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The Flames Catalogue: an engineering tool to predict flame geometry

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Abstract

Flames can be geometrically described from a simplified perspective by means of their length (or height), angle and depth. These parameters are key for fire safety calculations, to prevent injuries during entrapments or to design preventive infrastructures. Most methods to estimate flame geometry require information on fire behaviour (e.g. rate of spread or fireline intensity), which are not always available or straightforward. Within this context, we are developing a tool to estimate flame geometry only from environmental parameters (fuel, weather and terrain) and without the need of fire behaviour predictions beforehand. To achieve this, we have gathered data on field-scale fires and used them to fit binary logistic regressions, to obtain the probability of occurrence of a certain flame geometry for specific fuel structures. We have already modelled flame length probability from fine fuel load, moisture content and wind speed in different fuel structures and flame angle probability from fine fuel load and wind speed in grasslands. We are currently working to extend the dataset and cover a wider range of fuel structures and conditions.

1. Introduction

Wildfire flames are a complex and transient phenomenon, but can be geometrically described from a simplified perspective by means of their length (or height), angle, depth (Figure 1) and residence time.

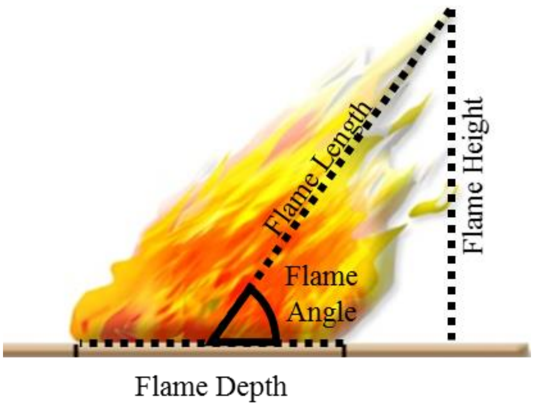

Figure 1- Flame geometry sketch.

Flame geometry is key for fire safety calculations involving radiative energy transfer, such as to estimate firefighter safety and survival zones (Page & Butler, 2017; Butler, 2014) or as input to solid flame models (*e.g.* Eisenberg *et al.*, 1975) to design preventive infrastructures by comparing the radiation profile with the resistance threshold of the elements to protect (*e.g.* Ricci *et al.*, 2021; Standards Australia, 2009). Several works attempted to estimate flame geometry from empirical and physical models (*e.g.* Alexander & Cruz, 2012; Nelson *et al.*, 2012; Anderson *et al.*, 2006), an approach that requires information on fire behaviour beforehand, namely rate of spread and intensity.

To overcome the need of *a-priori* fire behaviour predictions, our aim is to build a "Flames Catalogue" to estimate flame geometry for particular sets of environmental conditions (fuel, weather and terrain). The catalogue will consist on typical scenarios of interest for fire management linked to the range of expected flame geometries. In this short paper we present the current status of this tool and its potential to predict flame geometry in different fuel structures.

2. Methodology

2.1. Data gathering

We have gathered data from field-scale fires. These data consisted of environmental parameters (weather, terrain and fuel) and flame geometries (flame length and angle) from observations and measurements during wildfires and field experiments. We have excluded data from indoor experiments, wind-tunnel experiments and prescribed burnings, in which the aim of the burn constrains the free spread of the flame front. The sources of the data were the BONFIRE (Fernandes et al., 2020), Anderson et al. (2006) and CERTEC (unpublished) databases.

In this communication, environmental parameters refer to weather (wind speed) and fuel (Fine fuel load and moisture content of the dead fraction). We grouped the data in three fuel structures: open grasslands, open shrublands and undercanopy fuels (a mixture of litter, grasslands and shrublands). Flame geometries refer to flame length and flame angle, expressed in accordance with Figure 1.

2.2. Data modelling

We used these data to fit binary logistic regressions and estimate the likelihood of occurrence of certain flame length and flame angle at a given set of environmental parameters. Binary logistic regressions have the form of Eq. 1, with a logit of the form of Eq. 2:

$$P(Y=1|X)=\frac{e^{f(x)}}{1+e^{f(x)}} \qquad \text{Eq. 1}$$

$$f(x)=\beta_0+\sum_{i=1}^{i=n}\beta_i Var_i \qquad \text{Eq. 2}$$

Where $P(Y=1|X)$ is the probability of occurrence of an event under certain conditions (*e.g.* the probability of flames being smaller than 3 meters when fire burns dry grasslands with a fine fuel load of 1 kg/m^2 in still air). β_0 is a constant parameter and β_i are coefficients for the different independent variables (Var_i), namely fine fuel load (ffl), wind speed measured at a height of 2 (U_2) or 10 meters (U_{10}) and fuel moisture content of the dead fraction (FMC_d). The relation between an event and a predictor is expressed by means of its odds ratio; odds ratios greater than 1 indicate that the event is more likely to occur as the predictor increases, while odds ratios lower than 1 indicate that the event is less likely to occur as the predictor increases.

3. The Flames Catalogue

3.1. Flame length

Flame length results from the equilibrium between the release of pyrolysis gases, the diffusion of oxygen and the transmission of heat, among other factors involving combustion (Finney *et al.*, 2021). Generally, greater fuel loads (especially fine fuels) are a sign of a greater release of pyrolysis gases and hence larger flame lengths. Most models developed to predict flame length require fire behaviour predictions (*e.g.* Alexander & Cruz, 2012). Our approach dismisses fire behaviour predictions and relies exclusively on environmental parameters to predict flame length, which makes it easier to use for fire managers. To fit the binary logistic regressions, we used ffl for shrublands, ffl and U_2 for understory fuels and ffl, U_2 and FMC_d for grasslands. Table 1 shows the constant parameters and coefficients to fit Eq. 2 and Figure 2 computes Eqs. 1 and 2 to show the probability of having flames smaller than a certain length as a function of the expected variables. Data used to fit the model covered up to 3 kg/m², 1.2 kg/m² and 1.5 kg/m² of fine fuels in shrublands, grasslands and understory fuels respectively, 25 % of moisture content in grasslands and 25 km/h of wind speed.

Table 1- Constant parameters and coefficients for logistic regressions to estimate flame length probability from fine fuel load (ffl), wind speed at 2 meters above the ground (U_2) and fuel moisture content of dead fuels (FMC_d). "FL" stands for Flame Length (m). Underlined values indicate p<0.05 in Pearson goodness of fit test.

		FL ≤ 0.5	FL ≤ 1	FL ≤ 2	FL ≤ 3	FL ≤ 4	FL ≤ 6	Odds ratio
Shrubland	β_0	3.10	3.88	3.68	4.79	4.57	4.91	-
(n = 117)	β_{ffl}	– 6.22	– 5.74	– 3.72	– 3.34	– 2.32	– 1.80	0.05±0.06
Grassland	β_0	0.96	2.10	2.78	4.06	5.64	-	-
(n = 173)	β_{ffl}	– 5.87	– 5.52	– 5.05	– 5.23	– 5.00	-	0.01±0.002
	β_{U_2}	0.08	0.06	0.05	0.08	0.07	-	1.07±0.01
	β_{FMC_d}	– 0.11	– 0.14	– 0.09	– 0.08	– 0.15	-	0.89±0.02
Understory	β_0	1.42	2.15	4.49	6.66	8.98	-	-
(n = 395)	β_{ffl}	– 1.94	– 0.99	– 1.51	– 2.11	– 2.51	-	0.18±0.11
	β_{U_2}	– 0.36	– 0.30	– 0.41	– 0.51	– 0.66	-	0.64±0.09

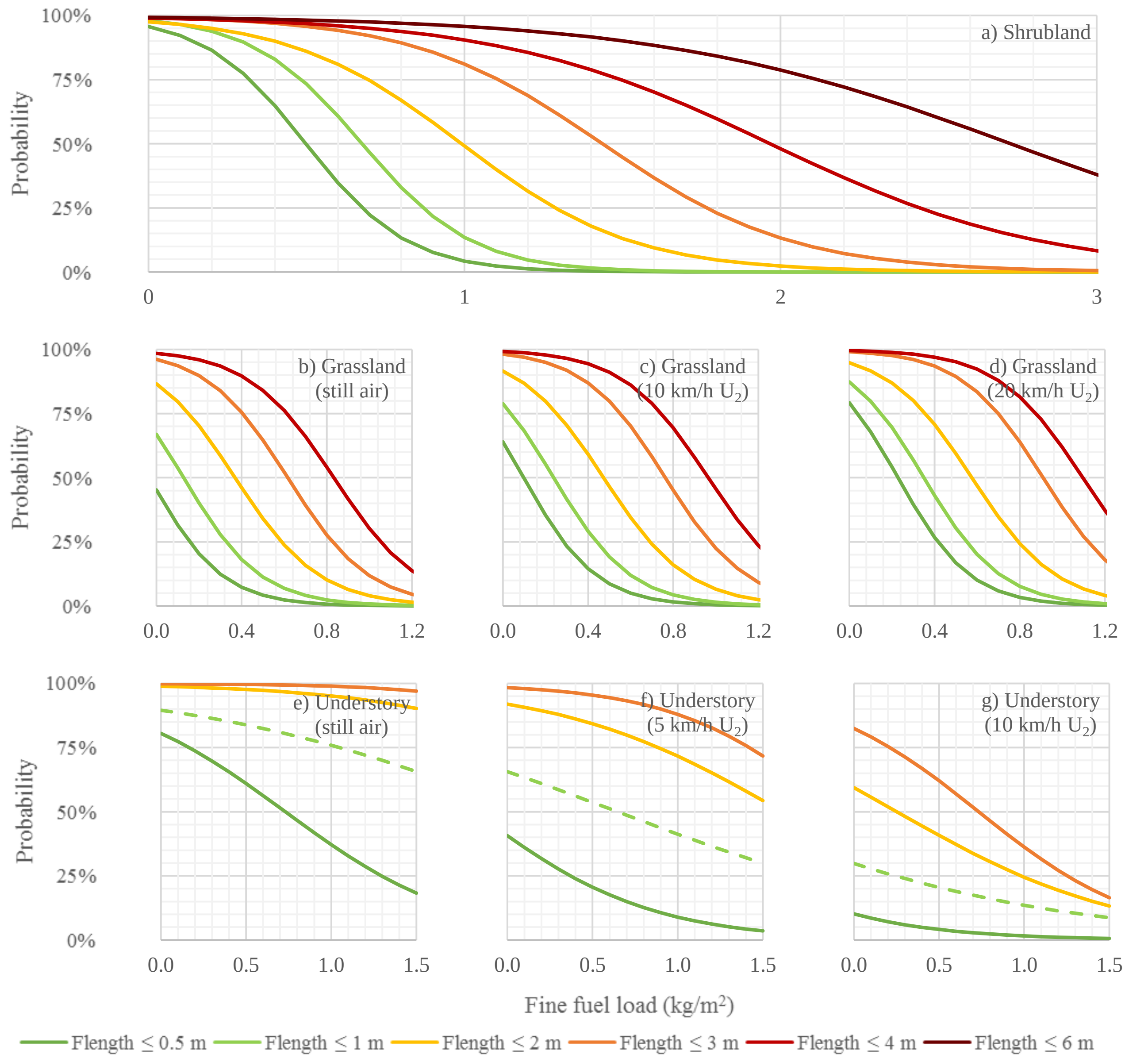

Figure 2- Logistic regressions to estimate flame length probability (y-axis) from the variables in Table 1. Dashed lines indicate p<0.05 in Pearson goodness of fit test.

3.2. Flame tilt angle

Flame tilt angle results from the equilibrium between buoyancy forces, that raise the fire plume, and wind, that pushes the flame forward (Finney *et al.*, 2021). Most models developed to predict flame angle require fire behaviour predictions (*e.g.* Nelson *et al.*, 2012). Our approach uses fine fuel load (ffl) as a proxy for buoyancy forces and wind speed at 10 meters above the ground (U_{10}), dismissing fire behaviour predictions and making it easier to use for fire managers.

Table 2 shows the constant parameters and coefficients to fit Eq. 2 and Figure 3 uses Eqs. 1 and 2 to show the probability of having flames with a certain angle from grassfires. Data used to fit the model covered up to 1 kg/m^2 of fine fuel load and 35 km/h of wind speed.

Table 2- Constant parameters and coefficients for logistic regressions of flame angle in grasslands.

		α < 80	**α < 60**	**α < 45**	**Odds ratio**
Grasslands	β_0	0.601	– 0.787	– 1.85	-
(n = 211)	β_{ffc}	– 2.311	–1.867	– 2.970	0.10±0.05
	$\beta_{U_{10}}$	0.235	0.152	0.105	1.18±0.08

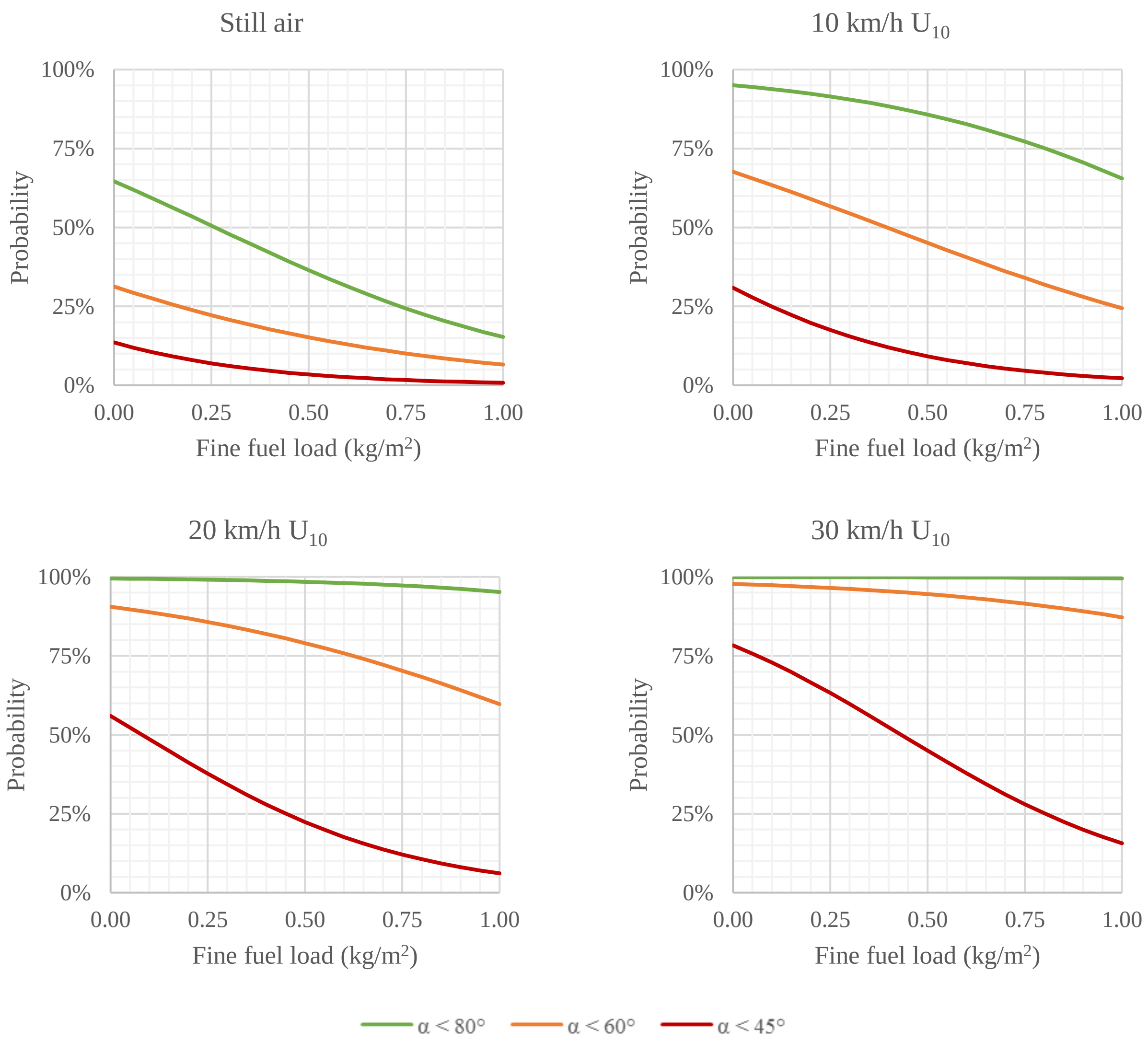

Figure 3- Logistic regressions to estimate flame angle in grasslands.

3.3. Study case

As part of the fire prevention program, the Fire Service is building safety areas for sheltering in a firebreak network. This firebreak network is surrounded by shrublands, with a fine fuel load of 1 kg/m^2. These safety areas have been dimensioned for flames of 6 meters, at most. The Fire Service aims to outline their validity, with an acceptance threshold of 95% probability. Using Eqs. 1 and 2 and data in Table 1 for shrublands, the probability of flames equal or smaller than 6 meters is 96%, which is acceptable.

4. Conclusions

We have presented a novel approach to predict flame geometry from environmental parameters and fuel consumption, independent of *a priori* fire behaviour knowledge. With it, it is possible to manage fire prevention from a small number of inputs, easily measurable in the field. This Flames Catalogue does not intend to substitute empirical and physical approaches to estimate fire geometry, but to serve as a complementary tool for fire managers.

Prior to develop a definitive tool, the dataset should be extended to cover existing gaps, like the prediction of flame angles with fuel structures other than grasslands, or introducing slope values in the logit functions for flame length. Some obstacles to reach this goal are the lack of common criteria to measure flame geometry among the various existing studies and the difficulty to perform accurate measurements during large experiments and wildfires. The Flames Catalogue is aimed to include other important parameters such as flame depth or residence time.

5. Acknowledgements

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