Graphical aids for visualizing Byram's fireline intensity in relation to flame length and crown scorch height

by Martin E. Alexander¹ and Miguel G. Cruz²

ABSTRACT

Summary graphs depicting 20 individual flame length–fire intensity relationships grouped by four different fuel complex types or settings (forest, grassland, shrubland, and laboratory) and 12 individual fireline intensity–crown scorch height relationships for two broad forest stand types (conifer- and eucalypt-dominated) are presented. Users will find these quick reference visual aids of value in a wide variety of fire management applications.

Key words: crown fire, fire behaviour, fire impact, fire management, fire suppression, flame dimensions, prescribed fire, surface fire, wildland fire

RÉSUMÉ

Cet article présente des graphiques récapitulatifs décrivant 20 relations indépendantes entre la hauteur des flammes et l'intensité du feu regroupées selon quatre différents types de combustibles ou d'environnements (forêt, prairie sèche, prairie boisée et laboratoire) et 12 relations entre l'importance du coupe feu et la hauteur des cimes brûlées pour deux grands types de peuplement (à dominance de conifères ou d'eucalyptus). Ces guides visuels et rapides à consulter seront d'une grande valeur pour les utilisateurs dans un grand nombre de situations de contrôle de feux.

Mots clés : feu de cime, comportement du feu, impact du feu, contrôle des feux, extinction des feux, dimensions des flammes, brûlage dirigé, feu de surface, feu hors contrôle

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Introduction

We recently published a review article examining the interrelationships amongst four widely used descriptors of surface fire behaviour (Fig. 1) and post-fire impacts in wildland fire science and management (Alexander and Cruz 2012a); namely, fireline intensity, flame length, stem-bark char height, and crown scorch height—terms that should be part and parcel of a forester's lexicon (Beck *et al.* 2005). This note will serve to compliment that effort by offering graphical representations of the flame length–fireline intensity and fireline intensity–crown scorch height relationships as listed in Alexander and Cruz (2012a,b). Users will find the graphical aids presented here of value in support of a wide variety fire management decision-making activities.

Flame Length–Fireline Intensity Relationships

Byram (1959) defined fireline intensity as the rate of heat energy release per unit time per unit length of fire front, regardless of the depth or width of the zone of active flaming combustion (Alexander 1982). The formula to compute fireline intensity is as follows:

$$[1] \quad I_B = H \cdot w_a \cdot r$$

where I_B is Byram's fireline intensity (kW/m), H is the net low heat of combustion (kJ/kg), w_a is the fuel consumed in the active flame front (kg/m²), and r is the linear rate of fire spread (m/sec).

Byram (1959) derived the following relationship based on observations of flame length (L , m) (Fig. 2a) and computations of I_B using eq. [1] and measurements of w_a and r coupled with an assumed value for H (from Alexander 1982):

$$[2] \quad L = 0.0775 \cdot I_B^{0.46}$$

A list of 19 other $L-I_B$ equations or models is presented in Alexander and Cruz (2012b). The experimental data range in the variables associated with these equations is given in Alexander and Cruz (2012a). The graph represented by Fig. 3 has now in turn been produced from the equation list. The variation evident in Fig. 3 is due in large part to differences in fuel complex structure and type of fire as well as the measurement methodologies as discussed by Alexander and Cruz (2012a).

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Fig. 1. Surface heading fire in a 15-year-old unthinned and unpruned maritime pine (*Pinus pinaster* Aiton) plantation (2×1 m spacing) in the Viseu region of central Portugal on February 1, 2007. Dominant trees are 12 m in height with a diameter-at-breast height of 15 cm. PHOTO BY PAULO M. FERNANDES, UNIVERSIDADE DE TRÁS-OS-MONTES E ALTO DOURO, VILA REAL, PORTUGAL.

Fig. 2. Schematic diagram illustrating the flame length (L) dimension of a wind-aided (a) surface fire and (b) crown fire on level terrain and (c) crown scorch height (h_s) in the overstorey tree canopy resulting from the upward heating by the flames following passage of the advancing flame front. Flame length and flame height are equivalent in the case of no wind and no slope.

Fireline Intensity-Crown Scorch Height Relationships

Above any forest fire burning on the ground surface, providing it is sufficiently intense and the live overstorey canopy is not too high, there will be a height to which the tree foliage will be scorched by hot gases rising upwards from the flames (Byram 1958). Van Wagner (1973) was the first to formally link crown scorch height (h_s , m) (Fig. 2c) to I_B based on a series of experimental fires carried out at the former Petawawa Forest Experiment Station near Chalk River, Ontario (from Alexander 1982):

$$[3] \quad h_s = 0.1483 \cdot I_B^{0.667}$$

Taking the inverse or reciprocal of equation [3] allows one to estimate I_B from h_s (from Alexander and Cruz 2012a):

$$[4] \quad I_B = 17.49 \cdot h_s^{1.5}$$

A list of 11 other I_B - h_s equations or models, including the experimental data range in the variables associated with these equations, is presented in Alexander and Cruz (2012a). The graph represented by Fig. 4 has now in turn been produced

Fig. 3. Graphical representation of Byram's (1959) flame length – fireline intensity relationship for pine litter with grass understorey (represented by curve **1**) and other models (field and laboratory based) reported in the literature by four broad fuelbed types according to the listings given in Alexander and Cruz (2012b): **2** – wood cribs (Fons *et al.* 1963); **3** – wood cribs (Thomas 1963); **4** – lodgepole pine slash (Anderson *et al.* 1966); **5** – Douglas-fir slash (Anderson *et al.* 1966); **6** – general rule of thumb (Newman 1974); **7** – understorey fuels (Nelson 1980); **8** – southern USA fuels (Nelson 1980); **9** – grasslands-head fire (Clark 1983); **10** – grasslands-backfire (Clark 1983); **11** – litter and shrubs (Nelson and Adkins 1986); **12** – fynbos shrublands (van Wilgen 1986); **13** – eucalypt forest (Burrows 1994); **14** – excelsior (Weise and Biging 1996); **15** – shrublands (Vega *et al.* 1998); **16** – shrublands (Catchpole *et al.* 1998); **17** – shrublands (Fernandes *et al.* 2000); **18** – 10-m tall jack pine forest-crown fire (Butler *et al.* 2004); **19** – maritime pine-head fire (Fernandes *et al.* 2009); and **20** – maritime pine-backfire (Fernandes *et al.* 2009). All of the relationships, unless otherwise specified, are for heading surface fires. The relationships represented by curves **7** and **11** are very similar but not truly identical.

from that equation list. The variation shown in Fig. 4 is a reflection of the tree species, stand structure and surface fuel characteristics as well as measurement methodologies (Alexander and Cruz 2012a). However, the levels of ambient air temperature and in-stand wind speed associated with the experimental fires involved in the model development can also have a significant influence (Alexander and Cruz 2012a).

Fire Management Applications

There will be occasions where there is a requirement to calculate L from I_B , where I_B is in turn provided for by some other model or system (e.g., Cruz *et al.* 2008, Wotton *et al.* 2009), for matters other than predicting crown fire initiation (Keyes and O'Hara 2002) or perhaps even crown scorch height (Norum 1977). For example, L is a required input in comput-

Fig. 4. Graphical representation of Van Wagner's (1973) fireline intensity – crown scorch height relationship for red pine-white pine-jack pine-northern red oak forests (represented by curve **1**) and other models reported in the literature according to the listings given in Alexander and Cruz (2012a): **2** – slash and Caribbean pine (McArthur 1971 based on adaptation by Alexander 1998); **3** – eucalypt forest (Cheney 1978 based on adaptation by Alexander 1998); **4** – eucalypt forest (Luke and McArthur 1978 based on adaptation by Alexander 1998); **5** – radiata pine thinning slash (derived by Alexander 1998 based on data presented in Burrows *et al.* 1988); **6** – radiata pine wildings (Burrows *et al.* 1989); **7** – ponderosa pine (Saveland *et al.* 1990); **8** – coast redwood (Finney and Martin 1993); **9** – jarrah forest-spring (Burrows 1994); **10** – jarrah forest-summer (Burrows 1994); **11** – grassland-eucalypt savanna (Williams *et al.* 1998); and **12** – maritime pine (Fernandes 2002). All of the relationships are for heading surface fires.

ing maximum potential spotting distance in non-forested fuel types such as grass, shrubs and slash (Albini 1983, Morris 1987), in estimating the width of firebreak needed to stop a fire of a given intensity level in the absence of severe spotting (Byram 1959; Wilson 1988; Tymstra *et al.* 2010), in gauging firefighter safety zone size (Butler and Cohen 1998), and in judging an initial attack fire suppression effectiveness (Murphy *et al.* 1991, Hirsch *et al.* 1998).

Similarly, there could be a need to estimate I_B from post-burn observations or measurements of h_s (Wilson and Ferguson 1986, Martinson and Omi 2008). As Agee (1993) notes, "It is often desirable to reconstruct fireline intensity in post-fire monitoring to compare fire effects in different fires or different areas of a single fire."

Fig. 3 and Fig. 4 can be used jointly to help relate h_s to L in prescribed underburning (McRae *et al.* 1994). Regardless of the situation, fire management practitioners will find the graphical aids presented here (Fig. 3 and Fig. 4) a handy ref-

erence to quickly visualizing the relationships between flame length and fireline intensity as well as crown scorch height in relation to fire intensity for a number of fuel complexes.

For many years now, equations [2] and [3] have been viewed as largely generic in nature (Alexander and Cruz 2012a). It should be clear from the graphical aids presented here that fuel complex structure needs to be considered in mathematical relationships involving fireline intensity and that the development of single, standardized $L-I_B$ and I_B-h_s models is not possible. The graphs also give some sense of the variability that exists for broad fuel or vegetation types.

It is worth noting that all of the models displayed in Fig. 3 and Fig. 4 are for surface fires (Fig. 1) except for the crown fire $L-I_B$ model of Butler *et al.* (2004) where L constitutes the free flame above the overstorey tree canopy (Fig. 2b). When this value is added to the average stand height it provides for an approximation of the height of the nearly vertical "wall of flame" typically associated with crown fires (Fig. 2b).

While the present compilation of relationships represented by Fig. 3 and Fig. 4 cover a considerable range in vegetation and fuelbed characteristics, there are undoubtedly gaps in the coverage (e.g., masticated fuel treatments, blowdown, matted leaf litter) that presumably will be addressed by fire research in the future. In the meantime, how might one best go about selecting the most applicable $L-I_B$ model from the present list of 20 choices or the most appropriate I_B-h_s model from the 12 different options?

In some cases, a good or fair match will readily exist. For example, maritime pine can be used for ponderosa pine or other long-needle pines. In other situations, judgement will be required based on comparisons to fuel properties like size, shape, texture, quantity, and arrangement, including the presence or absence of ladder fuels. This will require the user to consult the original source documents. In other cases the differences in L or h_s within a certain range of I_B maybe inconsequential. Extrapolation between relationships will also undoubtedly be required in some instances. Comparisons between estimates of I_B and observed L or h_s values may also prove useful. Rothermel (1991), for example, recommended using Thomas's (1963) model for predicting the flame length of crown fires based in part on general observations and subsequent comparisons.

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