in Fig. 1 is the focus of this paper. For the

convenience of the reader, a summary list of the variables referred to in the equations and text, including their symbols and units, is given at the end of this article.

Estimating fireline intensity from flame length

Byram's (1959) fireline intensity (I_B , kW m⁻¹) in its most fundamental form is determined from measurements or observations of fire spread rate and fuel consumption:

$$I_B = H \cdot w_a \cdot r \quad (1)$$

where H is the net 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 linear rate of fire spread (m s⁻¹). This approach to determining I_B has been utilised around the globe in many different fuel complexes for a variety of purposes (e.g. Van Loon 1969; Simard *et al.* 1982; Vasander and Lindholm 1985; Wendel and Smith 1986; Weber *et al.* 1987; Burrows *et al.* 1990; Engle and Stritzke 1995; Fernandes *et al.* 2000; McRae *et al.* 2005;

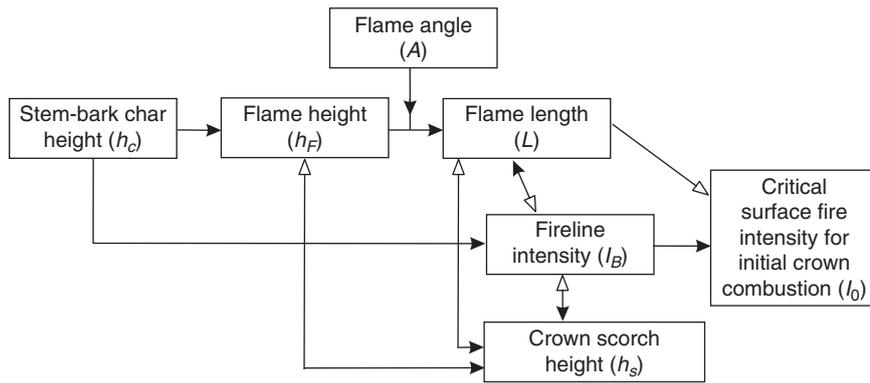


Fig. 1. The inter-relationships involved among commonly used descriptors of surface fire behaviour and fire impacts covered in this review. The solid arrowheads indicate primary relationships established from field data. The hollow arrowheads represent derivations obtained from the primary relationships by solving the equation for the independent variable or using a combination of two primary relationships.

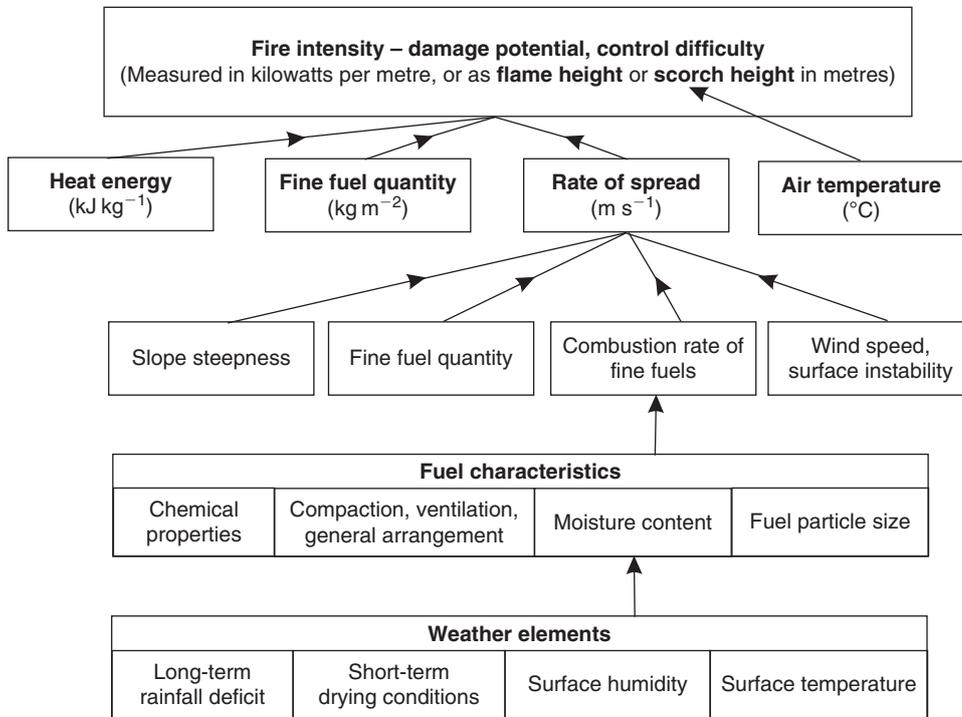


Fig. 2. Schematic diagram illustrating the various elements contributing to fireline intensity and in turn flame height and crown scorch height (after Richmond 1981).

Gould *et al.* 2007; Tanskanen *et al.* 2007; Sağlam *et al.* 2008; Fidelis *et al.* 2010). Accurate determinations of I_B using Eqn 1 are dependent on accurate measurements of w_a and r , with the latter quantity being subject to the greatest amount of variation. For an in-depth look at the calculation of I_B on the basis of Eqn 1, readers are encouraged to consult Alexander (1982).

I_B incorporates several factors of the fire environment into a single number (Fig. 2) useful in both wildfire suppression and prescribed burning (McArthur 1962; Wilson 1988; Hirsch and Martell 1996). I_B has, for example, been correlated with the likelihood of crown fire initiation (Van Wagner 1977; Alexander

1998) and in assessing certain crown fire impacts (Van Wagner 1973), in addition to serving as a direct measure of post-fire tree mortality (Weber *et al.* 1987). I_B can be calculated for any point on the perimeter or edge of a free-burning fire (Catchpole *et al.* 1982, 1992) and any variables related directly to it (e.g. flame zone characteristics, scorch height, crowning potential).

Byram (1959) also indicated that I_B could be calculated for fine, homogeneous fuelbeds (e.g. cured grass) using the following simple relation:

$$I_B = C_R \cdot D \tag{2}$$

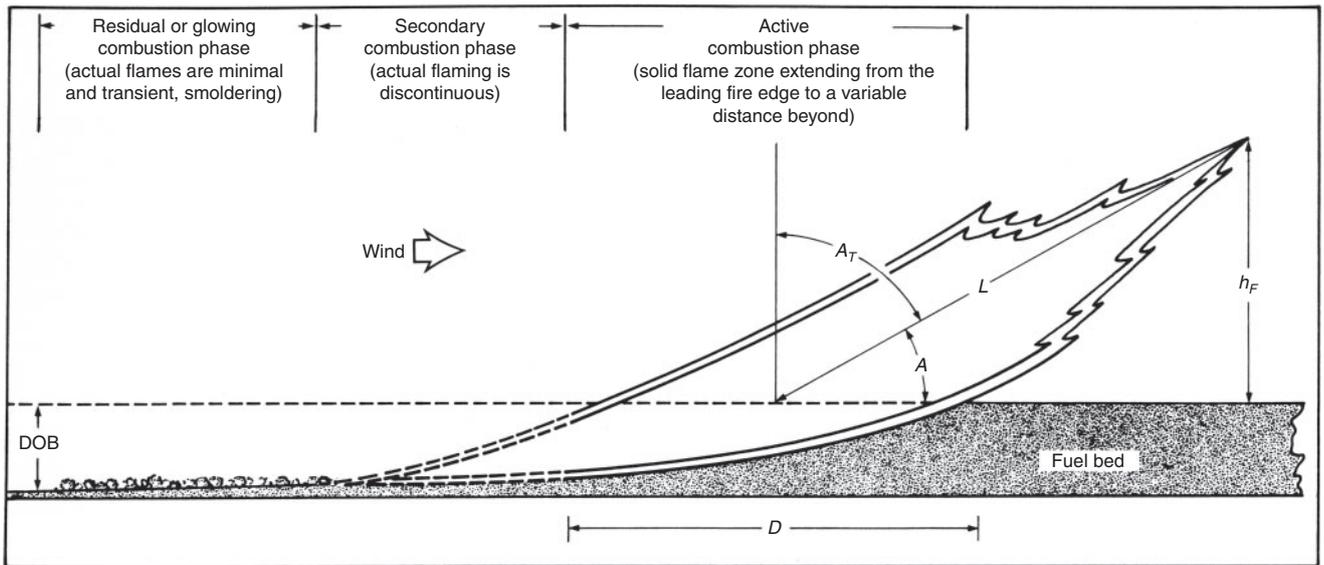


Fig. 3. Cross-section of a stylised, wind-driven surface head fire on level terrain illustrating the energy or heat-release stages during and following passage of the flame front, flame length (L), flame height (h_F), flame angle (A), flame tilt angle (A_T), horizontal flame depth (D), and the resulting depth of burn (DOB) (from Alexander 1982).

where C_R is the combustion rate (kW m^{-2}) and D is the horizontal flame depth (m) as illustrated in Fig. 3. D is in turn represented by the following formula (after Fons *et al.* 1963):

$$D = r \cdot t_r \tag{3}$$

where t_r is the flame-front residence time (s).

In various US fire modelling systems, I_B is calculated from Rothermel's (1972) reaction intensity (I_R , kW m^{-2}) as follows (Albini 1976; Andrews and Rothermel 1982):

$$I_B = I_R \cdot t_r \cdot r \tag{4}$$

In Eqn 4, an estimate of t_r is obtained from the following equation (Anderson 1969):

$$t_r = 189 \cdot d \tag{5}$$

where d is the fuel particle diameter (cm). The Eqn 4 method of calculating I_B yields results comparable with those obtained from Eqn 1 if I_R and t_r are accurately determined. This will only occur in a laboratory setting where I_R is estimated from the knowledge of the rate of weight loss (Rothermel 1972). If Eqn 4 is used in a predictive approach in a field situation, the uncertainty in predicting I_R and t_r will lead to departures from results obtained with Eqn 1. The extent of the differences between Eqns 1 and 4 is mainly a function of the fuelbed characteristics. It has been shown that Eqn 4 yields I_B values consistently lower than those produced by Eqn 1 (Cruz *et al.* 2004; Cruz and Alexander 2010a).

Byram (1959) established an empirical relationship between I_B and flame length^A for surface fires that is widely applied in wildland fire science and management (from Alexander 1982):

$$L = 0.0775 \cdot I_B^{0.46} \tag{6}$$

where L is flame length (m) as illustrated in Fig. 3. In lieu of using Eqn 1 to determine I_B , a common procedure (Rothermel and Deeming 1980) has been to estimate I_B indirectly from field observations or measurements of L in many distinctly different fuel complexes for several years now (e.g. Bevins 1976; Woodard 1977; Chase 1984; Wyant *et al.* 1986; Kauffman and Martin 1989; Zimmerman 1990; Sapsis and Kauffman 1991; Smith *et al.* 1993; Cornett 1997; McCaw *et al.* 1997; Gambiza *et al.* 2005; Kobziar *et al.* 2006; Ansley and Castellano 2007). This estimation is accomplished by using the inverse or reciprocal of Eqn 6 or a similar equation (Table 1) as follows (from Alexander 1982):

$$I_B = 259.833 \cdot L^{2.174} \tag{7}$$

Cain (1984), for example, carried out experimental fires in unthinned and thinned stands of 9-year-old loblolly pine (*Pinus taeda*)–shortleaf pine (*Pinus echinata*) in southern Arkansas, USA. Backfires were employed on the unthinned areas and head fires were used on the thinned plots. Although rate of fire spread was monitored and preburn fuel load sampling undertaken, post-burn fuel sampling was apparently not and as a result I_B was therefore not calculated using Eqn 1. Cain (1984) elected to use the relation represented by Eqn 7 and observations of L made to the nearest 0.3 m by six independent observers to

^AIt is worth calling attention to the fact that conversions of Byram's (1959) original L - I_B equation from imperial units to SI units, as represented here by Eqn 6, have been incorrectly done by several authors in the past (e.g. Wilson 1980; Chandler *et al.* 1983; Barney *et al.* 1984; Windisch 1987; van Wagtenonk 2006).

Table 1. Listing of fireline intensity–flame length relationships presented in Fig. 4

Graph numbers are from Fig. 4. Scientific names for tree and shrub species for fuel type or fuelbed not included in the text are as follows: lodgepole pine, *Pinus contorta*; Douglas-fir, *Pseudotsuga menziesii*; eucalypt, *Eucalyptus* spp.; maritime pine, *Pinus pinaster*; jack pine, *Pinus banksiana*. Variables used are I_B , fireline intensity (kW m^{-1}); L , flame length (m). The reciprocals of the equations given below are presented in the Supplementary material (see http://www.publish.csiro.au/?act=view_file&file_id=WF11001_AC.pdf)

Graph number	Reference	Fuel type or fuelbed	Equation	Experimental basis	Range in L (m)	Range in I_B (kW m^{-1})
1	Byram (1959) ^A	Pine litter with grass understorey	$I_B = 259.833 \cdot L^{2.174}$	Field	0.5–2.1	56–2232
2	Fons <i>et al.</i> (1963)	Wood cribs	$I_B = 22.1 \cdot L^{1.50}$	Laboratory	0.4–1.8	68–510
3	Thomas (1963) ^B	Wood cribs	$I_B = 229 \cdot L^{1.5}$	Laboratory	1.2–5	36–3600
4	Anderson <i>et al.</i> (1966)	Lodgepole pine slash	$I_B = 54.6 \cdot L^{1.54}$	Laboratory	1.1–2.9	781–3438
5	Anderson <i>et al.</i> (1966)	Douglas-fir slash	$I_B = 103.4 \cdot L^{1.5}$	Laboratory	0.8–2.2	619–4645
6	Newman (1974) ^C	Unspecified	$I_B = 300 \cdot L^2$	Rule of thumb	NA	NA
7	Nelson (1980)	Understorey fuels	$I_B = 510.7 \cdot L^{2.0}$	Field	0.1–1.2	21–387
8	Nelson (1980)	Southern USA fuels	$I_B = 703.6 \cdot L^{2.0}$	Field	0.1–2.1	5–3320
9	Clark (1983)	Grasslands (head fire)	$I_B = 1488.7 \cdot L^{1.01}$	Field	0.1–4.2	65–12 602
10	Clark (1983)	Grasslands (backfire)	$I_B = 147.2 \cdot L^{0.57}$	Field	0.3–1.7	41–474
11	Nelson and Adkins (1986)	Litter and shrubs	$I_B = 483.3 \cdot L^{2.03}$	Field and laboratory	0.5–2.5	98–2755
12	van Wilgen (1986)	Fynbos shrublands	$I_B = 402 \cdot L^{1.95}$	Field	1.0–4.5	194–5993
13	Burrows (1994)	Eucalypt forest	$I_B = 245.1 \cdot L^{1.3}$	Field	0.1–10	37–4368
14	Weise and Biging (1996)	Excelsior	$I_B = 367.7 \cdot L^{1.43}$	Laboratory	0.07–2.1	9–820
15	Vega <i>et al.</i> (1998)	Shrublands	$I_B = 141.6 \cdot L^{2.03}$	Field	1.5–6.5	294–6905
16	Catchpole <i>et al.</i> (1998)	Shrublands	$I_B = 454.3 \cdot L^{1.79}$	Field	0.5–18	100–77 000
17	Fernandes <i>et al.</i> (2000)	Shrublands	$I_B = 695.0 \cdot L^{2.21}$	Field	0.2–3.1	12–7605
18	Butler <i>et al.</i> (2004) ^D	Jack pine forest (crown fire)	$I_B = 431 \cdot L^{1.5}$	Field	–	–
19	Fernandes <i>et al.</i> (2009)	Maritime pine forest (head fire)	$I_B = 302.2 \cdot L^{1.84}$	Field	0.1–4.2	30–3527
20	Fernandes <i>et al.</i> (2009)	Maritime pine forest (backfire)	$I_B = 133 \cdot L^{1.38}$	Field	0.1–2.0	7–232

^AContrary to Ryan's (1981) claim that Byram's (1959) L – I_B relation represented by Eqn 6 constitutes a laboratory-derived relationship, according to Lindenmuth and Davis (1973), it 'was partly theoretical and partly empirical, based on some degree on longleaf and loblolly pine real-world research fires, in which Lindenmuth collaborated'. In this regard, Byram (1959) indicates that the data contained in fig. 3.3 of his publication, illustrating the effect of wind speed on rate of fire spread, involved small test fires carried out as part of a prescribed burning study on the Francis Marion National Forest in South Carolina, USA. The surface fuels were considered 'light' with fairly uniform mixtures of grass and pine needles in rather open stands composed of longleaf pine (*Pinus palustris*) and loblolly pine, weighing approximately '0.1 pound per square foot, or ~2 tons per acre'. R. M. Nelson Jr (USDA Forest Service [retired], pers. comm., 2010), a protégé of G.M. Byram during the 60s and early 70s, suggested that perhaps a rough estimate of the experimental range in I_B could be made using the range in r given in fig. 3.3 of Byram (1959) and assuming that $w = 0.5 \text{ kg m}^{-2}$. The range in I_B presented above was in fact determined in this manner, using a value of $H = 18\,000 \text{ kJ kg}^{-1}$. Then the corresponding range in L was determined using Eqn 6.

^BData for Thomas (1963) L – I_B model was extracted from fig. 5 in Thomas (1971), using a value of $H = 18\,000 \text{ kJ kg}^{-1}$.

^CChandler *et al.* (1983, p. 26) is commonly cited as the source for the SI unit version of a simple formula designed for field use as originally put forth by Newman (1974) in imperial units. Newman (1974) limited the chart associated with his rule of thumb to an L of ~12 m.

^DIn this case, L represents the height of the flame above the canopy top (Butler *et al.* 2004, fig. 1). The constant in the equation was derived by Albini and Stocks (1986) on the basis of experimental crown fire 13 documented by Stocks (1987) in a 10-m tall jack pine forest where L was judged to be ~7.25 m and in $I_B = 15\,790 \text{ kW m}^{-1}$.

estimate I_B for both head fires ($L = 0.9 \text{ m}$ and $I_B = 208 \text{ kW m}^{-1}$) and backfires ($L = \sim 0.6 \text{ m}$ and $I_B = 104 \text{ kW m}^{-1}$).

In lieu of using Eqn 7 to directly estimate I_B , some authors (e.g. Burrows 1984) have chosen to determine L from separate observations or measurements of flame height and flame angle (Fig. 3) using the following relation (Ryan 1981; Finney and Martin 1992):

$$L = h_F \cdot (\cos S) / \sin(A - S) \quad (8)$$

where h_F is the flame height (m), A is the flame angle in degrees ($^\circ$) from the horizontal, and S is the slope angle ($^\circ$). L and h_F can only truly be considered equal under no-slope, no-wind (calm) conditions (Brown and DeByle 1987). It is worth noting that some authors have chosen to relate I_B to h_F as opposed to L (e.g. Luke and McArthur 1978; Marsden-Smedley and Catchpole 1995).

Both visual and photographic, including video (Adkins 1995), assessments with or without specially designed standards (Britton *et al.* 1977) have been the most common means of determining flame-front characteristics (Gill and Knight 1991). Ocular estimates are known to vary among observers (Johnson 1982; Andrews and Sackett 1989; Jerman *et al.* 2004). As Rothermel and Reinhart (1983) note, 'It is difficult to measure flame length. The flame tip is a very unsteady reference. Your eye must average the length over a time period that is representative of the fire behaviour'. Even photographic techniques can prove challenging (Clements *et al.* 1983). In this respect, Adkins *et al.* (1994) had this to say about the interpretation of flame measurements:

It is important to recognise that instantaneous images of fire recorded with video (1/30 s) present a different picture of flames than human vision. When viewing a sequence of

video flame images at a slow framing rate, pulsations in flame length can be seen. Flame lengths of lower intensity fires will pulsate at a higher frequency with a small variation in flame length. High intensity fire will pulsate at a lower frequency with greater variation in flame lengths. In both cases an observer will see the flames as being more or less solid shapes with the apparent length being the maximum flame extension through the pulse cycle when viewed at the normal rate; this is attributed to human visual persistence integrating the apparent flame lengths.

As Rothermel (1991) so eloquently points out, 'flame length is an elusive parameter that exists in the eye of the beholder. It is a poor quantity to use in a scientific or engineering sense, but it is so readily apparent to fireline personnel and so readily conveys a sense of fire intensity that it is worth featuring as a primary fire variable' (e.g. Murphy *et al.* 1991). Cheney and Sullivan (2008) have indicated that one should not expect a great degree of precision when it comes to estimating flame heights, suggesting that at least for grass fires, 'flame height estimates in steps of 0.25, 0.5, 1, 2, 4 and >4 m should be adequate for most purposes'.

Eqn 6 is used in several US fire modelling systems as the means of predicting surface fire L . Albini (1976) claimed that Eqn 6 tended to give realistic results over a wide range in I_B , although Byram (1959) considered it a better approximation for low- rather than for high-intensity fires. Subsequent evaluations based on experimental fires conducted in the field and laboratory have shown both close agreement and considerable deviation (Sneeuwjagt and Frandsen 1977; Nelson 1980; Ryan 1981; van Wilgen 1986; Nelson and Adkins 1986; Weise and Biging 1996; Anderson *et al.* 2006). Eqn 6 is most commonly viewed as applicable to surface heading fires, although some investigators, for example Nelson (1980), Clark (1983) and Fernandes *et al.* (2009), have developed separate $L-I_B$ models for backing fires.

Many research and operational users of fire modelling systems have come to view Eqns 6 and 7 as universal in nature, probably as a result of the manner in which they are oftentimes treated in the wildland fire science and management literature (e.g. Rothermel and Deeming 1980; Norum 1982; Simard *et al.* 1989; Johnson and Miyaniishi 1995; Andrews *et al.* 2011) and more recently on certain websites such as *Forest Encyclopaedia Network* (Kennard 2008a). As Nelson and Adkins (1986) point out, this is 'despite the fact that it was developed from a field study in a single fuel type' (see footnote A in Table 1). However, as illustrated earlier by Alexander (1998), at least 19 other $L-I_B$ relationships exist and their outputs vary widely (Fig. 4 and Table 1).

It is worth noting that Byram (1959) indicated that his $L-I_B$ relation represented by Eqn 6 would underpredict L for 'crown fires because much of the fuel is a considerable distance above the ground'. He suggested, on the basis of visual estimates, that 'this can be corrected for by adding one-half of the mean canopy height' to the L value obtained by Eqn 6. Rothermel (1991) suggested using Thomas' (1963) relation to estimate L values for crown fires from I_B . More recently, Butler *et al.* (2004) proposed a specific relation for calculating L of crown fires based on I_B . None of these methods, however, seem to work consistently well based on comparisons made against data obtained from experimental crown fires (Alexander 1998; Cruz and Alexander 2010b).

There are several reasons for the variation in the $L-I_B$ relationships evident in Fig. 4, including the sample size and range in I_B sampled, the manner in which the data were collected (e.g. visual estimates of L v. photographic documentation), assumptions made concerning the calculation of I_B by Eqn 1 (e.g. the method used to derive w_a , value of H used), and the interpretation of the L measurement (because an internationally recognised standard is lacking), and differences in fuelbed structure (Alexander 1998; Anderson *et al.* 2006).

With respect to the latter influence, Methven (1973) made the following comments concerning two experimental fires that exhibited nearly identical I_B levels (i.e. 76 v. 78 kW m⁻¹) carried out at the Petawawa Forest Experiment Station (PFES), Ontario, Canada, in a mature red pine (*Pinus resinosa*)–eastern white pine (*P. strobus*) stand with a balsam fir (*Abies balsamea*) understorey:

The calculated intensities, however, reflect only the average fire conditions and in fact the first fire resulted in some overstorey damage due to localised but fairly widespread peaks of intensity. These were due to a clumped distribution of balsam fir saplings which resulted in live branches close to the ground and a foliage bulk density great enough to carry fire upwards. Wherever these concentrations of fir occurred, therefore, flame heights were raised from less than 30 cm to over 3 m with a much increased energy output per unit ground area and scorching of overstorey crowns. The increase in intensity was not so much a product of the increased fuel loading which amounted to only 0.04 g cm⁻², but to the rate of combustion of this fuel, which, due to its arrangement or bulk density, burned much more rapidly than an equivalent quantity of ground fuel.

Methven (1973) noted that the higher fuel consumption of the first fire compared with the second (0.589 v. 0.465 kg m⁻²) was balanced by the faster rate of spread of the second fire as a result of lower relative humidity, drier litter fuels and a greater in-stand wind speed.

Cheney (1990) has noted that 'the flame characteristics associated with a specific fire intensity are only applicable to fuel types with the same fuel structure characteristics'. He illustrated the significance of this fact by contrasting the physical characteristics of free-burning fires in two widely varying fuel types found in Australia, namely native forest and grasslands, with each exhibiting an $I_B = 7500$ kW m⁻¹:

A grass fire ... will travel at 5 km h⁻¹ in an average fuel of ~3 t ha⁻¹ and will have a flame length of up to 4 m. This fire can be fought directly and there is a 90% probability that the head fire will be stopped by a 5 m wide firebreak ... [A] fire ... in a dry eucalypt forest has very different characteristics. Burning in a 15 t ha⁻¹ forest fuel, the fire will travel at ~1 km h⁻¹ and have flames which extend up through the crowns to a height of perhaps 10 m above the tree tops and more than 30 m above the ground from the surface fire. The fire will be throwing firebrands up to 1 km ahead of the fire and have extensive short-distance spotting and will be unstoppable by any means unless there is a change in some factor influencing fire behaviour.

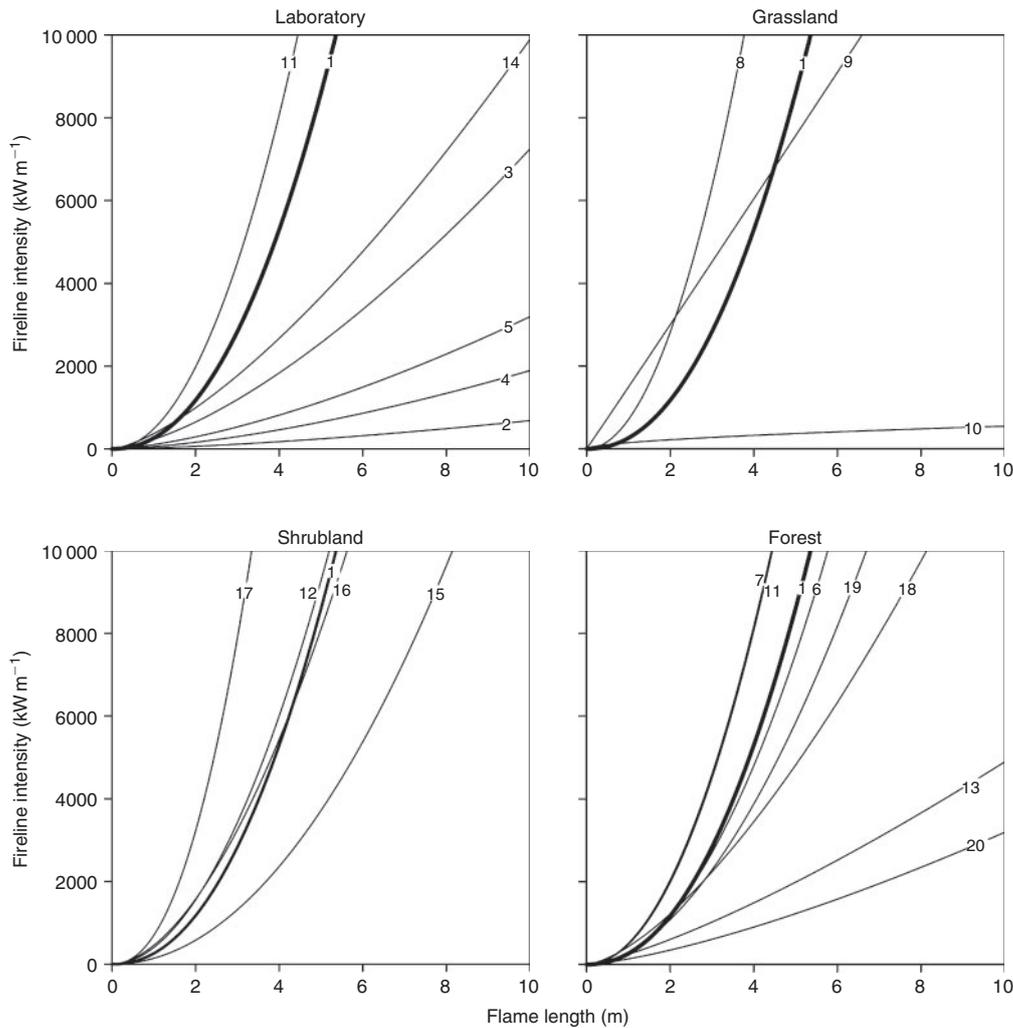


Fig. 4. Graphical representation of Byram's (1959) fireline intensity–flame length relationship (represented by curve 1) and other models reported in the literature. Refer to Table 1 for details of each plotted relationship.

Cheney (1990) concluded that 'Byram's fireline intensity is useful to quantify certain flame characteristics and to correlate with fire effects but should not be used to compare fires in fuel types which are structurally very different'. Thus, one should not necessarily always expect good agreement between observed flame lengths and predictions using Eqn 6 (Brown 1982; Smith *et al.* 1993).

Substituting flame length for fireline intensity in Van Wagner's (1977) crown fire initiation model

Van Wagner's (1977) model for predicting crown fire initiation has been implemented within many fire modelling or decision support systems (Cruz and Alexander 2010a). His model can be represented by the following composite equation:

$$I_0 = (0.010 \cdot \text{CBH} \cdot (460 + 25.9 \cdot \text{FMC}))^{1.5} \quad (9)$$

where I_0 is the critical surface fire intensity for crown combustion (I_0 , kW m^{-1}), CBH is the canopy base height (m),

and FMC is the foliar moisture content (%). The onset of crowning is expected to occur when the surface fire I_B meets or exceeds I_0 .

As first suggested by Alexander (1988), crown fire initiation can also be expressed in terms of L instead of I_B , thereby permitting a ready comparison of CBH *v.* L and thus a rough guide to the likelihood of crowning (Albini 1976). Several authors have chosen to take this approach for their particular applications (e.g. Graham *et al.* 1999; Scott and Reinhardt 2001; Keyes and O'Hara 2002; Hummel and Agee 2003; Scott 2003; Peterson *et al.* 2005; Dimitrakopoulos *et al.* 2007; Battaglia *et al.* 2008; Crecente-Campo *et al.* 2009; Ager *et al.* 2010). To do this, Wilson and Baker (1998), for example, derived a regression equation from the data contained in a tabulation constructed by Agee (1996), in part, using Eqn 9. However, this can be done more directly by simply combining Eqns 6 and 9, for example, resulting in the following formulation:

$$L_0 = 0.0775 \cdot (0.010 \cdot \text{CBH} \cdot (460 + 25.9 \cdot \text{FMC}))^{0.69} \quad (10)$$

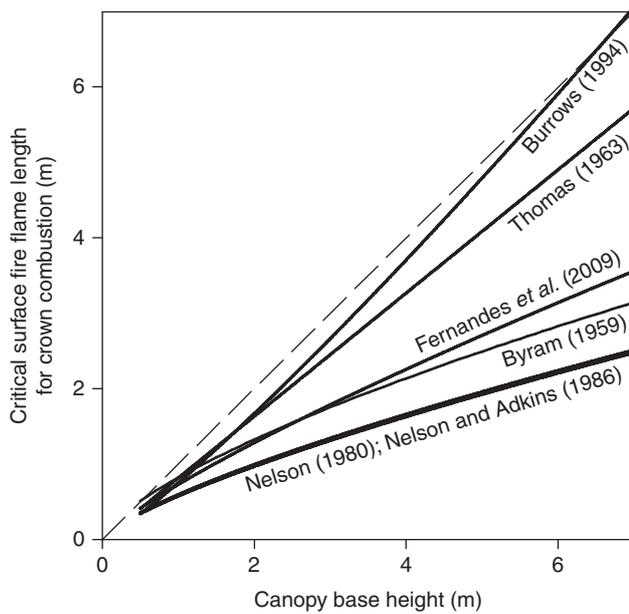


Fig. 5. Critical surface fire flame length for crown combustion in a conifer forest stand as a function of canopy base height according to various flame length–fireline intensity models for forest fuel complexes based on Van Wagner’s (1977) crown fire initiation model. A foliar moisture content of 100% was assumed in all cases. The dashed line represents the boundary of exact agreement between flame length or height and canopy base height.

where L_0 is the critical surface fire flame length for crown combustion (m). Regardless, the formulation represented by Eqn 10 should be viewed as a modelling assumption rather than as an accepted generalisation given the manner in which Van Wagner (1977) derived the empirical constant (0.010) given in Eqn 9 on the basis of I_B determined from Eqn 1 as opposed to observations of L (Cruz and Alexander 2010b). It is worth noting that the flames of a surface fire don’t necessarily have to reach or extend into the lower tree crowns in order to initiate crowning (Fig. 5).

Validity of linkages between the Rothermel (1972) surface fire behaviour and Van Wagner (1973) crown scorch height models

The degree of crown scorch is reflected in the post-fire (within a few days) browning or yellowing of needles or leaves in trees (Fig. 6) or shrubs as a result of heating to lethal temperature during the passage of a surface fire. Crown scorch height is an output in some fuel treatment effectiveness simulation studies in coniferous forests aimed at mitigating crown fire potential (e.g. Johnson 2008; Roccaforte *et al.* 2008). These studies use fire modelling systems like First Order Fire Effects Model (FOFEM) (Reinhardt *et al.* 1997), BehavePlus (Andrews *et al.* 2008), and the Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS) (Reinhardt and Crookston 2003) that have incorporated one or all three of Van Wagner’s

(1973) models^B for predicting the crown scorch height in conifer trees (after Alexander 1985):

$$h_s = 0.1483 \cdot I_B^{0.667} \quad (11)$$

$$h_s = \frac{4.4713 \cdot I_B^{0.667}}{T_L - T_a} \quad (12)$$

$$h_s = \frac{0.74183 \cdot I_B^{0.667}}{(0.025574 \cdot I_B + 0.021433 \cdot U_{1.2}^3)^{0.5} \cdot (T_L - T_a)} \quad (13)$$

where h_s is the crown scorch height (m), T_L is the lethal temperature for crown foliage ($^{\circ}\text{C}$), T_a is the ambient air temperature ($^{\circ}\text{C}$), and $U_{1.2}$ is the in-stand wind speed measured at a height of 1.2 m above ground (km h^{-1}) as specified much later on by C. E. Van Wagner (Canadian Forestry Service, pers. comm., 1984). Thus, quite understandably, Albin (1976) didn’t specify in his publication the wind speed height or exposure in the imperial version of Van Wagner’s (1973) h_s model represented by Eqn 13. As a result, some authors subsequently assumed it was the 6.1-m open wind standard as used in fire danger rating and fire behaviour prediction purposes in the US (Crosby and Chandler 1966) as opposed to the $U_{1.2}$ height and exposure standard used by Van Wagner (1963, 1968) in his field studies. Dieterich (1979), for example, on the basis of data for T_a , I_B and the 6.1-m open wind speed for three different conditions (i.e. ‘high’ daytime, ‘extreme’ daytime and night) associated with the 1973 Burnt Fire in northern Arizona, USA, computed h_s values of 2.4, 4.3 and 1.5 m respectively, using the imperial unit version of the Van Wagner (1973) model represented by Eqn 13 as presented in Albin (1976). Assuming a wind adjustment coefficient or factor of 0.3 (Rothermel 1983), the correct computed h_s values would have instead been 11.2, 19.1 and 5.6 m respectively.

Van Wagner’s (1973) h_s models are based on 13 experimental fires carried out at PFES. Eight of these took place in a red and white pine stand (Van Wagner 1963), two in jack pine, one in northern red oak (*Quercus rubra*), and two in a red pine plantation (Van Wagner 1968).

Van Wagner’s (1973) h_s models include empirical constants based on determining I_B , from pre- and post-burn fuel sampling coupled with observations of fire spread rate, much in the same manner as in parameterising his crown fire initiation model (Van Wagner 1977). The estimation of h_s using one of Van Wagner’s (1973) models that rely on Eqn 4 (e.g. FOFEM, BehavePlus and FFE-FVS) instead of Eqn 1 can potentially lead to substantial underpredictions in h_s (Fig. 7) as a result of underestimating t_r and in turn w_a , as discussed by Cruz and Alexander (2010a).

There has been very little research undertaken to evaluate the performance of the Van Wagner (1973) h_s models when implemented within the context of the US fire modelling systems such

^BIt is worth calling attention to the fact that conversions of Van Wagner’s (1973) three original h_s equations from old metric units to SI units presented here as Eqns 11–13 have been incorrectly done numerous authors in the past (e.g. Chandler *et al.* 1983; Barney *et al.* 1984; Kercher and Axelrod 1984; Keane *et al.* 1989; Johnson 1992; Johnson and Gutsell 1993; Johnson and Miyayishi 1995; Burrows 1997; Gould *et al.* 1997; Dickinson and Johnson 2001).

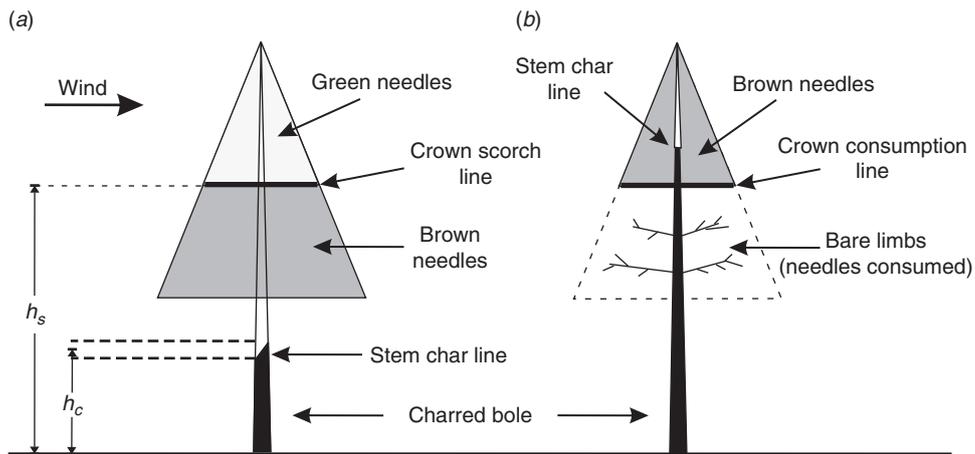


Fig. 6. Variation in direct effects of (a) low- to (b) high-intensity surface fires on tree crowns and stem boles (adapted from Storey and Merkel 1960).

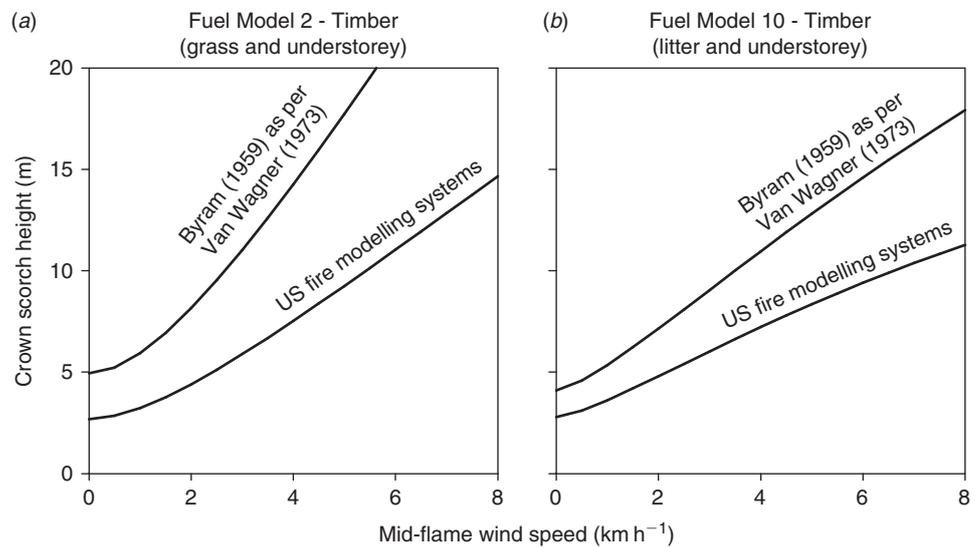


Fig. 7. Crown scorch height as per Van Wagner’s (1973) model as a function of mid-flame wind speed for two US fire behaviour fuel models (Anderson 1982) based on different methods of calculating fireline intensity (i.e. Byram 1959 as per Van Wagner 1973 v. US fire modelling systems). The following environmental 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%; live fuel moisture content, 30%; and ambient air temperature, 25°C. 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).

as FOFEM, BehavePlus and FFE-FVS. Wade (1993) pointed out that the validity of Van Wagner’s (1973) work for use in southern pine stands had yet to be demonstrated and recommended that the BEHAVE system (Andrews and Chase 1989) not be used in young loblolly pine stands ‘where small differences in scorch height can have major consequences’.

Jakala (1995) reported a substantial discrepancy between the observed h_s (15 to 17 m) in the overstoreys of red pine–eastern white pine stands compared with predicted values of h_s (0.3 to 0.9 m) based on the BEHAVE system associated with operational prescribed fires carried out in Voyageurs National Park in

northern Minnesota, USA. The higher-than-expected scorch heights were undoubtedly due to significant amount of torching and subcanopy crown fire activity observed in the understorey (Methven 1973; Methven and Murray 1974; Van Wagner 1977), as shown in Fig. 8. Such episodic cases of vertical fire development are not readily accounted for in BehavePlus or any other fire modelling system.

Knapp *et al.* (2006) conducted experimental fires in masticated surface fuels at two different ponderosa pine (*Pinus ponderosa*) sites in northern California. They observed substantial crown scorch and found that the BehavePlus

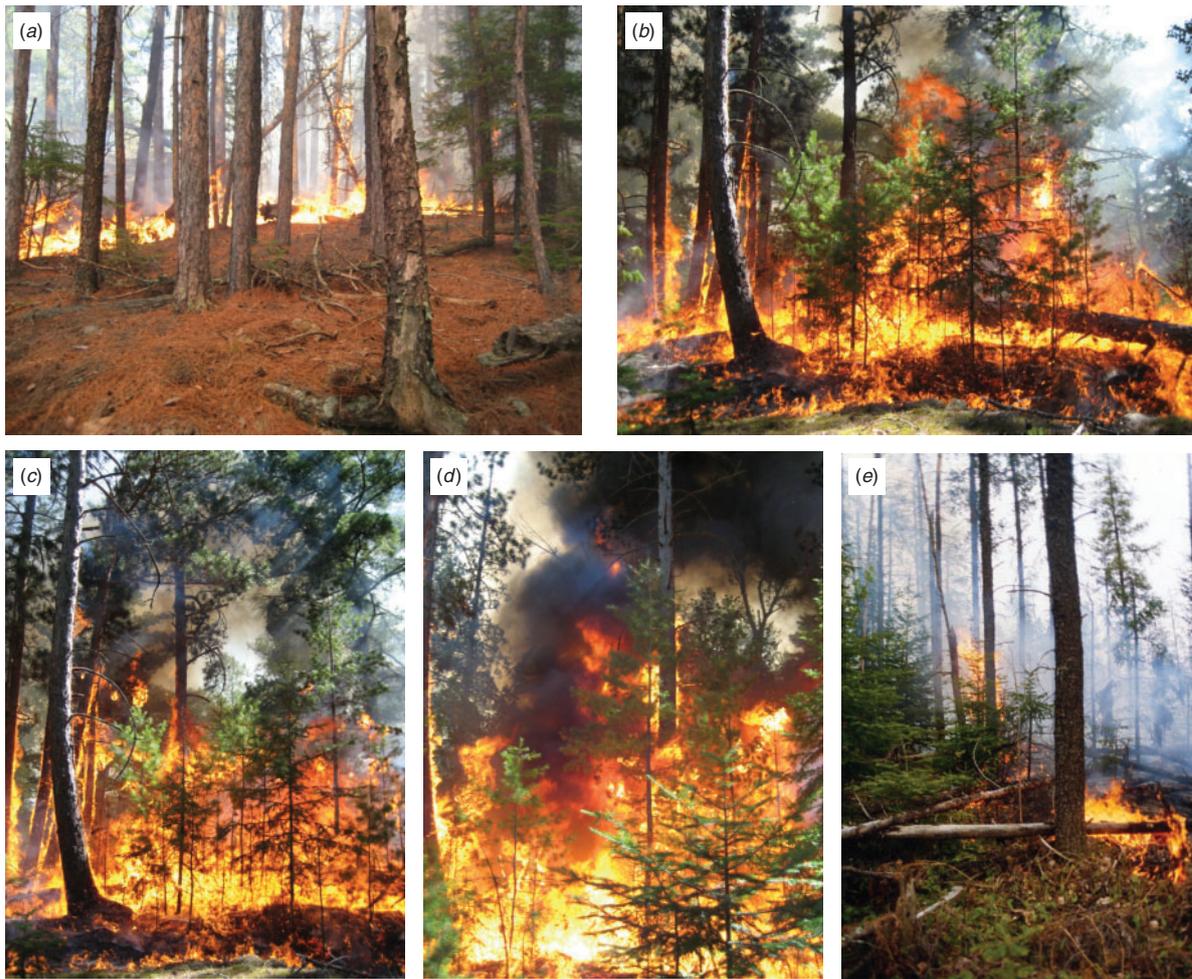


Fig. 8. Transitions from (a) a mild surface fire to (b–d) intense torching and subcanopy crown fire activity, and (e) back to a low-intensity state during prescribed burning operations in a mixed red pine and eastern white pine stand containing pockets of jack pine and understory thickets of balsam fir, Voyageurs National Park, northern Minnesota, USA. Photos courtesy of S. G. Jakala.

modelling system underpredicted h_s on their ‘high’ (0.718 kg m^{-2}) and ‘low’ (0.261 kg m^{-2}) woody fuel load sites by factors of approximately four and two times. Part of the under-prediction bias noted by Knapp *et al.* (2006) could conceivably be attributed to the use of field observations of L to estimate I_B from Eqn 7 and in turn to compute h_s from one of the Van Wagner (1973) h_s models (i.e. Eqns 11–13). The higher than expected h_s levels could also have been due to the way the masticated fuels burned, with considerable heat being produced even though flame length was apparently suppressed by the compactness of the fuelbed (E. E. Knapp, USDA Forest Service, pers. comm., 2010).

Albini (1976) was the first to suggest that by using Eqn 7, L could be used in place of I_B to estimate h_s and accordingly constructed various graphical representations of Van Wagner’s (1973) h_s models for field use (e.g. Norum 1977; Reinhardt and Ryan 1988). In this manner, given a value for L , the resultant I_B output can be utilised as input in any one of the Van Wagner (1973) h_s models. Using Eqns 7 and 13, Reinhardt and Ryan



Fig. 9. Wind-driven surface fire in a Scots pine (*Pinus sylvestris*) stand in central Siberia illustrating the increased flame height on the lee-side of tree stems well above the general level of the advancing flame front in between trees (from McRae *et al.* 2005).

(1988) prepared a nomogram for predicting h_s from L and T_a , assuming $U_{1,2} = 8 \text{ km h}^{-1}$. Like the prediction of crown fire initiation represented by Eqn 10, these types of decision aids should be regarded as a modelling assumption rather than as an accepted generalisation.

The height of crown scorch has been linked directly to h_F (e.g. Cheney *et al.* 1992). Gould (1993), for example, derived the following relationship from a graph included in McArthur's (1962) prescribed burning guide for eucalypt forests in Australia:

$$h_s = 5.232 \cdot h_F^{0.756} \quad (14)$$

A 6-to-1 h_s/h_F ratio is a commonly cited rule of thumb in prescribed burning in Australia and South Africa (e.g. Van Loon and Love 1973; Byrne 1980; de Ronde 1988; de Ronde *et al.* 1990). This generalised guideline apparently was first introduced by McArthur (1962) for eucalyptus forests and has since been reinforced by the comment of Luke and McArthur (1978) that 'Flame height has a considerable bearing on scorch height. Broadly speaking, flames associated with prescribed burning are likely to cause scorch with a zone equivalent to six times flame height'. Subsequent evaluations have shown that there are limitations to this appealing rule of thumb (Gould 1993; Beck 1994; Burrows 1994, 1997), possibly due to excluding the effect of important factors such as T_a , t_r , wind speed and stand structure characteristics, and thus it may not be appropriate for particular fuel types and geographical areas.

Estimating flame height from post-fire observations of stem-bark char height

Another commonly used post-fire indicator of surface fire behaviour in forest fires is the height of charring or blackening of the outer bark from exposure to flaming combustion (Fig. 6) on the lower portion of tree boles (Davis and Cooper 1963; Cain 1984; Weber *et al.* 1987). As Burrows (1984) points out, this technique works best for non-fibrous-barked trees (Loomis 1973; Brown and DeByle 1987), where the bark cannot ignite and be consumed well above the height of the original flames.

Several authors (e.g. McNab 1977; Nickles *et al.* 1981; Waldrop and Van Lear 1984; Hély *et al.* 2003) have inferred h_F directly from post-fire observations of the stem-bark char height (h_c , m). In some of these studies, the authors have in turn estimated I_B using Eqn 7, assuming that h_F is approximately equal to L ; as Agee (1993) notes, 'If the bark is flammable or has heavy lichen cover, the height of bark char may exceed flame height ... resulting in overestimates of fireline intensity' such as would be the case with many eucalypt tree species, for example (Luke and McArthur 1978; Gould *et al.* 2007). In taking this approach, one of the fundamental assumptions being made by the authors, whether explicitly stated or not, is that there is little or no wind effect, even though this may not actually be the case (i.e. calm conditions such that h_F and L are essentially the same). This would be a reasonably valid assumption for the fire described by McNab (1977) that spread at $\sim 0.3 \text{ m min}^{-1}$, reflecting very light, in-stand wind conditions.

Cain (1984) contended that there was no documentation available to show that h_c provides an accurate estimate of either L or h_F for that matter and accordingly set out to correlate L to h_c . It is unfortunate that no measurements or observations were made of h_F . Measurements of h_c were made to the nearest 0.03 m. Cain (1984) found that h_c underestimated L by 47% for head fires ($h_c = 0.48 \text{ m}$) and 40% for backfires ($h_c = 0.36 \text{ m}$). Considering that the experimental fires were undertaken with open ground level winds of 8 km h^{-1} and associated spread rates of 1.8 and 0.4 m min^{-1} for heading fires and backing fires, this result is not unexpected.

In wind-driven surface fires, bole charring will be higher on the leeward side of a tree stem owing to the taller flame heights (Gill 1974) as illustrated here (Fig. 9) and in Cheney and Sullivan (2008, fig. 9.1) for example. As Gutsell and Johnson (1996) explain, 'When a fire passes by a tree, its height increases on the tree's leeward side because of the occurrence of two leeward vortices. The flame height increases in the vortices because the turbulent mixing of fuel and air is suppressed. The flow of gaseous fuel in the vortices becomes greater than the rate of mixing with the air, and hence there is an increased height along which combustion can occur'. The formation of the leeward vortices that in turn control the height of the flames is viewed as a function of wind speed and the diameter of the stem bole (Gutsell and Johnson 1996).

The measurement of h_c may involve both the minimum and maximum heights (Van Wagner 1963; Dixon *et al.* 1984; Hély *et al.* 2003), the maximum height (Cain 1984; USDI National Park Service 2003), or an average (Menges and Deyrup 2001; Kennard 2008b). As wind speed increases, the ratio between the leeward and windward heights will increase (Inoue 1999); this would of course be accentuated by an increase in slope steepness. In experimental fires carried out in maritime pine in Portugal involving h_F values of 0.2 to 3.5 m, Fernandes (2002) found that the maximum leeward h_c in heading fires was just slightly greater than the observed h_F ($h_c = 1.1 \times h_F$) and for backing fires, h_F was a little less than half the h_c ($h_c = 2.5 \times h_F$). In support of Gutsell and Johnson's (1996) theoretical analysis, Fernandes (2002) found an increase in the difference between leeward and windward h_c with increasing wind speeds. The ratio between leeward or maximum and windward or minimum h_c varied between 2.0 at low wind speeds (i.e. in-stand winds $< 2 \text{ km h}^{-1}$) and 6.0–7.0 for in-stand winds of $\sim 10 \text{ km h}^{-1}$. Van Wagner (1963) reported ratios between 2.0 and 3.0 in underburning of red and white pine stands with in-stands winds of $< 5.0 \text{ km h}^{-1}$.

A better method to the general approach described above is to simply use Eqn 8 to calculate L and, if one wishes, I_B as well. This is done again by assuming that h_F and h_c are equivalent or that an established ratio exists. The value of A can then be obtained directly from either ocular estimates made in the field or by measurements derived from photography. An estimate of A can also be inferred from models based on h_F or I_B and wind speed as inputs (e.g. Albin 1981; Nelson and Adkins 1986; Alexander 1998) as undertaken for example by Hély *et al.* (2003).

One of the major problems with using tree stems as passive sensors for determining h_F for a fire as a whole, assuming they were relatively uniformly distributed, is the fact that the fuels

around a tree bole tend to be drier and greater in quantity than those found between trees (Wotton *et al.* 2005), thereby introducing a bias. In this regard, it might be more appropriate to consider estimating I_B directly from measurements of h_c (e.g. Tozzini and Soares 1987; Batista and Soares 1994), at least for surface fires, based on a previously established relationship between the two variables for a given fuel complex. The following equation, for example, is adapted from a relation derived for a jack pine stand in eastern Ontario, Canada, by Weber *et al.* (1987) based on five experimental fires ($R^2 = 0.76$):

$$I_B = \exp\left(2.64 + \frac{h_c}{0.36}\right) \quad (15)$$

The ranges in I_B and h_c were 70 to 3800 kW m⁻¹ and ~0.3 to 2.0 m. Alternatively, I_B could also be related to the height to the 'crown consumption line' (Fig. 6) or leaf-char height (i.e. the height above ground of blackened leaves) as Williams *et al.* (1998) was able to accomplish in a grassland-eucalypt savannah fuel complex in the Northern Territory of Australia.

Estimating fireline intensity from post-fire observations of crown scorch height

Norum (1975, 1976) was the first to suggest using Van Wagner (1973)'s work to estimate I_B from field observations of h_s . In this regard, he used the inverse or reciprocal of Eqn 12:

$$I_B = \left(h_s - \frac{T_L - T_a}{4.4713}\right)^{1.5} \quad (16)$$

In applying Eqn 16, it is assumed that winds are relatively light and in the same general range ($U_{1,2} = \sim 2.3$ to 4.7 km h⁻¹)^c as experienced in the experimental fires conducted by Van Wagner (1973). Norum (1975, 1976), like Van Wagner (1973), assumed $T_L = 60^\circ\text{C}$ although it varies according to the plant or crown component (needle foliage *v.* bud) and by species as well as by the duration of heating (Hare 1961; Peterson and Ryan 1986; Alexander 1998; Michaletz and Johnson 2006).

Over the years, other investigators (e.g. Woodard 1977; Cain 1984; Harmon 1984) have also estimated I_B from h_s using Eqn 16 or by simply using the inverse or reciprocal of Eqn 11:

$$I_B = 17.49 \cdot h_s^{1.5} \quad (17)$$

In addition to the same assumption as Eqn 16 regarding wind conditions, in using Eqn 17, it is assumed that ambient air temperatures are in the same general range ($T_a = \sim 23.0$ to 31.5°C) as experienced in the experimental fires conducted by Van Wagner (1973). Cain (1984), for example, carried out his experimental burning under stronger surface winds ($U_{1,2} = 8$ km h⁻¹) and cooler conditions ($T_a = 13.9^\circ\text{C}$) than those of

Van Wagner's (1973) study. Both of these factors would have had the effect of reducing h_s owing to the entrainment of colder air into the buoyant plume (Byram 1958) and reducing the plume angle (Van Wagner 1973). From Eqn 17, he calculated I_B of the heading fires to be 66 kW m⁻¹ on the basis of the observed h_s of 2.4 m based on measurements made to the nearest 0.03 m. This is in contrast to $I_B = 208$ kW m⁻¹ calculated from Eqn 7 using the observed L . According to Eqn 17, h_s would have had to be 5.2 m to have matched this I_B level. In the case of the backing fires, I_B was estimated to be 31 kW m⁻¹ on the basis of the observed h_s of 1.5 m, in contrast to 104 kW m⁻¹ based on the observed L , dictating that h_s would have had to have been 3.3 m. Cain (1984) acknowledged that these discrepancies could be due to differences in fuel and weather conditions between his study and that of Van Wagner (1973) but not that his application of Eqn 7 might be inappropriate owing to differences in fuelbed structure.

The use of Eqn 17 has become quite popular in post-fire investigations of wildfires in recent years (e.g. Omi and Martinson 2002; Cram *et al.* 2006). Of course, this method is not valid for tree crowns that have received no scorch or conversely, if a tree is fully scorched (Cain 1984; Tozzini and Soares 1987; Burrows 1994).

Although Van Wagner (1973) was the first to formally publish h_s models that utilised I_B as an input, like the various $L-I_B$ relationships that exist, many other similar models have since been developed for distinctly different fuel complexes, as illustrated earlier on by Alexander (1998). The differences evident in Fig. 10 could be due to several factors in addition to differences in fuel complex characteristics, number of fires and range in I_B sampled (Alexander 1998), namely: (i) the manner in which I_B was determined (e.g. using Eqn 1 *v.* Eqn 7); (ii) the season or time of year the burning took place (e.g. dormant period or growing season), including the level of drought stress; (iii) the environmental conditions under which the fires took place with respect T_a and $U_{1,2}$ as previously discussed; (iv) the criteria used to define crown scorch (e.g. bud kill *v.* foliage scorching); and (v) the firing technique or ignition pattern employed; the Saveland *et al.* (1990) relation, for example, is based on a combination of single and multiple strip head fires as well as backfires. Considering the well-known effect of T_a on h_s (Byram 1958), users may want to consider utilising the models listed in Table 3 in lieu of their counterparts presented in Table 2.

The h_s models of Van Wagner (1973) represented by Eqns 11, 12 and 13 are applicable to a single, heading line-source fire and not to backing fires, as some authors like Cain (1984) have attempted to do. The significance or appreciation of this is often overlooked by users of Van Wagner's (1973) work. For example, the elaborate process-based model developed by Michaletz and Johnson (2006) for predicting h_s fails to acknowledge that the firing technique or ignition pattern used in prescribed burning is not only a practical consideration but is also a controlling variable (Sackett 1968; Johansen 1987; Wade and Lunsford 1988; Weir 2009) and that their model is only applicable to a single, heading line-source fire. Line-source fires can also be

^cMiller (1994) indicates that the range in $U_{1,2}$ was 3.4 to 4.8 km h⁻¹ but this is clearly in error for the lower bound according to Fig. 3 in Van Wagner (1973).

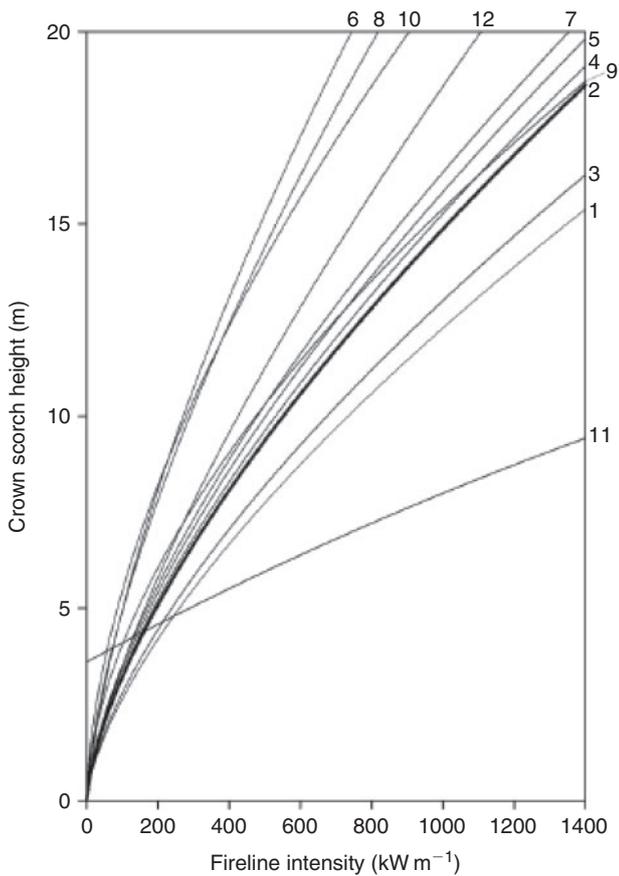


Fig. 10. Graphical representation of Van Wagner's (1973) crown scorch height–fireline intensity relationship (represented by curve 2) and other models reported in the literature. Refer to Table 2 for details of each plotted relationship.

ignited so as to back or flank into the wind. A multipoint source or grid ignition pattern is also commonly employed (Johansen 1984), wherein each fire increases its spread rate and intensity with elapsed time (McAlpine and Wakimoto 1991). Variations in these basic firing techniques or ignition patterns have been devised specifically with the idea of limiting the degree of crown scorch (e.g. Sackett 1969; Weatherspoon *et al.* 1989).

Depending on the spacing between lines and their timing, a strip head-fire ignition pattern can lead to higher than expected scorch heights as a result of the enhanced upward convective activity resulting from the junction zone effects created by the merging lines of fires (McArthur 1962; Sackett 1972; Rothermel 1985; McRae 1996). In such cases, increased flame heights up to three times their previous level can be expected (Cheney 1981). Large clumps or 'jackpots' of surface and ladder fuels can also lead to increases in convective activity, but as point sources of, as opposed to line sources of heat energy (McRae *et al.* 1994; Gould *et al.* 1997).

All of the h_s models listed in Tables 2 and 3 were developed for level terrain. Presently, there is no way to make an adjustment for the effect of slope steepness on h_s predictions (Andrews and Chase 1989). On a slope, flames tend to attach themselves,

resulting in hot convective gases and smoke flowing up the slope close to the surface (Fig. 11) rather than rising more vertically as would be the case on flat terrain (Cheney and Sullivan 2008), in which case the height of crown scorch will be less than model predictions. However, 'further up the slope at a ridge line where the convection column breaks from the surface and rises, the concentration of hot gases will scorch higher than expected on the flat' (Rothermel 1985).

The firing technique or ignition pattern employed by Jakala (1995), consisting of strip head fires placed ~ 20 m apart, might approximate the Van Wagner (1973) situation, although the torching experienced in the understorey balsam fir thickets no doubt contributed to localised crown scorch of the overstorey canopy (Methven 1973; Methven and Murray 1974; Van Wagner 1977). However, there is a great deal less certainty with the ignition pattern used by Knapp *et al.* (2006), involving strip head fires placed ~ 2 m apart. Because strips were ignited at irregular intervals, it was not possible to determine how much of the area burned in a backing fire *v.* a heading fire (E. E. Knapp, USDA Forest Service, pers. comm., 2010).

Implications for wildland fire research and management

Many of the mathematical relationships commonly used in characterising wildland fire behaviour and post-fire impacts such as L and h_s are empirical in nature. Their bounds of application are easily visualised (although seldom acknowledged) by users in their simulation modelling studies. Few universally accepted, physically based models for predicting flame zone characteristics and post-fire impacts exist. Albin (1981) and Michaletz and Johnson (2006) constitute two such exceptions. Without field validation of these models, however, it is uncertain as to what the bounds or limits of their application are.

The summaries of fireline intensity–flame length and crown scorch height–fireline intensity relationships presented in this paper (Figs 4, 10) illustrate the inherent variation due to differences in fuel complex structure, type of fire propagation or spread regime, burning conditions (e.g. T_w , $U_{1,2}$), slope steepness, and in some cases, the ignition pattern. The acknowledgment of these differences go a long way in explaining the apparent incongruent outcomes reported by Cain (1984), a widely cited paper on the inter-relationships between I_B , L , h_c and h_s . It should be apparent that inferring h_F or L and in turn I_B from h_c is fraught with challenges.

Treating Byram's (1959) $L-I_B$ model or its reciprocal (i.e. Eqns 6, 7) as simple generic relationships is not appropriate. Application of these models needs to be done more judiciously than has been the case in the past. In this respect, authors should not only document their modelling assumptions but justify their use of specific fire behaviour models. The same suggestion applies to any of the Van Wagner (1973) h_s models or their reciprocals (e.g. Eqns 11 and 17 or 12 and 16). It should be clear that there is considerable likelihood of error propagation when, for example, observations of h_F and A are used to calculate L , which in turn is used to estimate I_B for correlation with h_s (Fig. 1). It might very well be far better to simply relate h_s directly to h_F (e.g. Cheney *et al.* 1992; Gould 1993).

Table 2. Listing of crown scorch height–fireline intensity relationships presented in Fig. 10 and their reciprocals

Graph numbers are from Fig. 10. Scientific names for tree species for stand or fuel type not given in Table 1 or in the text are as follows: slash pine, *Pinus elliottii*; Caribbean pine, *Pinus caribaea*; radiata pine, *Pinus radiata*; coast redwood, *Sequoia sempervirens*; jarrah, *Eucalyptus marginata*. Variables used are h_s , crown scorch height (m); I_B , fireline intensity (kW m^{-1})

Graph number	Reference	Stand or fuel type	Equation $h_s = a \cdot I_B^b$	Equation $I_B = a \cdot h_s^b$	Range in h_s (m)	Range in I_B (kW m^{-1})
1	McArthur (1971) ^A	Slash and Caribbean pine	$h_s = 0.1226 \cdot I_B^{0.667}$	$I_B = 23.26 \cdot h_s^{1.5}$	2.1–20	50–2500
2	Van Wagner (1973)	Red pine, white pine, jack pine and northern red oak	$h_s = 0.1483 \cdot I_B^{0.667}$	$I_B = 17.49 \cdot h_s^{1.5}$	2–17	67–1255
3	Cheney (1978) ^A	Eucalypt forest	$h_s = 0.1297 \cdot I_B^{0.667}$	$I_B = 21.38 \cdot h_s^{1.5}$	1.8–17	50–1500
4	Luke and McArthur (1978) ^A	Eucalypt forest	$h_s = 0.1523 \cdot I_B^{0.667}$	$I_B = 16.80 \cdot h_s^{1.5}$	<10	<500
5	Burrows <i>et al.</i> (1988) ^B	Radiata pine thinning slash	$h_s = 0.1579 \cdot I_B^{0.667}$	$I_B = 15.92 \cdot h_s^{1.5}$	2.5–10	26–455
6	Burrows <i>et al.</i> (1989)	Radiata pine wildings	$h_s = 0.248 \cdot I_B^{0.667} - 0.41$	$I_B = 8.09 \cdot (0.41 + h_s^{1.5})$	1.5–8.8	22–225
7	Saveland <i>et al.</i> (1990)	Ponderosa pine	$h_s = 0.063 \cdot I_B^{0.667}$	$I_B = 63.24 \cdot h_s^{1.5}$	1–26	16–857
8	Finney and Martin (1993) ^C	Coast redwood	$h_s = 0.228 \cdot I_B^{0.667}$	$I_B = 9.18 \cdot h_s^{1.5}$	2.7–20.1	40–1833
9	Burrows (1994)	Jarrah forest – spring	$h_s = 0.28 \cdot I_B^{0.58}$	$I_B = 8.976 \cdot h_s^{1.724}$	1.2–8.1	45–439
10	Burrows (1994)	Jarrah forest – summer	$h_s = 0.36 \cdot I_B^{0.59}$	$I_B = 5.65 \cdot h_s^{1.69}$	1.1–24	37–1140
11	Williams <i>et al.</i> (1998)	Grassland–eucalypt savanna	$h_s = 21.2 - 17.6 \cdot \exp(0.000287 \cdot I_B)$	$I_B = -34843 \cdot \log(0.057 \cdot (22.2 - h_s))$	3–22	100–18000
12	Fernandes (2002)	Maritime pine head fire	$h_s = 0.125 \cdot I_B^{0.724}$	$I_B = 17.675 \cdot h_s^{1.38}$	1.8–14.1	63–1954

^AThe h_s – I_B equations for McArthur (1971), Cheney (1978) and Luke and McArthur (1978) were derived by Alexander (1998) from the graphs presented in these publications assuming that h_s varies with the 2/3 power of I_B as per Van Wagner (1973). The data range in these cases reflects the minimum and maximum values given on the graphs.

^BThe h_s – I_B equation was derived by Alexander (1998) from the data presented in Burrows *et al.* (1988).

^CMeasurements of h_f and A were used to calculate L . I_B was in turn estimated from L using the I_B – L models of Byram (1959) and Nelson and Adkins (1986).

Table 3. Crown scorch proportionally constant (k) and experimental range in ambient air temperatures (T_a) associated with some of the studies listed in Table 2 that have also developed crown scorch height (h_s)–fireline intensity (I_B) models of the form $h_s = k \cdot I_B^{0.667} / (60 - T_a)$ and in turn $I_B = (h_s - (60 - T_a)/k)^{1.5}$

Reference	k	Range in T_a ($^{\circ}\text{C}$)
Van Wagner (1973)	4.47	23–31
Burrows <i>et al.</i> (1988)	8.95 ^A	14–20
Burrows <i>et al.</i> (1989)	8.74 ^B	16–25
Saveland <i>et al.</i> (1990)	2.66	13–29
Finney and Martin (1993)	8.92 ^B	16–24
Fernandes (2002)	5.05	2–20

^AAs derived by Alexander (1998) from data contained in Burrows *et al.* (1988).

^BAs estimated by Michaletz and Johnson (2006).

Closing remarks

The precautions and insights provided in this article will hopefully inspire new wildland fire behaviour-related research, thereby leading to improvements in both simulation modelling and related field studies. This review would not be complete, however, without a word on the spatial and temporal variability in fire behaviour and post-fire impacts (Van Loon and Love 1973; Taylor *et al.* 2004; McRae *et al.* 2005). Model predictions are quite often quoted to a decimal place, implying considerable precision in the outcome. It is easy to forget that any empirical model for predicting fire behaviour and fire effects carries with it

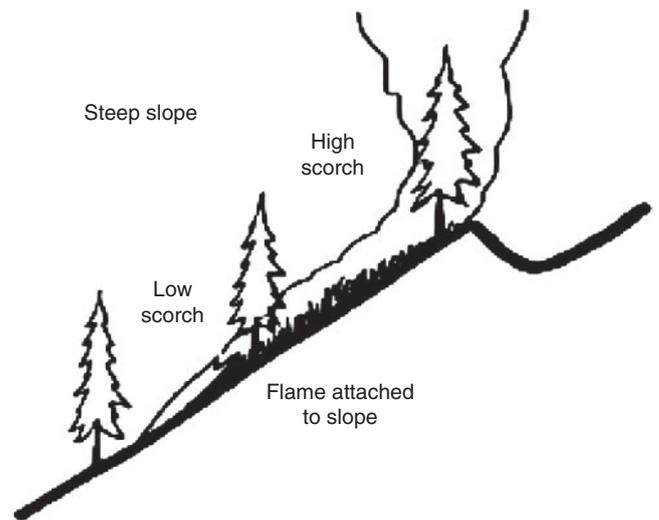


Fig. 11. Schematic diagram illustrating conditions that lead to crown scorch on steep slopes (from Rothermel 1985).

an inherent degree of variation. This variation is further exacerbated by the variance associated with the heterogeneity in fuelbed structure and the capricious nature of surface winds, for example. Thus, the more uniform the environmental conditions, the more idealised the situation that can be visualised. The value of utilising a Monte Carlo-based ensemble method to predict wildland fire behaviour has recently been demonstrated (e.g. Cruz

and Alexander 2009; Cruz 2010). This approach provides for error bounds to be established and a probabilistic output of the uncertainties associated with model predictions, and allows one to capture the variability in bi-modal fire propagation systems, such as encountered when a fire transitions back and forth between surface and ladder fuels or surface and understorey fuels and overstorey crown fuels (i.e. intermittent crowning).

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

A , flame angle ($^{\circ}$)
 A_T , flame tilt angle ($^{\circ}$)
 CBH, canopy base height (m)
 C_R , combustion rate (kW m^{-2})
 d , fuel particle diameter (cm)
 D , horizontal flame depth (m)
 DOB, depth of burn (cm)
 FMC, foliar moisture content (%)
 h_c , stem-bark char height (m)
 h_F , flame height (m)
 h_s , crown scorch height (m)
 H , low heat of combustion (kJ kg^{-1})
 I_B , fireline intensity (kW m^{-1})
 I_0 , critical surface fire intensity for crown combustion (kW m^{-1})
 I_R , reaction intensity (kW m^{-2})
 k , crown scorch proportionally constant (dimensionless)
 L , flame length (m)
 L_0 , critical surface fire flame length for crown combustion (m)
 r , rate of fire spread (m s^{-1})
 S , slope angle ($^{\circ}$)
 t_r , flame front residence time (s)
 T_a , ambient air temperature ($^{\circ}\text{C}$)
 T_L , lethal temperature for plant material ($^{\circ}\text{C}$)
 $U_{1.2}$, in-stand wind speed measured at a height of 1.2 m above ground (km h^{-1})
 w_a , fuel consumed in the active flaming front (kg m^{-2})

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Supplementary material

Interdependencies between flame length and fireline intensity in predicting crown fire initiation and crown scorch height

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Estimating flame length from fireline intensity

Table 1 presents equations for calculating fireline intensity (I_B , kW m⁻¹) from flame length (L , m). Reciprocals of these equations can be useful for estimating flame length where fireline intensity is known. To facilitate estimation of flame length, Table S1 contains reciprocals of the equations from Table 1.

Table S1. Reciprocals of the fireline intensity–flame length equations in Table 1

Reference	Equation
Byram (1959)	$L = 0.0775 \cdot I_B^{0.46}$
Fons <i>et al.</i> (1963)	$L = 0.127 \cdot I_B^{0.667}$
Thomas (1963)	$L = 0.02665 \cdot I_B^{0.46}$
Anderson <i>et al.</i> (1966) – lodgepole pine slash	$L = 0.074 \cdot I_B^{0.651}$
Anderson <i>et al.</i> (1966) – Douglas-fir slash	$L = 0.0447 \cdot I_B^{0.67}$
Newman (1974)	$L = 0.0577 \cdot I_B^{0.50}$
Nelson (1980) – understorey fuels	$L = 0.04425 \cdot I_B^{0.50}$
Nelson (1980) – Southern US fuels	$L = 0.0377 \cdot I_B^{0.50}$
Clark (1983) – grasslands (head fire)	$L = 0.00015 \cdot I_B^{1.75}$
Clark (1983) – grasslands (backfire)	$L = 0.000722 \cdot I_B^{0.99}$
Nelson and Adkins (1986)	$L = 0.0475 \cdot I_B^{0.493}$
van Wilgen (1986)	$L = 0.0075 \cdot I_B^{0.46}$
Burrows (1994)	$L = 0.0147 \cdot I_B^{0.767}$
Weise and Biging (1996)	$L = 0.016 \cdot I_B^{0.7}$
Vega <i>et al.</i> (1998)	$L = 0.087 \cdot I_B^{0.493}$
Catchpole <i>et al.</i> (1998)	$L = 0.0325 \cdot I_B^{0.56}$
Fernandes <i>et al.</i> (2000)	$L = 0.0516 \cdot I_B^{0.453}$
Butler <i>et al.</i> (2004)	$L = 0.0175 \cdot I_B^{0.667}$
Fernandes <i>et al.</i> (2009) – maritime pine (head fire)	$L = 0.045 \cdot I_B^{0.543}$
Fernandes <i>et al.</i> (2009) – maritime pine (backfire)	$L = 0.029 \cdot I_B^{0.724}$