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Field-based generic empirical flame length–fireline intensity relationships for wildland surface fires

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ABSTRACT

Background. Fireline intensity (I_f) quantifies the power of the fireline and is used for various purposes. I_f and flame length (L_f) are relatable to each other using an empirical power function, which has been considered fuel-specific. **Aims.** The aim of this study was to develop generic $L_f - I_f$ relationships based on a robust set of field head fires from the literature ($n = 797$) conducted worldwide in forest, shrubland and grassland. **Methods.** L_f was determined from the base of the fuel bed for comparability across fires in different fuel heights, and the effect of vegetation type was examined. **Key results.** Although I_f could be approximately described using the same function in forest and shrubland, fires in grassland required different fitted coefficients; we speculate that fuel particles' surface area-to-mass ratio is the main fuel metric influencing flame structure. **Conclusions.** Fuel-generic relationships for I_f are reasonably accurate and encompass the high end of surface fire I_f. Previous studies suggested their unviability, most likely because of limitations in the number of observations and data ranges, difficulty in objectively measuring L_f and variation in L_f definition. **Implications.** The generic relationships presented in this work will be of interest for research and management purposes when specific models for I_f are non-existent.

Keywords: combustion metrics, fire behaviour, fire management, forest, fuel metrics, grassland, head fires, shrubland, surface area-to-mass ratio.

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Introduction

Fireline intensity (I_f), also referred to as frontal fire intensity (usually in units of kW m^{-1}), quantifies the energy released per unit time (power) by unit fireline length of a vegetation fire and has been described as 'the single most valid characteristic of a fire's general behaviour' (Alexander 1982, p. 350). I_f is useful for various ends, namely the appraisal of aboveground fire effects (e.g. Weber *et al.* 1987), or as a guide for fire suppression difficulty (Hirsch and Martell 1996). By definition (Byram 1959), I_f is calculated as

$$I_f = H\,w\,R \tag{1}$$

where H, w and R are, respectively, fuel heat yield, fuel load consumed by flaming combustion and fire spread rate. Byram (1959) established flame length (L_f) as a power function of I_f. The reciprocal of the relationship, or of empirically derived relationships of the same form, has been subsequently widely used to estimate I_f from L_f (Alexander and Cruz 2012):

$$I_f = a\,L_f^b \tag{2}$$

where a and b are fitted coefficients. The simplicity of Eqn 2 is appealing, but the existence of a wide variety of reported relationships has led to the assumption that its coefficients must be fuel-dependent (Alexander 1982; Cheney 1990; Alexander and Cruz 2012). Yet, the usual practice, namely in North-American fire modelling systems

(Andrews 2018), is to assume a single $L_f - I_f$ equation for general use regardless of fuel bed nature and structure.

Some of the existing $L_f - I_f$ models for surface head fires have been derived from laboratory data in both natural fuel beds, like slash (Anderson *et al.* 1966), and artificial fuels, like wood cribs (Fons *et al.* 1963; Thomas 1963) and excelsior (Weise and Biging 1996). However, the majority of available $L_f - I_f$ relationships were obtained from field fires in forest (Byram 1959; Nelson 1980; Burrows 1994; Fernandes *et al.* 2009), shrubland (Van Wilgen 1986; Catchpole *et al.* 1998; Vega *et al.* 1998; Fernandes *et al.* 2000) and grassland (Nelson 1980; Clark 1983). A visual assessment of all plotted functions (Alexander and Cruz 2012) for field head fires seems to suggest that grassland requires shorter flames to produce the same I_f of fires in forest and shrubland, but the extant wide variation among the fitted relationships is not conclusive in this regard.

A proper evaluation of the feasibility of using generic $L_f - I_f$ relationships is impaired mostly by three limiting factors. Firstly, both laboratory and field fire measurements have important shortcomings: (1) laboratory experiments have scale issues and are limited in terms of the maximum L_f values that can be obtained; and (2) in field fires, it is usually difficult to accurately assess vegetation metrics and the amount of fuel consumed. Secondly, individual studies are usually: (1) limited in terms of the number of observations; and (2) developed for specific fuel complexes and thus limited in terms of the range in fuel structure descriptors. Thirdly, estimates of average L_f can be very subjective because: (1) flame pulsation causes great variations in instantaneous L_f (Byram and Nelson 1970); and (2) L_f is often assessed by visual estimation, which is known to vary among observers (Johnson 1982).

An additional difficulty in evaluating L_f is that many studies do not specify if the measure is taken from the fuel bed base or from its top (e.g. Fons *et al.* 1963; Anderson *et al.* 1966; Clark 1983). This typically makes little difference in litter fuels because fuel height (h) is usually small when compared with L_f but has the potential to cause great discrepancies in deeper fuel complexes, such as tall shrubland. Whether it is possible or not to derive generic $L_f - I_f$ relationships, an appropriate comparison between fuel-specific functions can only be made if L_f is assessed from the base of the fuel bed, as proposed for example by Rothermel and Deeming (1980). Because L_f is a visual manifestation of the combustion rate, i.e. the amount of fuel burnt per unit time (Byram 1959) and thus of the released thermal power, we must consider all visible flame, including within the fuel bed, to correspond as accurately as possible with the actual combustion rate. Fig. 1 shows the flame geometry of a wind-driven head fire (Rossa and Fernandes 2018*a*), as considered in the present study; favourable slope produces a similar flame configuration (Dupuy *et al.* 2011), because its effect is equivalent to that of wind in tilting fire towards the unburned fuel.

The $L_f - I_f$ relationship of Byram (1959) is currently almost universally used. However, it was seemingly developed from a limited number of fires ($n = 41$) in a single fuel type (pine forest with a grassy understorey), and the validity of its widespread application has never been properly evaluated. $L_f - I_f$ functions, suitable for a wide diversity of fuel complexes, would thus be of great interest for both scientific and operational purposes. Here we have developed such relationships, based on a large number of well-documented worldwide experimental fires in forest, shrubland and grassland.

Methods

Data sources

The BONFIRE worldwide database (Fernandes *et al.* 2020) was the source of data for this study. BONFIRE comprises outdoors fire behaviour characteristics and the corresponding fire environment descriptors gathered from an exhaustive search of the peer-reviewed and grey literature. Included are data pertaining to the forward spread of individual experimental fires in any vegetation type, as well as from prescribed fire operations and wildfires, but excluding fires initiated by exceedingly narrow ignition lines (<2-m length) or featuring potential interaction between fire fronts.

Each BONFIRE record includes data reliability ratings as per Cheney *et al.* (2012) and was attributed a generic vegetation type (forest, shrubland, grassland), a broad fuel type (e.g. long needle conifer) and a fuel complex defined by the fuel layer(s) carrying the fire (e.g. litter + shrub). The compiled records were considered eligible for our analysis if they pertained to an experimental study represented by a minimum of three fires and if rated with high reliability. After applying these restrictions, we identified just 797 fires for which all variables required by the analysis (w, R and L_f) were available. Nonetheless, this BONFIRE subset spans worldwide and covers a diverse array of fuel types and fuel complexes, as can be seen in Table 1, where the original data sources are indicated.

Fireline intensity and flame length

I_f was computed as per Eqn 1. H can be obtained as a fraction of fuel heat of combustion determined in a bomb calorimeter, accounting for the heat losses occurring during outdoors combustion, like moisture vaporisation, incomplete combustion and radiative heat losses by the convection column (Byram 1959). We retrieved average values for the heat of combustion of forest and shrubland fuels (22 111 kJ kg^{-1}) and grass fuels (19 850 kJ kg^{-1}) from Susott (1982). We considered that the fraction of the heat of combustion assumed to be H was 0.75, which was roughly the value calculated by Byram (1959) and Nelson and Adkins (1986, 1988). As a result, we obtained $H = 16\,583$ kJ kg^{-1}

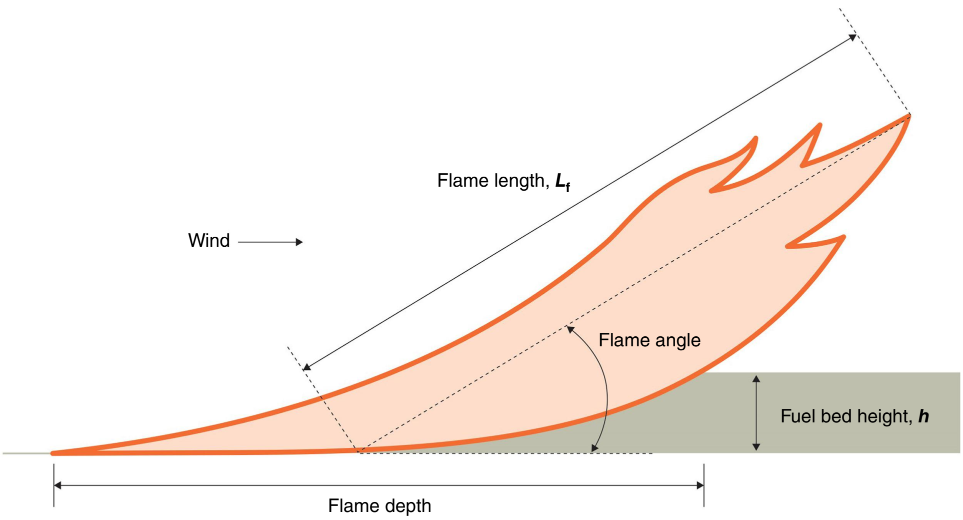

Fig. 1. Schematic representation of the cross-section of a wind-driven head fire showing flame length (L_f) as considered in the present study, i.e. assessed along its axis from the tip of the flame to the base of the fuel bed.

for forest and shrubland fuels and $H = 14\,888$ kJ kg^{-1} for grass fuels.

Quantifying precisely how much fuel is consumed in the active flame zone of a field fire is nearly impossible. We therefore adopted the common and reasonable assumption that w equals surface fine (<6 mm thickness) fuel load (live and dead) and that most of the consumption of coarser fuels (when existent) occurs in the form of residual or glowing combustion and, therefore, has a minor contribution to the flame generated at the fire front (Alexander 1982).

Although L_f is typically measured above the fuel bed by default (Alexander 1982), Eqn 2 uses L_f measured from the base of the fuel bed, being assessed from the tip of the flame along its axis (Fig. 1). Because in many fires flame angle was not provided, we estimated L_f by adding fuel height h, instead of h/sin(flame angle), to the reported flame length. With increasing wind or slope, flames tilt towards the unburned fuel, flame angle diminishes and L_f becomes progressively underestimated. However, because L_f is expected to increase, the error also becomes less significant. The number of fires was unevenly distributed across the I_f range, with many more low-I_f fires. For this reason, for each vegetation type, we ordered the experiments by increasing I_f, grouped the fires into 100 kW m^{-1} bins ([0–100], [100–200], etc.) and averaged L_f and I_f within those groups to obtain a better distribution of data points across the I_f range, and thus more reliable fits.

Data analysis

Coefficients a and b were determined by fitting the log-transformed form of Eqn 2 by least-squares (e.g. Cheney *et al.* 2012). We fitted Eqn 2 using the full dataset and examined the effect of vegetation type (forest, shrubland, grassland) as a categorical variable (significant at $P < 0.05$) to probe for the possibility of using the same coefficients for more than one fuel complex, and we proceeded with model development based on the results from this analysis. The bias from model back-transformation was corrected according to Snowdon (1991).

Predictions were evaluated based on the coefficient of determination (R^2), root mean square error (RMSE), mean absolute error (MAE) and mean bias error (MBE). Residuals were checked for normality with the Shapiro–Wilk test ($P > 0.05$) or, when significance was below the threshold value, for approximate normality by visually inspecting their histograms. Independence from predicted values was evaluated by correlation analysis. We determined the reciprocals of the developed models (L_f as a function of I_f). We also plotted Byram's (1959) $L_f - I_f$ relationship with the present models for a graphical comparison.

Results

Parameter ranges and data points

The wide span in fuel bed structure and flame dimensions inherent to the dataset can be inferred from the h and L_f ranges (Table 1): 0.1–1.0 m and 0.1–8.9 m for forest ($n = 406$), 0.16–4.8 m and 0.5–16.7 m for shrubland ($n = 207$) and 0.04–0.9 m and 0.2–6 m for grassland ($n = 184$). Wind speed and slope angle were not reported in all studies. For those who did, ranges were 0.5–22 km h^{-1} (measured at 1.5–2-m height) and 0–22° in forest, 0.3–33.9 km h^{-1} and 0–30° in shrubland and 2.5–53.1 km h^{-1} and 0–7° in grassland. As a result of averaging L_f and I_f within 100 kW m^{-1} intervals, the distribution of data points across the I_f range became much more balanced. We obtained 45 $L_f - I_f$ data points for forest, 73 for shrubland and 85 for grassland.

Model development and evaluation

In the joint analysis of the full dataset, vegetation type was significant, yet differences between forest and shrubland

Table 1. Data sources and ranges for fuel metrics and fireline intensity.

Vegetation type	Broad fuel type (fuel complex)	Reference	Country	*n*	*h* (m)	*w* ($kg\ m^{-2}$)	ρ_b ($kg\ m^{-3}$)	*R* ($m\ s^{-1}$)	L_f (m)	I_f ($kW\ m^{-1}$)
Forest	Deciduous broadleaf (litter)	Bova and Dickinson (2008)	USA	12	0.02–0.29	0.17–1.05	2.57–9.09	0.01–0.13	1.17–1.44	70–1544
	Deciduous broadleaf (litter + shrub)	Patterson *et al.* (2005)	USA	3	0.52–1.03	0.50–0.55	0.54–0.99	0.01–0.08	1.09–4.5	107–727
	Eucalypt (litter)	Pinto *et al.* (2013)	Portugal	22	0.04–0.13	0.33–1.78	6.42–19.36	0.00–0.06	0.18–1.05	18–523
	Eucalypt (litter + grass)	Lacy (2008)	Australia	29	0.1–0.64	0.32–1.26	0.81–8.34	0.00–0.09	0.5–2.54	28–1084
	Eucalypt (litter + grass/shrub)	Gould *et al.* (2008)	Australia	95	0.01–0.56	0.34–2.15	1.62–72.74	0.00–0.32	0.29–8.94	53–7379
	Long needle conifer (litter)	Botelho *et al.* (1994)	Portugal	3	0.05–0.06	0.49–0.64	9.63–12.50	0.01–0.02	0.33–0.79	111–191
		Fernandes *et al.* (2009)	Portugal	32	0.02–0.21	0.28–1.20	4.04–18.00	0.00–0.11	0.14–2.93	29–1220
		Sparks *et al.* (2017)	USA	9	0.05–0.08	0.20–2.30	2.38–40.35	0.00–0.10	0.31–1.12	22–859
	Long needle conifer (litter + grass)	Fernandes *et al.* (2009)	Portugal	6	0.21–0.25	0.79–1.53	3.20–6.24	0.01–0.23	1.15–4.36	154–3410
	Long needle conifer (litter + grass/shrub)	Alvarado (1986)	Mexico	38	0.07–0.40	0.09–1.45	0.46–12.57	0.00–0.09	0.16–2.36	9–957
		Fernandes *et al.* (2009)	Portugal	13	0.27–0.33	0.81–1.21	2.45–3.99	0.01–0.14	1.03–3.70	195–1964
	Long needle conifer (litter + shrub)	Botelho (1996)	Portugal	1	0.19	0.59	3.06	0.01	1.00	99
		Botelho *et al.* (1994)	Portugal	5	0.21–0.50	0.60–1.29	1.68–3.58	0.01–0.07	0.94–3.18	84–982
		Fernandes *et al.* (2004)	Portugal	3	0.09–0.45	0.80–2.47	5.48–9.77	0.02–0.10	1.31–4.67	267–2419
		Fernandes *et al.* (2009)	Portugal	36	0.33–0.61	0.82–1.85	1.83–3.74	0.01–0.13	0.88–4.66	156–2415
		Patterson *et al.* (2005)	USA	3	0.23–0.61	0.55–0.77	1.26–2.65	0.02–0.14	0.64–3.39	167–1764
		UTAD unpublished data on file	Portugal	7	0.10–0.45	0.48–2.26	2.34–5.02	0.01–0.07	0.61–1.96	192–1249
	Mixed conifer–deciduous (litter)	Norton-Jansen (2005)	USA	3	0.05–0.09	0.75–0.81	8.23–15.55	0.02–0.03	0.34–0.55	253–346
	Mixed conifer–deciduous (litter + shrub)	Norton-Jansen (2005)	USA	3	0.17–0.20	1.32–1.56	6.79–9.33	0.02–0.07	1.08–1.57	442–1473
	Short needle conifer (litter)	Lawson (1972)	Canada	8	0.02	0.97	49.43	0.01	0.35–0.87	90–212
	Short needle conifer (litter + moss/lichen)	Lawson (1972)	Canada	20	0.02	0.77–0.97	35.5–49.43	0.00–0.03	0.11–1.85	60–529
	Conifer slash (slash)	Kucuk *et al.* (2008)	Turkey	30	0.10–0.38	0.64–4.99	4.57–17.08	0.00–0.05	0.20–2.58	36–4273
		Brown (1972)	USA	25	0.16–0.89	0.54–2.10	1.85–7.41	0.00–0.04	0.33–2.87	15–1308
Shrubland	Deciduous shrub (litter + shrub)	Patterson *et al.* (2005)	USA	3	0.20–0.84	0.54–0.65	0.67–2.77	0.01–0.07	0.47–1.97	93–672
	Evergreen shrub (grass + shrub)	Anderson *et al.* (2015)	Australia	2	0.40	1.62–1.62	4.05–4.05	0.13–0.14	8.30–8.30	3582–3716

(*Continued on next page*)

Table 1. (*Continued*)

Vegetation type	Broad fuel type (fuel complex)	Reference	Country	*n*	*h* (m)	*w* (kg m^{-2})	ρ_b (kg m^{-3})	*R* (m s^{-1})	L_f (m)	I_f (kW m^{-1})
		Anderson *et al.* (2015)	New Zealand	11	0.30–2.50	0.10–2.22	0.12–1.17	0.02–0.42	1.30–9.90	99–15 326
		Marsden-Smedley and Catchpole (1995)	Australia	85	0.20–0.50	0.37–2.51	1.52–6.28	0.00–0.24	0.70–10.91	37–4905
	Evergreen shrub (litter/moss + shrub)	Davies and Legg (2011)	Scotland	19	0.16–0.45	0.72–1.67	3.34–5.38	0.01–0.20	0.59–3.30	159–4337
	Evergreen shrub (shrub)	Anderson *et al.* (2015)	Australia	13	0.25–4.80	0.30–3.82	0.20–3.53	0.05–0.43	1.85–16.70	249–27 127
		Anderson *et al.* (2015)	New Zealand	15	0.60–3.60	1.16–4.81	0.57–3.22	0.14–0.45	3.10–14.10	3620–25 259
		Anderson *et al.* (2015)	Portugal	19	0.28–1.90	0.53–2.79	0.86–3.00	0.01–0.33	1.20–7.80	130–10 061
		Fernandes (2001)	Portugal	6	0.46–0.63	1.74–4.09	3.63–6.89	0.07–0.15	3.68–5.46	2540–7340
		Van Wilgen *et al.* (1985)	South Africa	6	0.84–1.15	0.59–1.48	0.51–1.54	0.21–0.47	2.86–5.35	3015–9064
	Open evergreen shrub (grass + shrub)	Bushey (1985)	USA	6	1.32–2.29	0.05–0.29	0.03–0.20	0.03–0.55	1.72–3.97	24–2677
	Open evergreen shrub (shrub)	McCaw (1997)	Australia	17	0.21–2.40	0.48–1.67	0.52–2.44	0.02–0.72	0.65–13.4	119–14 737
	Open evergreen shrub (shrub)	Van Wilgen *et al.* (1985)	South Africa	5	1.00–1.23	1.05–1.70	0.94–1.38	0.04–0.55	2.61–7.57	752–15 524
Grassland	Cereal stubble (grass)	New Zealand Forest Research (2002)	New Zealand	27	0.10–0.50	0.19–0.75	0.94–1.97	0.27–1.78	0.62–6.00	1029–17 065
	Grass (grass)	Van Wilgen and Wills (1988)	South Africa	10	0.44	0.37–0.37	0.85–0.85	0.04–1.00	1.44–4.94	231–5562
		Clark (1983)	USA	60	0.04–0.57	0.10–0.89	0.75–4.80	0.01–0.92	0.15–4.76	52–10 492
		Cruz *et al.* (2018)	Australia	14	0.29–0.90	0.67–1.04	0.85–2.83	0.37–1.18	3.00–5.23	5233–14 890
		Hély *et al.* (2003)	Zambia	8	0.20–0.44	0.36–0.60	0.89–1.82	0.02–1.76	0.50–4.61	106–9590
		Kunst *et al.* (2001)	Argentina	7	0.36–0.66	0.20–0.78	0.55–1.20	0.21–0.56	4.00–4.91	630–6427
		Pearce *et al.* (2009)	New Zealand	4	0.48–0.56	3.25–3.76	6.63–7.56	0.10–0.14	2.48–3.02	5458–7641
		Sneeuwjagt and Frandsen (1977)	USA	42	0.09–0.53	0.04–0.47	0.44–2.33	0.00–1.02	0.21–3.58	1–6353
	Grass (grass + shrub)	Kunst *et al.* (2001)	Argentina	12	0.45	0.66–1.24	1.47–2.75	0.23–0.70	2.10–3.95	2864–12 219

Variables used are: *h* (m), fuel bed height; *w* (kg m^{-2}), fine fuel load; ρ_b (kg m^{-3}), fuel bed density; *R* (m s^{-1}), fire spread rate; L_f (m), average flame length; I_f (kW m^{-1}), fireline intensity.

were small, with the confidence interval estimates for the latter totally included within the confidence interval for the former, so we separately fitted Eqn 2 to forest–shrubland data and to grassland data. The back-transformed forest–shrubland equation (Fig. 2) accounted for 76.6% (Table 2) of the existing variability, with an MAE of 1812 kW m^{-1}. The explanation of variability (82.1%) was higher for grasslands (Fig. 3) and MAE was slightly lower (1734 kW m^{-1}). MBE was approximately zero in both cases. Residuals were approximately normally distributed for forest–shrubland, normally distributed for grassland, and weakly correlated with predicted values. Reciprocals of Eqn 2 are $L_f = 0.04001\ I_f^{0.5846}$ for forest–shrubland and $L_f = 0.03888\ I_f^{0.5111}$ for grassland. Byram's (1959) equation is $L_f = 0.0775\ I_f^{0.46}$; its reciprocal yields similar results to the equation derived for grassland (Fig. 4) but severely, and increasingly, overestimates I_f for flames longer than ~2 m in forest and shrubland.

Discussion

Model performance and influence of fuel properties

The $L_f - I_f$ models performed well, explaining about 80% of the observed variability and providing unbiased estimates. In forest and shrubland fires, I_f can be estimated from L_f using the same empirical relationship. Fires in grassland need different fitted coefficients, thus revealing differences in flame characteristics, which have already been noted by Cheney (1990). However, L_f scales approximately with the square root of I_f in both cases, as expected from theory (Nelson 1980).

Fuel consumption will not exactly equal fine fuel load. Consequently, I_f calculation with the latter in lieu of the former is expected to introduce uncertainty when fitting a $L_f - I_f$ relationship, but judging from model evaluation statistics, this simplification was not an influent factor. The wide data range in w and fuel bed density (ρ_b), shown by their interquartile ranges for forest (0.66–1.3 kg m^{-2}, 2.9–11.0 kg m^{-3}), shrubland (0.76–1.7 kg m^{-2}, 1.3–3.7 kg m^{-3}) and grassland (0.25–0.67 kg m^{-2}, 1.0–2.0 kg m^{-3}), and the fact that these metrics are not required as predictors to produce accurate $L_f - I_f$ models, leaves no doubt about their reduced influence on flame structure. Also, it is reasonable to assume that variation in fuel bed structure descriptors (like h, w and ρ_b) would similarly affect flame properties in forest–shrubland or grassland. On the other hand, a fuel metric that fundamentally distinguishes forest–shrubland and grassland, and significantly influences R, is the surface area-to-mass ratio of the fuel particles (S_m) (Rossa and Fernandes 2018a). R increases with S_m, which is much higher for grassland. In fact, the S_m of mediterranean forest–shrubland foliage follows a normal distribution, with an average value of 8.2 m^2 kg^{-1}, contrasting with the much higher values of 20–40 m^2 kg^{-1} observed for herbaceous fuels (Rossa and Fernandes 2018b).

L_f is a visible manifestation of the hot combustion gases, and the chemical composition of wildland fuels is very similar, thus producing little variation between H values. Thus, the same 'amount of flame' should be produced for the same I_f, regardless of the fuel bed. Contrasting S_m fuels will produce structurally different flames, which seem to become more compact as S_m increases. Additional evidence supports this idea: based on laboratory experiments in conifer slash fuel, Anderson et al. (1966) obtained an $L_f - I_f$ relationship that predicts $L_f = 10$ m to yield $I_f = 2000$ kW m^{-1}, whereas our models result in $L_f = 4$ m for forest–shrubland (Fig. 2a) and $L_f = 2$ m for grassland (Fig. 3a). Even the thinnest woody fuels within a slash fuel bed have very low S_m; for example, a 4 mm round eucalypt twig will have $S_m = 1.5$ m^2 kg^{-1}, contrasting with typical values of 8.2 m^2 kg^{-1} for foliar fuels and 30 m^2 kg^{-1} for grass fuels (Rossa and Fernandes 2018b).

Model applicability and application

Although our models performed better within the fire behaviour range most commonly associated to surface fire spread, say up to an I_f of 4000 kW m^{-1}, a relevant feature of the fitted equations is the inclusion of high-intensity fire data in their development. For more flammable fuel complexes, namely tall shrublands and forests with a well-developed woody understorey, this is expected to improve L_f or I_f estimates over those afforded by the previously available relationships. Flame size quantification in forest crown fires is scarce, but a cursory inspection of the predictive ability of our $L_f - I_f$ relationship in such cases is warranted. Flame height data is available for five active crown fires in jack pine stands in Canada (Stocks et al. 2004; Butler et al. 2004a), for which mean I_f varied between 39 896 and 78 533 kW m^{-1}, calculated as previously described. Assuming that L_f equals flame height, i.e. inputting underestimates of L_f, our $L_f - I_f$ equation estimates I_f with a mean absolute percentage error of 13.2% (range 1.8–35.2%), which is encouraging.

Beyond the already mentioned putative S_m effect, the supposed influence of fuel structure or other fuel bed-specific effects on fire behaviour properties does not preclude generic $L_f - I_f$ relationships from producing useful estimates, especially for operational fire management purposes. For low-I_f fires, MAE represents a greater percentage of the observed I_f values. Thus, the present models are more appealing for use in high-I_f fires (>~2000 kW m^{-1}), which typically occur under low fuel moisture content and strong winds (high R) in tall fuel complexes (high w). To obtain accurate I_f estimates for low-I_f fires, the use of fuel bed-specific $L_f - I_f$ relationships may be a better option. Finally, different $L_f - I_f$ relationships have been reported for backing and heading fires in the same fuel type (Clark 1983; Fernandes et al. 2009). The L_f of fires spreading under

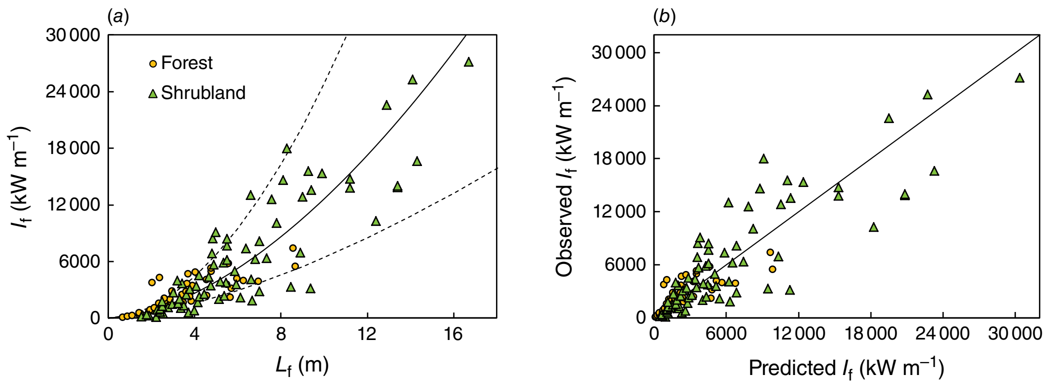

Fig. 2. Eqn 2 fit and evaluation for forest–shrubland after back transformation: (*a*) Fireline intensity (I_f) as a function of flame length (L_f), dashed lines are the 95% CI; and (*b*) observed vs predicted I_f values. Fitted coefficients and evaluation metrics are given in Table 2.

Table 2. Coefficients and evaluation metrics for Eqn 2 after back-transformation.

Vegetation type	*n* data points	*a*	*b*	R^2	RMSE (kW m^{-1})	MAE (kW m^{-1})	MBE (kW m^{-1})
Forest–shrubland	118	246.0 (186.9–323.9)	1.711 (1.536–1.885)	0.766	2689	1812	0
Grassland	85	574.2 (468.9–703.1)	1.956 (1.757–2.156)	0.821	2368	1734	0

95% confidence intervals for fitted coefficients *a* and *b* are shown in parenthesis. R^2, coefficient of determination; RMSE, root mean square error; MAE, mean absolute error; MBE, mean bias error.

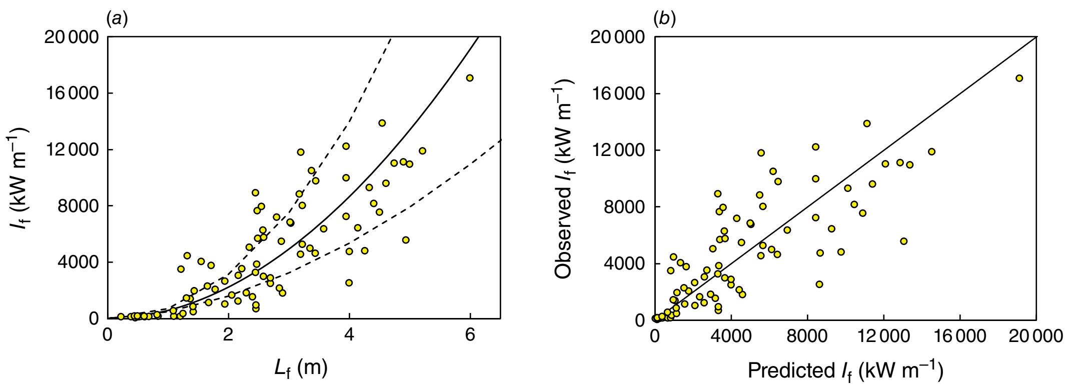

Fig. 3. Eqn 2 fit and evaluation for grassland after back-transformation: (*a*) Fireline intensity (I_f) as a function of flame length (L_f), dashed lines are the 95% CI; and (*b*) observed vs predicted I_f values. Fitted coefficients and evaluation metrics are given in Table 2.

calm conditions theoretically scales with the 2/3 power of I_f (Fons *et al.* 1963; Thomas 1963; Albini 1981), which also applies to fires backing into the wind (Nelson 1980). Consequently, our $L_f - I_f$ relationships should not be extrapolated to backing fires.

The $L_f - I_f$ relationships can be applied for various purposes and in different ways. The reciprocals of Eqn 2 can be integrated in fire behaviour prediction schemes to produce estimates of L_f from I_f whenever the former is a variable of interest, e.g. in the frame of fire suppression and firebreak construction (Alexander 2000), or for fire hazard or fire risk assessment and mapping (e.g. Thompson *et al.* 2011). The usefulness of I_f estimates is thoroughly covered by Alexander and Cruz (2020). Estimation of I_f from L_f is expedient when the latter can be measured or calculated based on visual observation, either during or after the fire. If fire-spread rate is concurrently assessed, fine fuel consumption can be estimated as well (as per Eqn 1), without the need for destructive pre-burn and post-burn sampling, which is relevant for prescribed burning operations and fire effects studies. Estimates by personnel in the fireline can thus assist decision-making during fire control or fire use operations and can be used to anticipate fire effects such as crown scorch height and tree mortality. Likewise, post-fire surveys

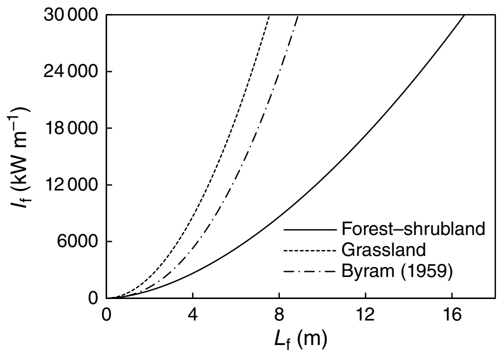

Fig. 4. Graphical representation of Byram's (1959) fireline intensity (I_f)–flame length (L_f) relationship ($I_f = 259.8\ L_f^{2.174}$) and the corresponding models developed in the present study (Table 2).

are able to translate fire effects in terms of the associated fireline intensity, which is useful for prescribed burning monitoring and wildfire study cases.

Comparison with Byram's relationship

The pioneer $L_f - I_f$ relationship of Byram (1959) is the best known and most widely used. Oddly, although Byram's model is most commonly viewed as applicable to surface heading fires (Nelson 1980; Alexander and Cruz 2012), it was presumably based mostly on backing fires (34 out of a total of 41). Interestingly, it was derived from outdoor fires in a forest fuel type with a grass component, which might explain why it compares better with our grassland equation instead of that for forest–shrubland. Our results highlight the inadequacy of using the Byram (1959) model for forest and shrubland fires with L_f above ~2 m, consistent with the findings of recent laboratory experiments (Finney and Grumstrup 2023).

Rothermel (1991) stated that Byram's equation severely underestimates the L_f of crown fires, and as such, recommended the more realistic equation of Thomas (1963), where L_f is proportional to $I_f^{0.67}$, as in the equation of Butler *et al.* (2004*b*) for crown-fire L_f. The $L_f - I_f$ relationship for the forest–shrubland variant displays $b = 0.58$, midway of the coefficients of Byram ($b = 0.46$) and Thomas. This may be an outcome of the substantial presence in the dataset of high-intensity observations in fuel complexes dominated by an elevated and aerated component, either in shrubland or in forest.

Study relevance

The discrepancies between previous results suggesting that generic $L_f - I_f$ functions are unviable (Alexander and Cruz 2012) are most likely explained by the following reasons: (1) individual studies are usually limited in the number of fires and observed I_f range, which may lead to substantial differences in predicted values when models are extrapolated much beyond the development data range; (2) flame pulsation makes L_f evaluations subjective and originates discrepancies between measurements taken in real time or using video images (allowing for a visual average) and measurements based on photographs (capturing a single snapshot); and (3) most studies do not specify how the flame is measured and lack a standard method of measurement. We advocate that L_f should be assessed from the fuel base level to enable comparability between fires in different fuel heights and adequacy to heat transfer modelling (Nelson and Adkins 1986; Anderson *et al.* 2006), whereas Alexander (1982) proposes measuring L_f from the flame-depth midpoint at the fuel surface level to the tip of the flame.

I_f is a versatile fire metric that can be used for a wide variety of purposes; it can be estimated from L_f, and vice versa. Although L_f assessment is subjective and greatly depends on its definition and mode of observation and calculation, it is a readily apparent descriptor (Rothermel 1991) and therefore practical to use. Particular situations may benefit from the use of fuel bed-specific $L_f - I_f$ relationships to assure increased accuracy of I_f estimates, e.g. for prescribed burning planning purposes for which the most accurate relationships between fire behaviour and fire effects are required (Fernandes *et al.* 2012; Hiers *et al.* 2020). However, deriving specific models for all existing fuel complexes is not feasible. As a consequence, the generic relationships developed in the present study will be of interest in many situations. Moreover, our results are based on a great amount of data from very diverse literature sources reporting field fires conducted worldwide – in a wide range of fuel species, vegetation structure, wind speed, slope angle and flame dimensions, and thus are robust.

Conclusions

We found that the generic description of I_f from L_f should be based on different functions for forest–shrubland and for grassland fires, and we speculate that S_m is the main fuel metric influencing flame structure. Mean L_f must be assessed from the base of the fuel bed for comparability between fires burning in fuel beds with different depths. The absence of standards to assess L_f, and the fact that many studies do not specify if the measure is taken from the base or the top of the fuel bed, has likely contributed to some of the discrepancies among previous results, which suggested fuel-specific relationships are unfeasible. Because I_f is a frequently used fire metric and developing specific models for all existing fuel complexes is not practical, the generic relationships presented in this work will be of interest for both research and management purposes, namely in higher-intensity surface fires.

List of symbols, units and definitions

a and b	fitted coefficients
h (m)	fuel bed height
H (kJ kg^{-1})	heat yield per unit mass of fuel

I_f (kW m^{-1}) fireline intensity
L_f (m) average flame length (measured from the base of the fuel bed, unless otherwise specified)
R (m s^{-1}) fire spread rate
S_m (m^2 kg^{-1}) surface area-to-mass ratio of the fuel particles
w (kg m^{-2}) fuel load consumed by flaming combustion (approximated to fine fuel load)
ρ_b (kg m^{-3}) fuel bed density

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Data availability. Data are available upon request from the authors.

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