

Article

The Influence of Particle Surface Area-to-Mass Ratio on Flame Residence Time and Mass Loss Rate of Forest Fuel Beds

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Abstract

Combustion duration is a fire behaviour feature relevant for both the effects and management of fire. We burned small-scale laboratory fuel beds ($n = 135$) of eight fuel types and developed empirical models to describe variation in flame residence and burn-out times, and fuel mass fraction loss rates during flaming and non-flaming combustion; each fuel sample was ignited at once and burned as a pile. Surface area-to-mass ratio of the fuel particles, by itself, allowed accurate prediction of all combustion properties with better performance than surface area-to-volume ratio. Fuel bed structure was also shown to have an influence, fuel load being the variable that further improved all predictions. This work provides evidence that surface area-to-mass ratio is an adequate descriptor of the combustion characteristics of forest fuel beds. Our expectation is that this approach will assist future modelling efforts to obtain simple empirical models to predict the combustion features of free-spreading fires in a wide range of vegetation types.

Keywords: fire effects; combustion properties; empirical models

1. Introduction

Rate of spread [1], flame size [2], and Byram's fireline intensity [3] have captured the attention of most studies modelling the behaviour of a moving fire front in vegetation [4] because of their immediately apparent importance for fire management activities. Conversely, relevant combustion properties like flaming duration or fuel mass (m) loss rate have received little attention. Yet, measuring and predicting these combustion properties is important from the standpoint of a comprehensive understanding and an interpretation of fire behaviour and its effects, namely to ascertain differences in flammability and to assess variation associated with the physical properties of fuel particles and fuel beds [5]. The duration of combustion, either flaming or total, determines the intensity and depth of penetration or vertical reach of the heat pulse, thus determining the extent of lethal heating of plant organs [6,7] and the effects on soils [8], and influencing fire behaviour phenomena such as crown fire initiation [9] and spotting distance [10].

Fons et al. [11] defined flame residence time (t_{fl}) as the time required by a moving flame to pass a reference point in the fuel bed. However, the period during which flames are observed can also be assessed if a fuel sample is ignited simultaneously and burned as



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a pile [12]. Few observational studies of t_{fl} exist, either in the laboratory [13–16] or in the field [15,17–19]. While even fewer studies have modelled t_{fl} either empirically [12,14,16,17] or physically [5], they are all fuel-specific or lack the validation to be used over a wide range of fuel types; the same applies to m loss rates [12]. In fact, models for predicting the combustion properties for a generic fuel bed are still missing.

The surface area-to-volume ratio ($S_v = S/V$) has a great influence in the processes of heat transfer underlying fire spread [20], which explains its frequent use as a predictor in empirical models for combustion properties [12,14,17]. However, Rossa and Fernandes [21] concluded that S_v does not fully account for the influence of fuel particles' physical characteristics on flammability, because in fuel beds of a similar S_v fire spreads faster when the particle density (ρ_p) is lower. The surface area-to-mass ratio ($S_m = S/m$) is a better predictor and can allow the generalisation of fire spread rate models to generic vegetation [22]. Thus, it seems legitimate to question if S_m would also be a better predictor of combustion properties than S_v . Yet, currently, no study has addressed this hypothesis.

In the present work, we burned small-scale fuel beds built from several fuel types, ignited these as a pile, and tested the hypothesis that the combustion properties of very distinct fuels can be estimated empirically based on S_m . The results are discussed in terms of their expected applicability to predict the combustion features of free-spreading fires.

2. Materials and Methods

2.1. Laboratory Experiments

The laboratory work was carried out at the University of Trás-os-Montes e Alto Douro (Vila Real, Portugal). The air in the laboratory was not conditioned, but the ambient temperature (T_a) and relative humidity (RH) were monitored. The experimental apparatus (Figure 1) consisted of a square aluminium basket (10 cm wide) mounted on a precision balance (Denver Instrument APX-1502, Bohemia, NY, USA) with a resolution of 0.01 g to allow monitoring m loss over time; m measurements were recorded manually. The bottom of the basket was drilled with 3 mm diameter holes approximately 3 cm apart to allow for air intake.



Figure 1. Experimental apparatus and fuel types: (a) combustion test using a fuel bed of *Pinus pinaster* needles; (b) fuel types: top row from left to right—*Triticum* spp. and *Secale cereale* leaves, *Acacia dealbata* leaves, *Triticum* spp. and *S. cereale* straw, and *Eucalyptus obliqua* leaves; bottom row from left to right—*Eucalyptus globulus* leaves, *P. pinaster* needles, *E. globulus* bark, and *E. globulus* twigs.

Eight fuel types were used to obtain a wide range in S_m : *Eucalyptus globulus* Labill. (blue gum) twigs (mean diameter: 3.3 mm); *E. globulus* bark; *Pinus pinaster* Ait. (maritime pine) needles; *E. globulus* leaves; *Eucalyptus obliqua* L'Her. (messmate stringybark) leaves; *Triticum* spp. L. and *Secale cereale* L. (wheat and rye) straw; *Acacia dealbata* Link. (silver wattle) leaves; and *Triticum* spp. and *S. cereale* leaves. All fuels were collected dead except for *A. dealbata* leaves. Still, regardless of their initial vegetative condition, we chose to perform the tests using oven-dried fuels to facilitate the ignition of the fuel bed. Therefore, all fuels were pre-conditioned at 105 °C for 24 h [23].

E. globulus twigs were cut into approximately equal-length pieces of and bark into equal-size squares. We measured the m of twig and bark samples ($n = 30$) and considered them to be, respectively, cylinders and rectangular prisms to determine S and V ; we then computed $S_v = S/V$, $S_m = S/m$, and $\rho_p = m/V$. For *Triticum* spp. and *S. cereale* leaves ($n = 45$), we approximated the S_v to $2/\text{thickness}$ [24] and used $\rho_p = 285 \text{ kg m}^{-3}$ from Rossa and Fernandes [21] to compute $S_m = S_v/\rho_p$. For the remaining fuel particles, the S_v , ρ_p , and S_m were retrieved from Rossa and Fernandes [21].

For each fuel type, the m used in each test was initially adjusted (m_{in}) so that the basket area was fully covered but the fuel layer was shallow enough to ignite simultaneously; since all fuels were pre-conditioned at 105 °C, m_{in} corresponds to the oven-dry initial fuel mass. After placing the fuel in the basket, we took the m_{in} and determined the fuel load (w). The fuel bed height (h) was measured and used to compute the fuel bed density (ρ_b). The porosity (ϵ) was also computed using the relationship $\epsilon = 1 - \rho_b/\rho_p$.

The fuel beds were sprayed with a small amount (below 10% of m_{in}) of ethyl alcohol to facilitate instantaneous and generalised ignition. Although this increased the initial m , we assumed that alcohol, which is highly volatile, would burn prior to the forest fuel and the stopwatch was started only when the m decreased down to the m_{in} . When flaming combustion was finished, we took the t_{fl} and residual fuel mass (m_{fl}).

During the non-flaming combustion phase, we registered the m at time intervals between 2 and 30 s, depending on the expected burn-out time (t_{bo}), i.e., the time between ignition and the end of combustion, which increased with the fuel particles' thickness. We took the t_{bo} when the residual m (m_{bo} , which was recorded) became constant or when it reached a minimum value before rising as a result of air moisture absorption.

We conducted 15 burn trials per fuel type and averaged the fuel bed and combustion properties. We carried out 15 additional trials for one of the eight fuel types, using a distinct m_{in} to assess the influence of the fuel bed structure. We used *E. globulus* bark in these supplementary tests because it was easy to increase the m_{in} without compromising the simultaneous ignition of the fuel bed. In total, 135 fuel bed samples were burned.

2.2. Computation of Combustion Properties

Knowing that the t_{bo} comprises flaming and non-flaming phases, we computed the duration of non-flaming combustion (t_{nf}) for each test from:

$$t_{bo} = t_{fl} + t_{nf} \quad (1)$$

based on the measured the t_{fl} and t_{bo} . For a fixed burning velocity, i.e., the speed at which reactants are moving into the flame, the m loss rate increases with the amount of available fuel. Thus, to overcome the fact that each treatment had different m_{in} , we obtained the m loss during flaming and non-flaming combustion as a fraction of m_{in} for comparison purposes:

$$x_{fl} = \frac{m_{in} - m_{fl}}{m_{in}} \quad (2)$$

$$x_{\text{nf}} = \frac{m_{\text{fl}} - m_{\text{bo}}}{m_{\text{in}}} \quad (3)$$

and then computed the x loss rates for each combustion phase:

$$\frac{dx_{\text{fl}}}{dt} = \frac{x_{\text{fl}}}{t_{\text{fl}}} \quad (4)$$

$$\frac{dx_{\text{nf}}}{dt} = \frac{x_{\text{nf}}}{t_{\text{nf}}} \quad (5)$$

The difference between unity and the sum of x_{fl} and x_{nf} yields the fraction of m_{in} remaining as residual ash.

2.3. Data Analysis and Modelling

In the two sets of *E. globulus* bark tests with different m_{in} , we checked the fuel bed (h , w , ρ_b , ϵ) and combustion properties (t_{fl} , t_{bo} , dx_{fl}/dt , dx_{nf}/dt) for differences between the sets using t -tests. For all treatments, combustion properties were modelled using power laws based on S_m , but we also obtained the coefficient of determination (R^2) using the S_v instead of the S_m for comparison purposes. Then, for models using the S_m , we tested which fuel bed metric would increase R^2 the most. Models were fitted by least-squares in their log-transformed form and the bias inherent to back-transformation was corrected [25]. Model evaluation was based on R^2 and deviation measures, including root mean square error (RMSE), mean absolute error (MAE), mean absolute percentage error (MAPE), and mean bias error (MBE) [26].

3. Results

Ambient air conditions remained fairly constant throughout the experiments, with the T_a and RH varying within a narrow range, respectively as 23.5–25.4 °C (mean: 24.6 °C) and 58–66% (mean: 61%). The S_m varied between 1.5 and 33.8 m² kg^{−1} (Table 1), with the highest value being achieved by an herbaceous fuel, which combined a high S_v with a low ρ_p . Naturally, lower S_m fuels formed shallow beds (low h) with a high w and were therefore dense (high ρ_b , low ϵ).

The duration of the t_{fl} was roughly in the 0.5–1 min range, except for the thicker twigs of *E. globulus*; the t_{bo} approximately doubled the t_{fl} , again with the exception of twigs but also the higher-mass *E. globulus* bark trials. Excluding *E. globulus* twigs, the x_{fl} and x_{nf} varied in a narrow range, respectively 0.85–0.92 (mean: 0.88) and 0.04–0.1 (mean: 0.06). This means that from these fuels m_{in} , an average of 88% burned in flaming combustion, 6% burned in non-flaming combustion, and 6% remained as residual ash. The large difference in the m loss rate in flaming versus non-flaming combustion is confirmed by the dx_{fl}/dt values always >10 times higher than the dx_{nf}/dt .

In the *E. globulus* bark tests with a distinct m_{in} , h and w were different, as opposed to ρ_b and ϵ that did not differ significantly; all combustion properties (t_{fl} , t_{bo} , dx_{fl}/dt , dx_{nf}/dt) differed between the two sets of experiments. Using the S_m instead of the S_v improved the explanation of the observed variability for all combustion properties. In all cases, w was the fuel bed metric that produced the greatest rise in R^2 when added to the S_m as an independent variable. Thus, for each combustion metric, we fitted two models (Table 2): one based solely on the S_m (for the sake of parsimony) and the other adding w as a predictor (for maximum accuracy).

Table 1. Summary statistics for the experimental fuel and combustion properties for each treatment.

Fuel Bed	S_v (m^{-1})	ρ_p ($kg\ m^{-3}$)	S_m ($m^2\ kg^{-1}$)	m_{in} (g)	h (cm)	w ($kg\ m^{-2}$)	ρ_b ($kg\ m^{-3}$)	ϵ	t_{fl} (s)	t_{bo} (s)	x_{fl}	x_{nf}	dx_{fl}/dt (s^{-1})	dx_{nf}/dt (s^{-1})
<i>Eucalyptus globulus</i> twigs	1288	837	1.5	12.2 (11.9–12.5)	1.2 (1.0–1.7)	1.22 (1.19–1.25)	101.3 (71.4–124.0)	0.879 (0.852–0.915)	86 (65–102)	486 (420–540)	0.77 (0.73–0.80)	0.15 (0.13–0.19)	0.0091 (0.0071–0.0120)	0.00038 (0.00032–0.00050)
<i>E. globulus</i> bark, m_{in} 1	2514	498	5.0	4.1 (3.9–4.9)	1.0 (0.8–1.2)	0.41 (0.39–0.49)	42.5 (35.9–51.5)	0.915 (0.897–0.928)	47 (41–53)	106 (86–131)	0.88 (0.84–0.91)	0.07 (0.04–0.10)	0.0186 (0.0164–0.0210)	0.00123 (0.00064–0.00235)
<i>E. globulus</i> bark, m_{in} 2	2514	498	5.0	7.4 (7.2–7.8)	1.8 (1.5–2.2)	0.74 (0.72–0.78)	42.2 (34.1–50.4)	0.915 (0.899–0.932)	62 (54–70)	217 (180–240)	0.85 (0.83–0.88)	0.10 (0.07–0.13)	0.0137 (0.0122–0.0154)	0.00064 (0.00048–0.00097)
<i>Pinus pinaster</i> needles	4470	600	7.5	4.8 (4.4–5.6)	1.8 (1.4–2.2)	0.48 (0.44–0.56)	26.8 (20.4–36.1)	0.955 (0.940–0.966)	38 (29–46)	100 (68–132)	0.89 (0.83–0.94)	0.07 (0.05–0.12)	0.0235 (0.0210–0.0308)	0.00115 (0.00054–0.00270)
<i>E. globulus</i> leaves	5740	660	8.7	4.3 (4.1–4.7)	1.5 (1.3–1.8)	0.43 (0.41–0.47)	29.2 (23.6–34.0)	0.956 (0.948–0.964)	43 (38–49)	86 (68–110)	0.92 (0.87–0.95)	0.05 (0.03–0.09)	0.0216 (0.0226–0.0403)	0.00117 (0.00069–0.00274)
<i>Eucalyptus obliqua</i> leaves	7245	620	11.7	4.2 (4.0–4.5)	1.5 (1.4–1.6)	0.42 (0.40–0.45)	28.0 (25.6–31.2)	0.955 (0.950–0.959)	42 (37–51)	76 (60–100)	0.89 (0.87–0.90)	0.04 (0.01–0.06)	0.0215 (0.0185–0.0251)	0.00109 (0.00040–0.00156)
<i>Triticum</i> spp. and <i>Secale cereale</i> straw	5265	285	18.5	3.9 (3.5–4.4)	2.7 (1.8–3.4)	0.39 (0.35–0.44)	15.0 (11.4–20.7)	0.947 (0.927–0.960)	32 (28–41)	73 (57–101)	0.88 (0.80–0.93)	0.07 (0.03–0.15)	0.0277 (0.0260–0.0394)	0.00161 (0.00083–0.00238)
<i>Acacia dealbata</i> leaves	15,360	600	25.6	3.1 (2.5–3.8)	3.7 (3.0–4.5)	0.31 (0.25–0.38)	8.6 (6.4–11.0)	0.986 (0.982–0.989)	27 (18–35)	52 (38–82)	0.88 (0.73–0.96)	0.05 (0.01–0.09)	0.0327 (0.0183–0.0320)	0.00220 (0.00064–0.00440)
<i>Triticum</i> spp. and <i>S. cereale</i> leaves	9637	285	33.8	3.1 (2.7–3.5)	4.2 (3.5–4.8)	0.31 (0.27–0.35)	7.6 (6.0–8.9)	0.973 (0.969–0.979)	28 (23–33)	55 (35–75)	0.89 (0.84–0.92)	0.06 (0.04–0.08)	0.0318 (0.0177–0.0243)	0.00239 (0.00099–0.00487)

Observed ranges are shown in round brackets. Variables are: S_v , fuel particle surface area-to-volume ratio; ρ_p , fuel particle density; S_m , fuel particle surface area-to-mass ratio; m_{in} , initial fuel mass; h , fuel bed height; w , fuel load; ρ_b , fuel bed density; ϵ , fuel bed porosity; t_{fl} , flame residence time; t_{bo} , burn-out time; x_{fl} , mass loss during flaming combustion as a fraction of initial fuel mass; x_{nf} , mass loss during non-flaming combustion as a fraction of initial fuel mass.

Table 2. Models fitted to the experimental combustion properties: coefficients and evaluation.

Model No.	Equation	a	b	c	R^2	RMSE	MAE	MAPE (%)	MBE
1	$t_{fl} = a S_m^b$	97.78 (77.01–124.2)	−0.3743 (−0.4740–−0.2746)	−	0.927	4.79	3.80	8.45	7.89×10^{-15}
2	$t_{fl} = a S_m^b w^c$	90.64 (73.55–111.7)	−0.2121 (−0.4037–−0.02056)	0.3891 (−0.02695–0.8052)	0.965	3.32	2.83	6.42	3.16×10^{-15}
3	$t_{bo} = a S_m^b$	528.8 (293.8–951.6)	−0.6940 (−0.9393–−0.4486)	−	0.886	44.2	33.7	24.9	$−1.26 \times 10^{-14}$
4	$t_{bo} = a S_m^b w^c$	389.1 (312.1–485.1)	−0.1390 (−0.3417–0.06320)	1.332 (0.8928–1.771)	0.997	7.62	6.66	6.53	1.11×10^{-14}
5	$dx_{fl}/dt = a S_m^b$	0.008367 (0.006347–0.01104)	0.4116 (0.2962–0.5271)	−	0.894	0.00240	0.00198	9.74	0
6	$dx_{fl}/dt = a S_m^b w^c$	0.009171 (0.007416–0.01134)	0.2006 (0.005896–0.3953)	−0.5064 (−0.9293–−0.08354)	0.951	0.00164	0.00129	5.75	$−1.54 \times 10^{-18}$
7	$dx_{nf}/dt = a S_m^b$	0.0003301 (0.0002143–0.0005085)	0.5694 (0.3889–0.7499)	−	0.910	0.000184	0.000147	13.8	1.81×10^{-20}
8	$dx_{nf}/dt = a S_m^b w^c$	0.0003874 (0.0002949–0.0005089)	0.2040 (−0.0461–0.4541)	−0.8769 (−1.420–−0.3337)	0.959	0.000124	0.000092	7.54	1.69×10^{-19}

95% confidence intervals for fitted coefficients a , b , and c are shown in round brackets. Abbreviations are: R^2 , coefficient of determination; RMSE, root mean square error; MAE, mean absolute error; MAPE, mean absolute percentage error; MBE, mean bias error. See the footnote of Table 1 for the definition of variables used in the equations.

Although variation in all combustion features was well explained by the S_m alone, the prediction of the t_{bo} benefitted considerably from using w . The S_m by itself was able to warrant good accuracy both for the remaining properties, namely the t_{fl} and dx_{fl}/dt (Figure 2). Except for Models 3 and 7, MAPE was below 10%. The fitted equations were unbiased (MBE ≈ 0).

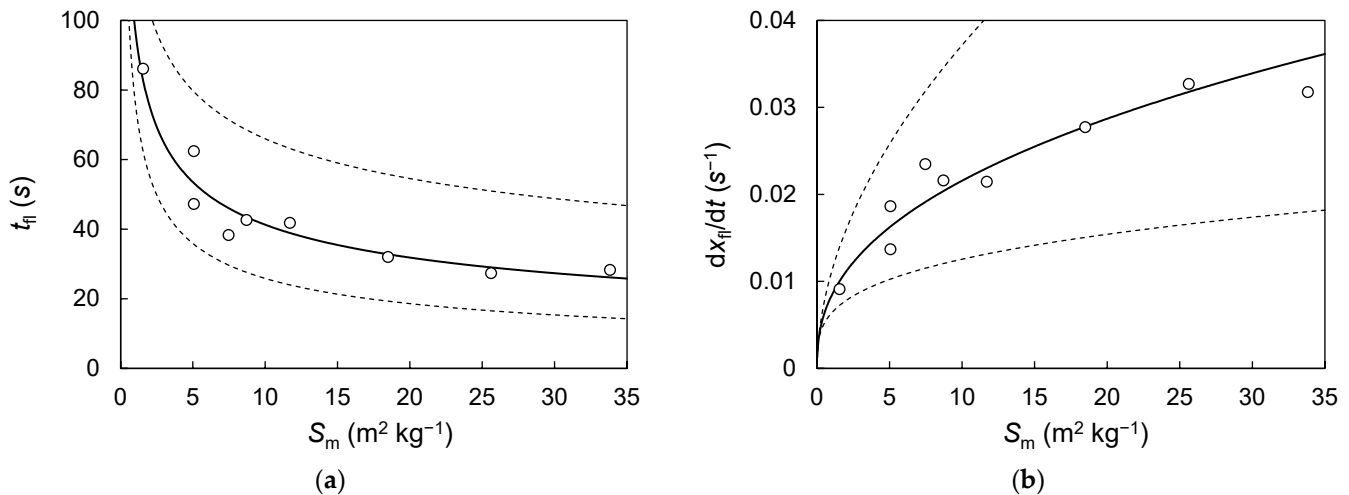


Figure 2. (a) Flame residence time (t_{fl}) as a function of fuel particle surface area-to-mass ratio (S_m), solid line is Model 1 in Table 2, dashed lines represent the 95% confidence interval; and (b) rate of mass loss during flaming combustion as a fraction of initial fuel mass (dx_{fl}/dt) as a function of S_m , solid line is Model 5 in Table 2, dashed lines represent the 95% confidence interval.

4. Discussion

We assessed the combustion features of small-scale laboratory fuel beds using eight fuel types, which provided a wide range in S_m . As hypothesised, the S_m by itself was able to warrant a good explanation of all combustion properties and always performed better than the S_v . Adding w as a predictor yielded improvements in all models, but mostly for the t_{bo} .

It could be anticipated that the best fuel metric for enhancing model predictability should be either h or w because in the *E. globulus* bark tests with a distinct m_{in} all combustion properties showed variation, although ρ_b and ε did not differ. The effect of the w on t_{fl} was also detected by Burrows [12] when burning single pieces and piles of *Eucalyptus marginata* Donn ex Sm. (jarrah) round wood in the laboratory; however, for fuel above 16 mm, the predicted t_{fl} for single fuel pieces was approximately the same as observed for piled twigs.

The difference between our results and the t_{fl} in other studies was mixed. Anderson [14] measured 76, 64, and 65 s, respectively for *Pinus ponderosa* Douglas ex C. Lawson (ponderosa pine), *Pinus contorta* Douglas (lodgepole pine), and *Pinus monticola* Douglas ex D. Don (white pine) needle laboratory fires, above our predicted values of 40, 38, and 34 s using Model 1 ($S_m = 11.2, 12.7, 17.1 m^2 kg^{-1}$). Conversely, Nelson and Adkins [15] obtained 27 s in *Pinus elliottii* Engelm. (slash pine) needle laboratory fires, slightly below our 38 s for *P. pinaster*. Wang et al. [27] derived values of 31 and 126 s in laboratory tests using fuel beds of *Pinus massoniana* Lamb. (Chinese red pine, $S_m = 9.4 m^2 kg^{-1}$) needles for w of 0.4 and $3 kg m^{-2}$, respectively; our Model 2 provides a similar value of 39 s for $w = 0.4 kg m^{-2}$ but underpredicts the t_{fl} at 86 s for $w = 3 kg m^{-2}$. Burrows [12] obtained 32 s for piles of *E. marginata* 3.3 mm twigs ($S_m = 1.6 m^2 kg^{-1}$, $w = 1 kg m^{-2}$), less than half of our 82 s value using Model 2; yet, the t_{bo} values were very similar, with 340 versus 364 s using Model 4. Stocks et al. [18] measured 46 and 66 s in savanna grass field fires, both above our observed values of about 30 s for herbaceous fuels (*Triticum* spp. and *S.*

cereale straw, *Triticum* spp. and *S. cereale* leaves). Taylor et al. [28] and Wotton et al. [19] reported mean t_{fl} of respectively 37 and 45 s in litter during high-intensity field experiments in forests, similar to our 38–43 s range obtained for *P. pinaster*, *E. obliqua*, and *E. globulus* leaves. Overall, our t_{fl} results agree reasonably well with those observed in free-spreading fires in litter fuels at w commonly attained in natural fuel beds ($\sim 0.5 \text{ kg m}^{-2}$) both in the laboratory and in real-world fires, despite the differences in scale, burning conditions, and evaluation methods.

A substantial part of the wide variation in reported combustion properties was most likely due to the great diversity of measurement procedures, like in the case of the t_{fl} . Some studies used thermocouples [13,16,18,19] to measure a threshold temperature that defined the transition between flaming and non-flaming combustion, but their location can vary from ground level to somewhere at the top or above the fuel bed and the temperature set varied widely (50–300 °C). Others used photocells to determine flame advancement [29] or did it by visual assessment, either measuring the t_{fl} directly [12] or determining flame depth and rate of spread [17] and then computing their ratio.

Even in the case where the measurement method was the same, there can be room for subjectivity. For example, both in Burrows [12] and in the present study, the t_{fl} and t_{bo} were visually assessed. However, Burrows [12] did not fully specify the criteria to define the t_{fl} and t_{bo} : it was not clarified if the t_{fl} was taken immediately after generalised flaming combustion ceased, even if some pockets of fuel continued to burn, or if the t_{bo} was taken when the m loss rate went below a threshold value. Thus, proper comparability between the results was facilitated if measurement methods were the same, but even in that case it was important to detail the criteria used for assessing the combustion properties. Comparing absolute m loss rates in units of g s^{-1} between studies was even more difficult because these rates depended on fuel quantity where using the same w is required for comparability, which is seldom verified because of diverse experimental conditions. Alternatively, measuring the dx_{fl}/dt and dx_{nf}/dt like we did, instead of absolute m loss rates, allowed for comparison independently of w .

The estimation of Byram's fireline intensity [30] relied on the x_{fl} to determine the fraction of w that burned in flaming combustion. We obtained a mean value of 0.88 for the finer fuels in our study (all except *E. globulus* twigs), whereas Burrows [12] measured 0.75. Not excluding that some of this discrepancy can arise from different criteria for defining the end of flaming combustion, it seems reasonable to speculate that the x_{fl} might decrease with w , since Burrows [12] used 1 kg m^{-2} piles and our w were always lower (0.31–0.74 kg m^{-2} , mean: 0.44 kg m^{-2}). Although the x_{fl} for finer fuels did not seem to be influenced by the S_m , the same will certainly not be valid for coarser fuels, as can be inferred from the results of Burrows [12], who observed a decrease in the x_{fl} for fuels above 6 mm (higher thickness means lower S_m). There seems to exist a threshold above which the x_{fl} changes from approximately constant to decreasing, which is most likely related with the passage of fuel particles from thermally thin (constant temperature throughout the fuel) to thermally thick (temperature gradient throughout the fuel).

The greatest limitations of this study were the scale effects of burning small-scale fuel beds and using a static combustion apparatus instead of a moving flame front. The ideal situation would be to measure the combustion characteristics of real-world moving fire fronts [19,28] in diverse vegetation. However, the inherent difficulties were manifest. Firstly, assessing properties like the t_{fl} by resorting to thermocouples or photocells [13,29] is problematic in the field; the easiest option is to resort to visual assessment [12,17]. But even so, conducting field experiments is costly in terms of preparation, material, and human resources; additionally, it is difficult to assess fuel metrics properly and to test in a wide range of vegetation types. Even in the laboratory, performing free-spreading burns in

large fuel beds with the purpose of reducing scaling effects can be challenging given the resources needed to collect and process large amounts of fuel. This was the reason why we chose to conduct our experimental programme in a small static combustion device, allowing us to focus on gathering various fuels covering a wide S_m range. Notwithstanding, given the similarities of the combustion process in a small or large fuel bed, we are convinced that even with these limitations our results on the effects of the S_m and w can be transferred to real-world free-spreading fires, as the comparison with results from other studies would suggest.

5. Conclusions

The main purpose of the present work was two-fold: to prove the hypothesis that the S_m is an adequate predictor of the combustion features of very diverse fuels and to develop models that could serve as a basis for predicting the combustion properties of free-spreading fires, namely the t_{fl} . Our empirical S_m -based models could accurately predict the combustion properties (t_{fl} , t_{bo} , dx_{fl}/dt , dx_{nf}/dt) of very diverse fuels, with a better performance than using the S_v . Although the S_m by itself provided good results, adding w as a predictor improved all models, especially in the case of the t_{bo} . We do not know at this point if our models can be used for moving fires exactly as they are presented in Table 2, since our small-scale experimental apparatus has probably introduced some edge effects. However, the t_{fl} from our models was in reasonable agreement with observations in free-spreading fires in litter fuels both in the laboratory (at $w \sim 0.5 \text{ kg m}^{-2}$) and in outdoor fires. Nonetheless, even if not directly applicable, we expect that the models functional form will remain valid for moving fire fronts, requiring only a refit using the t_{fl} data.

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Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

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List of Symbols, Units and Definitions

The following symbols are used in this manuscript:

a, b, c	Fitted coefficients used in several equations
h	Fuel bed height (cm)
m	Fuel mass (g)
m_{bo}	Residual mass after fuel burn-out (g)

m_{fl}	Residual mass at the end of flaming combustion (g)
m_{in}	Oven-dry initial fuel mass (g)
RH	Relative humidity (%)
S	Fuel particle surface area (m^2)
S_m	Fuel particle surface area-to-mass ratio ($m^2\ kg^{-1}$)
S_v	Fuel particle surface area-to-volume ratio (m^{-1})
T_a	Air temperature ($^{\circ}C$)
t_{bo}	Burn-out time (s)
t_{fl}	Duration of flaming combustion or flame residence time (s)
t_{nf}	Duration of non-flaming combustion (s)
V	Fuel particle volume (m^3)
w	Oven-dry fuel load ($kg\ m^{-2}$)
x_{fl}	Mass loss during flaming combustion as a fraction of initial fuel mass
x_{nf}	Mass loss during non-flaming combustion as a fraction of initial fuel mass
Greek symbols	
ε	Fuel bed porosity
ρ_b	Fuel bed density ($kg\ m^{-3}$)
ρ_p	Fuel particle density ($kg\ m^{-3}$)

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