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Fuel-related fire behaviour relationships for mixed live and dead fuels burned in the laboratory

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Abstract: A laboratory experimental program addressing fire spread in fuel beds composed of dead foliage litter and vertically placed quasi-live branches, representative of many natural fuel complexes, was carried out for either still air or wind conditions. Fuel bed characteristics, fire spread rate, flame geometry and fuel consumption were assessed and empirical models for estimating several parameters were developed. Weighted fuel moisture content (18–163%) provided good estimates of fire behaviour characteristics and accounted for most of the variation in still air and wind-driven spread rate (0.1–1.3 m min^{-1}). When predicting still-air fire spread rate, fuel height was the most relevant fuel bed structural parameter and fuel type had significant influence, whereas for wind-driven spread the effect of foliar fuel bed density was dominant and fuel type became irrelevant. Flame length (0.4–2.2 m) increased from still air to wind-assisted (8 km h^{-1}) fire spread but its height remained constant. The fraction of total fuel load and mean woody diameter consumed by fire were reasonably predicted from weighted fuel moisture content alone, but predictions for the latter variable improved substantially by adding foliar fuel load.

Key words: fuel moisture content, spread rate, flame geometry, fuel consumption.

Introduction

A century has passed after the first attempts at predicting forest fire behaviour. The models that have been developed since followed a wide variety of approaches, whose nature varied from purely empirical to a virtually complete physical description of the mechanisms of fire spread (Pastor 2003; Sullivan 2009). Spread rate (R_p) is the parameter most frequently sought to be estimated, for which fuel moisture content (M) has been recognized as a critical factor very early on (Show 1919).

The effect of dead fuel moisture content (M_d) on R_p is well established, but the same does not apply to live fuel moisture content (M_l). In fact, evidence from field fires hints at no influence of M_l on R_p (Alexander and Cruz 2013) or indicates a relatively weak and not entirely consubstantiated effect (Anderson et al. 2015). This contrasts with theoretical formulations (e.g., Rothermel 1972; Van Wagner 1989) and results from laboratory experiments (Plucinski et al. 2010; Marino et al. 2012; Weise et al. 2016). Recently, laboratory fire-spread experiments in quasi-live fuel beds, i.e., comprised of live plants when collected and whose M_l (13–180%) varied as a function of storage time, showed a significant M_l effect on R_p, albeit low (Rossa et al. 2016). However, the individual roles of M_d and M_l for fires spreading in mixtures of dead and live fuels remain to be quantified. Fire-spread moisture damping is expected to differ between dead and live fuel because differences in other fuel properties influence heat transfer and affect the ease with which moisture can be evaporated (Wilson 1990; Catchpole and Catchpole 1991).

Research needs on the influence of fuel bed properties on fire behaviour in mixtures of dead and live fuels go beyond the effect of M alone and extend to fuel bed structure as described by its load (w), height (h), and bulk density (ρ). Empirical field studies invariably report the difficulties in identifying and separating the effects of individual fuel properties on fire behaviour (Vega et al.

1998; Fernandes et al. 2000; Anderson et al. 2015). Obvious reasons for this are the natural heterogeneity in fuel complex properties, difficult to describe and to account for, and the existence of correlations between fuel descriptors, which complicates the detection and isolation of specific effects. Live fuel complexes have vertical orientation and are often tall and characterized by heavy fuel load, and for these reasons are difficult to be reproduced in the laboratory, having discouraged researchers from doing so. Weise et al. (2016) carried out an extensive set of laboratory fire spread experiments in shrub fuels, reported as 'high-density' and apparently not vertically oriented as in the field. Nelson and Adkins (1986) performed laboratory experiments of wind-driven fire spread in fuel beds of pine needles, over layered by vertical saw palmetto fronds, but fuel bed structure was maintained constant hindering the analysis of its effect on R_p. There is a great need for improved knowledge on the mechanisms of fire spread in live vegetation (Finney et al. 2013), because many fuel complexes are typically composed of live and dead fuels. Until those mechanisms are clearly established the task of predicting fire behaviour in natural fuel beds is greatly impaired.

We carried out a laboratory experimental burning program in mixed live and dead fuels, either in still air or wind conditions. The purpose was to increase understanding of the separate role of M_d and M_l on fire behaviour and to analyse the influence of relevant fuel structure descriptors such as h, w, and ρ. Spread rate, flame geometry and fuel consumption were measured and their variation described through empirical models.

Methods

Burn program

A total of 102 fire spread experiments in fuel beds composed of a litter layer (dead foliage) over layered by vertically oriented quasi-live fuels, thus approaching the natural fuel structure, were conducted in the University of Trás-os-Montes e Alto Douro (Vila Real, Portugal) between June 2015 and April 2016. All burn experiments were carried out on level ground, of which half under still air conditions and half at 8-km h^{-1} wind speed (U). Wind was measured in the absence of fire just above the center of the fuel bed area, and resulted from a laminar flow induced by a 2.2 kW ventilator (Soler & Palau Model CVTT-15/15). The experiments were time consuming, averaging 4–5 h per test, between fuel collection and preparation, building the fuel beds, and burning.

Fuel species, collection, and storage

The branches were obtained from two of the most abundant tree species in the Portuguese forest, respectively *Eucalyptus globulus* Labill. (blue gum) and *Pinus pinaster* Ait. (maritime pine). We collected one species at a time from a single location by cutting down ~5-year-old *P. pinaster* and ~10-year-old *E. globulus* trees, removing the branches from the trunk, and carrying them to the laboratory, where they were cut at 0.4 m and allowed to dry under ambient conditions for a variable amount of time in order to get a wide range of moisture contents. M_l in this work refers to quasi-live foliar moisture only and was measured independently from woody fuel moisture content (M_{wd}). The former was periodically monitored using a fuel moisture analyzer (Rossa et al. 2015) so that the experiments could be carried out over a well-distributed and wide M_l range. We used foliar litter from *P. pinaster*, *E. globulus*, and *Pinus resinosa* Ait. (red pine). Litter M_d is dependent on ambient conditions only, thus control of storage time was not a concern.

Test rig, fuel bed preparation, and pre-burn sampling

We used a 4-m long and 3.5-m wide combustion table uniformly covered with lightweight expanded clay aggregate particles (LECA), allowing upright stem insertion. Fuel beds were 1-m long and 1.2-m wide (Fig. 1). Three fuel complexes were used: *P. resinosa* litter with quasi-live *P. pinaster* canopy (PR), *P. pinaster* litter with quasi-live *P. pinaster* canopy (PP), and *E. globulus* litter with quasi-live *E. globulus* canopy (EG). The peculiar fuel combination used in the PR experiments was an attempt to obtain fuel beds with a thin litter layer since *P. resinosa* litter is more compact than *P. pinaster* litter. We carried out 24 PR tests but then proceeded with using *P. pinaster* only as it was difficult to acquire the required quantity of *P. resinosa* needles.

Fig. 1 about here

We used five nominal levels of litter load, respectively 0.3, 0.5, 0.7, 0.9, and 1.1 kg m^{-2}, mostly regularly distributed among the fuel type - wind mode combinations (Table 1). Litter load measurement on a wet basis was adopted to avoid computing the M_d-corrected fuel weight. Actual litter load (w_d) was calculated on a dry basis after measuring M_d. Branch load was not set to specific levels. The first test of the day was usually used for determining a weight that would allow a continuous canopy, and it was kept constant throughout the day. Nevertheless, the need for managing the available branches, whose collection and preparation was the most time consuming task, occasionally led to significant differences in the amount of fuel used in the experiments. Because quasi-live fuel load (w_l) considered just the foliar component, the foliar fraction of *P. pinaster* and *E. globulus* branches was estimated as the mean of 20 observations per species; each was obtained by randomly selecting a branch from the fuel pile, removing its foliage, and weighing the foliar and woody components. Fuel beds were prepared by spreading the litter fuel first, and vertically inserting the branches afterwards, attaining homogeneous horizontal distribution and vertical continuity with the litter layer (see Fig. 1).

Table 1 about here

Litter depth and distance from litter surface to the top of the fuel bed were measured (n = 5 for each), respectively before and after stem insertion. The sum of their means yielded h. Prior to ignition, air temperature (T) and relative humidity (RH) were measured with a pocket weather station. We collected three fuel samples to determine M_d (litter), M_l (quasi-live foliage) and M_{wd} (quasi-live woody fuel) by oven-drying at 105 ºC during 24 h. Each sample comprised material collected from various locations in the fuel bed and cut into small pieces for faster and thorough drying. Using M_d, M_l, and the fractions of dead (f_d) and quasi-live (f_l) foliage, we computed the weighted foliar fuel moisture content (M_w):

(1) $$M_w = f_d \cdot M_d + f_l \cdot M_l$$

where quantities f_d and f_l were calculated using eq. 2 with either w_d or w_l as the numerator, or using eq. 3 when one of the fractions was known:

(2) $$f_d = \frac{w_d}{w_l + w_d}$$

(3) $$f_d + f_l = 1$$

Eq. 2 denominator corresponds to w, which accounts for foliar fuels only. Thus, Eq. 1 is equal to the ratio between the water mass contained in the fuel bed foliage (dead and quasi-live) and the total foliar dry mass. We obtained ρ by computing the ratio w / h.

Ignition, fire behaviour, and fuel consumption

The burn area was preceded by a 10-cm wide and approximately 2-cm deep strip of *P. pinaster* litter for facilitating fire spread through the canopy from the beginning of the fuel bed. A line of fire was rapidly established by lighting up a wool thread soaked in a 6:4 gasoline to diesel mixture.

R_p was determined by measuring the time the base of the flame took to travel the length between two cotton strings placed above the litter, which broke almost immediately after flame contact. The strings were placed 0.9 m apart, leaving 5 cm at both the beginning and the end of the fuel bed to diminish border effects during measurement.

Flame geometry was assessed when fire reached the fuel-bed midway, by visually estimating average flame height (H_f), measured from the base of the fuel bed with the assistance of a tape measure, and angle (φ). We evaluated φ by visually dividing the 90º between the horizontal and the unburned fuel in two 45º sections, and then each of them in three 15º intervals and approximating the flame angle to the nearest value. Trigonometry was used to calculate flame length (L_f). We computed the ratio h/H_f, which for no-wind fires spreading on level ground is the same as h/L_f because $L_f \approx H_f$. Flames always develop above the fuel bed ($H_f > h$) in well-sustained fires, which means that $h/H_f < 1$. L_f cannot directly be inferred from h/H_f when fire spread is wind-driven. Nonetheless, estimating H_f from this non-dimensional ratio should provide some independence from fuel bed structure, because w is the structural parameter with greater influence on flame dimensions (Fernandes et al. 2009) and is highly correlated with h in natural fuel complexes (Fernandes 2001).

Five measurements were taken of the mean terminal diameter of woody fuels (D_{wd}) after fire extinction. Branch remnants were weighed and assumed to be virtually moist free due to heat exposure. We did not assess the remnants moisture content but they appeared extremely dry when collected. Fuel load consumption was estimated as 90% of the difference between total initial fuel dry weight and the remaining fuel, to account for ash (Burrows 2001). The fraction of fuel consumed by fire (f_{cs}) was determined as the ratio of fuel consumption to total initial load.

Data analysis and modelling

Fuel bed parameters h, w, and ρ were considered for R_p modelling. We analyzed their distributions by computing mean values and standard deviations, and 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.

R_p was modelled separately for the still air (R_0) and wind-driven fire spread (R_U) datasets. We examined the M effect on R_p both as an exponential decay (e.g., Wilson 1990; Anderson et al. 2015) and a power law function (e.g., Burrows 1999; Cheney et al. 2012), and examined whether M_d, M_l or M_w provided the highest explanation (coefficient of determination, R^2) of the observed variability. Fuel structure metrics were then examined for their ability to improve the best-fitting M-based equation. All functions were fitted in their log-transformed form by least-squares, as often is the case in empirical fire behaviour modelling (Marsden-Smedley and Catchpole 1995; Cheney et al. 2012). The bias inherent to back-transformation was corrected according to Snowdon (1991). Model selection for a given fire behaviour variable took into account its practical use and the R^2 value.

The ratio h/H_f and fuel consumption were modelled from the M metric that best explained R_p. We described h/H_f and D_{wd} using linear relationships and again tested which fuel structure variables added to the M-based explanation. As f_{cs} varies in the 0–1 range it was modelled using a generalized linear model (GLM), fitted through an iterative process by maximum likelihood estimation with a logit link function.

The influence of fuel bed type was examined after accounting for the effects of M and fuel bed structure. In joint analysis of still air and wind-driven trials the effect of wind mode was examined as a categorical variable. Residuals where checked for approximate normality by visually inspecting their histograms, and independence from predicted values was evaluated by correlation analysis. In models with more than one independent variable the existence of significant correlations between them was also verified. Predictions were evaluated based on deviation measures, respectively root mean square error (RMSE), mean absolute error (MAE), mean absolute percentage error (MAPE), and mean bias error (MBE) (Willmott 1982).

Results

Data ranges

The pre-burn duration of quasi-live fuel storage varied from one to 43 days. We aimed at maintaining M_l above 50%, the typical minimum value for Mediterranean shrubs (Viegas et al. 2001), but it was occasionally lower, ranging between 30 and 214% (Table 2). The drying rate of woody fuels was similar to that of foliage because M_{wd} (33–215%) was always very similar to M_l. M_d varied narrowly (10–22%) as a result of moderate variation in ambient air conditions inside the laboratory. M_w varied nine fold as a result of variation in M_l and M_d. The mass of foliage in *P. pinaster* and *E. globulus* branches was 74.8 and 74.2% of the total, respectively. Except for *h*, substantial variation was obtained regarding fuel structure, with f_d, w, and ρ varying approximately by factors of five, three, and three. Fuel variables were normally distributed according to the Shapiro-Wilk test, except the R_0-dataset w distribution, which from visual inspection of its histogram we concluded to be approximately normally distributed.

Table 2 about here

Fire behaviour and fuel consumption

Table 3 gives the R^2 for the tested models and Table 4 displays the results for those selected for further analysis, including the fitted coefficients (*a*, *b*, c) and evaluation metrics for each equation. R_p was better related to M_l than to M_d, both under still air and wind conditions, probably because of the much larger range of the former. However, it was M_w that accounted for more variability. A power law described the effect of M_w on R_p better than an exponential function, with R^2 increasing ~20% to 0.753 and 0.821, respectively for still air and wind-driven spread. M_w accounted for most of R_p variation but fuel bed parameters offered further improvement, with h and ρ producing the greatest increase in R^2, respectively for R_0 (up to 0.814) and R_U (up to 0.885) (eqs. 1 and 2 in Table 4). Fuel bed type exerted a significant ($P < 0.0001$) effect on R_0 and increased the R^2 by 17%, with EG>PP>PR. For the sake of generalization, we decided not to include this variable in the model (Fig. 2). The quality of fit was confirmed by MAPE of 18% and 13%, respectively for R_0 and R_U. Predicted R_0 and R_U as a function of M_w are given in Fig. 3, respectively for $h = 0.33$ kg m^{-3} and $\rho = 4.4$ kg m^{-3}, the experimental means. For comparison purposes, Fig. 3 also displays a model of the same form of eqs. 1 and 2 in Table 4, without the effects of fuel structure descriptors, and fitted to Rossa et al. (2016) data for slope-driven spread (R_S) in quasi-live woody fuel beds; in these experiments slope angle was 20º and h was 0.50–0.55 m.

Table 3 about here

Fig. 2 about here

Fig. 3 about here

When predicting h/H_f from M_w, the addition of w as an independent variable produced a modest R^2 increase (3.8%). The model retained M_w only (eq. 3 in Table 4) for the sake of parsimony, resulting in good fit (Fig. 4) with a MAPE of 11%.

Fig. 4 about here

The GLM model for f_{cs} (eq. 4 in Table 4, Fig. 5) had a MAPE of 15% (n = 88). Residuals of the model differed by wind mode (P = 0.007), showing a slight tendency for higher f_{cs} in the presence of wind. Using M_w alone to predict D_{wd} explained 66.7% of the existing variability. Adding w to the equation increased R^2 by 10%, which justified its inclusion as an independent variable (eq. 5 in Table 4). Predicted *v.* observed values are displayed in Fig. 6 and a MAPE of 12% indicates good performance.

Fig. 5 about here

Fig. 6 about here

Table 4 about here

Discussion

M_w was a good predictor of both R_0 and R_U in fuel beds that combined live and dead fuels in distinct layers, accounting for most of the variation in the dependent variables. This suggests that, at least for practical purposes, vegetation phenology is irrelevant to fire spread in the sense that the R_p response to M does not differ between live and dead fuels. The power-function damping effect of M_w was not affected by wind mode, being similar for R_0 (b = -0.7) and R_U (b = -0.6) (Fig. 3), and resulting in a R_p response equal to that observed in fuel beds composed of a single vegetative state, as in Rossa et al. (2016) (see Fig. 3). The weak damping effect at M_w above ~100% is explained by the ratio between fuel heat content and the energy necessary for fuel ignition variation with M (Rossa 2017). Marino et al. (2012) also found M_w to be a good predictor of R_U in laboratory-built shrub-litter fuel beds; their M_w range precluded conclusions about the effect on R_p at M_w >80%. It follows that fuel complexes increasingly dominated by live fuels will exhibit more marked seasonal variation in fire behaviour if drought impacts M_w, which is consistent with reports of M_l thresholds for increased fire activity (e.g., Dennison and Moritz 2009). The 'real world' performance of our $M_w^{-0.63}$ damping effect for wind-assisted tests could be examined using experimental field data, for which the role of M_l on R remains uncertain (e.g., Anderson et al. 2015).

The contribution of fuel bed metrics to improve the prediction of R_p was modest, first of all because the M effect was the study main focus and fuel structure was much less variable than M_w. Also, most tests were carried out with h, w, and ρ close to their mean values. In the R_0 dataset the means and coefficients of variation were $h = 0.33$ m (8.8%), $w = 1.5$ kg m^{-2} (16.5%), and $\rho = 4.4$ kg m^{-3} (18.8%). In the R_U dataset we obtained $h = 0.35$ m (7.4%), $w = 1.5$ kg m^{-2} (20.3%), and $\rho =$ 4.4 kg m^{-3} (19.0%). In the wind-driven fire spread experiments the fuel bed parameter with the highest leverage was ρ. A decrease of R_U with ρ is well established, both in the laboratory and in field studies. Our $\rho^{-0.49}$ effect is stronger than in Marino et al. (2012) ($\rho^{-0.21}$) and very similar to that reported by Anderson et al. (2015) ($\rho^{-0.48}$).

As ρ is given by w/h, a proper evaluation of the individual and interacting influences of w and h requires measuring R_U at variable w for fixed h levels and vice versa, using a wide range in both w and h. Catchpole et al. (1998) have shown that R_U rises with decreased w (at constant h) and increased porosity. Then, it can be speculated that the ρ influence might be explained by a combination of two effects: (*i*) higher w enhances combustion intensity and flames are more difficult to tilt, diminishing heat transfer; and (*ii*) higher h increases porosity and favours heat transfer (Holdich 2002).

The h/H_f equation revealed an interesting trait of flame geometry: H_f remained fairly constant when fire spread was wind-assisted, although L_f increased as expected. Further experimentation is needed for verifying if this relation holds for other wind speeds. If further studies confirm that h/H_f

can be reasonably predicted based on M_w alone, its estimation can be operationally useful. Both *h* and H_f can be visually assessed in the field and used to obtain a gross estimate of M_w in fuel complexes composed of live and dead fuels.

The ability to predict f_{cs} is also useful in fire management but has been neglected in shrub-dominated fuel types (Fernandes and Loureiro 2013; Ottmar 2014). The purpose of many prescribed fire operations is to reduce fuel load. Being able *a priori* to predict the degree of fuel consumption is important for planning and evaluating hazard-reduction burns. Predicting f_{cs} from fuel moisture alone is appealing, although the difficulty in estimating M_l is a relevant concern. Using M_w as a single independent variable was less effective when predicting D_{wd}, and adding *w* to the equation increased accuracy. The improvement makes sense, as burning a larger amount of fine fuels increases fireline intensity which in turn allows consuming a larger amount of coarse woody fuels, as found by several studies (e.g., Hollis et al. 2011).

Summary and conclusions

We carried out an experimental burning program in the laboratory in fuel beds composed of litter and vertically arranged quasi-live branches, representative of many natural fuel complexes, under either no-wind or wind conditions. We measured fuel bed characteristics, fire spread rate, flame geometry, and fuel consumption, and fitted empirical equations that describe the effects of the relevant independent variables.

M_w-based models allowed effective prediction of fire behaviour characteristics and fuel consumption. We found no support for a differential role of live and dead fuel moisture content in fire spread. M_w accounted for most of the observed variation in R_p for both still air and wind-driven spread, although in no-wind conditions *h* was the most relevant fuel structure variable, whereas the effect of ρ dominated wind-driven spread. H_f remained constant during wind-assisted fire spread although L_f increased. Reasonable predictions of f_{cs} and D_{wd} were obtained by using M_w alone, but adding w as an independent variable substantially improved D_{wd} estimates.

Fire behaviour studies dedicated to fuel complexes with a relevant live fuel component are scarce. This study results offer increased understanding of how fuel characteristics affect fire behaviour in mixed live-dead fuels and are useful to inform subsequent experimental efforts in relation to fire behaviour modelling and fire danger rating. As live and dead fuels in this study formed contiguous layers, future efforts could examine whether fuel-related fire behaviour relationships change with alternative fuel arrangements.

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List of symbols

a, b, c, fitted coefficients used in several equations

D_{wd} (mm), mean post-fire terminal diameter of woody fuels

f_{cs}, fraction of the total fuel load consumed by fire (including woody components)

f_d, fraction of dead fuels

f_l, fraction of live or quasi-live fuels

h (m), fuel bed height

H_f (m), flame height (measured from the base of the fuel bed)

L_f (m), flame length (measured from the base of the fuel bed)

M (%), fuel moisture content (dry basis)

M_d (%), dead foliage moisture content

M_l (%), live or quasi-live foliage moisture content

M_w (%), weighted foliar fuel moisture content

M_{wd} (%), woody fuel moisture content

R_p (m min^{-1}), fire spread rate

R_s (m min^{-1}), slope-driven fire spread rate

R_U (m min^{-1}), wind-driven fire spread rate

R_0 (m min^{-1}), basic fire spread rate (i.e., on level ground in the absence of wind)

RH (%), air relative humidity

T (ºC), air temperature

U (km h^{-1}), wind speed

w (kg m^{-2}), total foliar fuel load (dry basis)

w_d (kg m^{-2}), litter fuel load

w_l (kg m^{-2}), live or quasi-live foliage fuel load

Greek symbols

φ (º), flame angle (measured between the flame and the unburned fuel bed)

ρ (kg m^{-3}), foliar fuel bed density

Tables and table captions

Note: The tables below embedded as pictures were uploaded separately as individual files.

Table1. Nominal litter fuel load (wet-basis) repetitions per fuel bed and wind mode

Fuel load	PR		PP		EG	
(kg m^{-2})	no-wind	wind	no-wind	wind	no-wind	wind
0.3	4	4	4	5	4	5
0.5	4	4	4	5	4	5
0.7	4	4	4	5	4	5
0.9	-	-	9	9	-	-
1.1	-	-	6	-	-	-

Note: PR, litter of dead *Pinus resinosa* needles and canopy of quasi-live *Pinus pinaster* branches; PP, litter of dead *P. pinaster* needles and canopy of quasi-live *P. pinaster* branches; EG, litter of dead *Eucalyptus globulus* leaves and canopy of quasi-live *E. globulus* branches.

Table 2. Range of main experimental parameters (see 'List of symbols' for an explanation of variables).

Fuel bed	U (km h^{-1})	n	h (m)	T (ºC)	RH (%)	M_d (%)	M_l (%)	f_d	M_w (%)	w (kg m^{-2})	ρ (kg m^{-3})	R_p (m min^{-1})	φ (º)	L_f (m)	D_{wd} (mm)
PR	0	12	0.309–0.361	20.8–26.3	57.5–81.0	14.0–22.4	81.2–213.6	0.19–0.38	69.3–161.7	1.27–1.62	3.87–4.69	0.127–0.281	90	0.35–0.75	1.0–4.5
	8	12	0.292–0.380	20.8–26.3	57.5–81.0	14.8–19.4	74.8–221.1	0.20–0.39	59.1–163.0	1.24–1.65	3.91–4.85	0.143–0.540	45–75	0.37–0.92	2.0–4.2
PP	0	27	0.263–0.380	14.7–26.8	48.3–71.3	12.3–19.7	55.7–155.5	0.18–0.64	35.7–123.1	1.17–1.85	3.51–5.77	0.111–0.308	90	0.40–0.95	2.6–6.3
	8	24	0.305–0.374	14.7–26.8	47.5–71.3	12.7–21.6	47.1–158.7	0.18–0.47	34.3–124.0	1.14–1.92	3.57–5.88	0.249–0.666	45–60	0.57–1.27	2.6–5.8
EG	0	12	0.336–0.398	20.4–23.5	43.7–73.0	10.0–14.8	30.3–90.9	0.20–0.62	21.1–66.5	0.67–1.69	1.98–4.34	0.199–0.656	90	0.60–1.20	3.5–6.2
	8	15	0.327–0.406	20.0–23.5	43.7–73.0	9.8–12.8	28.9–95.8	0.13–0.61	18.0–77.1	0.66–2.43	2.02–6.10	0.416–1.285	30–45	1.27–2.20	3.5–6.0

Note: PR, litter of dead *Pinus resinosa* needles and canopy of quasi-live *Pinus pinaster* branches; PP, litter of dead *P. pinaster* needles and canopy of quasi-live *P. pinaster* branches; EG, litter of dead *Eucalyptus globulus* leaves and canopy of quasi-live *E. globulus* branches.

Table 3. Coefficient of determination R^2 for the tested models; for each variable the highest R^2 is shown in bold font (see 'List of symbols' for an explanation of variables).

Variable	Model	*n*	R^2
R_0	$a\ \exp(b\ M_d)$	51	0.067
	$a\ \exp(b\ M_l)$		0.641
	$a\ \exp(b\ M_w)$		0.647
	$a\ M_w^b$		0.753
	$a\ M_w^b\ h^c$		**0.814**
	$a\ M_w^b\ w^c$		0.770
	$a\ M_w^b\ \rho^c$		0.799
R_U	$a\ \exp(b\ M_d)$	51	0.143
	$a\ \exp(b\ M_l)$		0.655
	$a\ \exp(b\ M_w)$		0.665
	$a\ M_w^b$		0.821
	$a\ M_w^b\ h^c$		0.819
	$a\ M_w^b\ w^c$		0.881
	$a\ M_w^b\ \rho^c$		**0.885**
h/H_f	$a + b\ M_w$	102	0.833
	$a + b\ M_w + c\ h$		0.833
	$a + b\ M_w + c\ w$		**0.865**
	$a + b\ M_w + c\ \rho$		0.864
D_{wd}	$a + b\ M_w$	102	0.667
	$a + b\ M_w + c\ h$		0.676
	$a + b\ M_w + c\ w$		**0.732**
	$a + b\ M_w + c\ \rho$		0.712

Table 4. Coefficients and evaluation metrics for the selected models; 95% confidence intervals for *a*, *b* and *c* are shown in parenthesis (see 'List of symbols' for an explanation of variables).

Model	*a*	*b*	*c*	RMSE	MAE	MAPE	MBE
[1] $R_0 = a\ M_w^b\ h^c$	12.657 (5.078–31.55)	-0.7443 (-0.8592– -0.6295)	0.8090 (0.1389–1.479)	0.0556	0.0432	17.7	0.00
[2] $R_U = a\ M_w^b\ \rho^c$	13.14 (8.035–21.50)	-0.6253 (-0.7212– -0.5293)	-0.4895 (-0.7335– -0.2456)	0.0723	0.0545	12.7	0.00
[3] $h/H_f = a + b\ M_w$	0.1998 (0.1687–0.2310)	0.00443 (0.004036–0.004823)	-	0.0689	0.0535	11.1	0.00
[4] $f_{cs} = 1 / (1 + \exp(-(a + b\ M_w)))$	2.647 (1.415–4.047)	-0.03064 (-0.04974– -0.01346)	-	0.0757	0.0586	14.9	0.00
[5] $D_{wd} = a + b\ M_w + c\ w$	4.316 (3.617–5.015)	-0.02553 (-0.02886– -0.02221)	1.041 (0.621–1.461)	0.5782	0.4441	12.2	0.00

Figures and figure captions

Note: The figures below embedded as pictures were uploaded separately as individual files.

Fig. 1. Combustion table with a fuel bed of *Eucalyptus globulus* leaves litter over layered by quasi-live vertical *E. globulus* branches during a wind-driven (8 km h^{-1}) fire spread test.

Fig. 2. Predicted *v.* observed: (*a*) basic fire spread rate (R_0); (*b*) wind-driven fire spread rate (R_U, U = 8 km h^{-1}). The solid lines correspond to perfect agreement. Model equations, coefficients, and evaluation metrics are in Table 4.

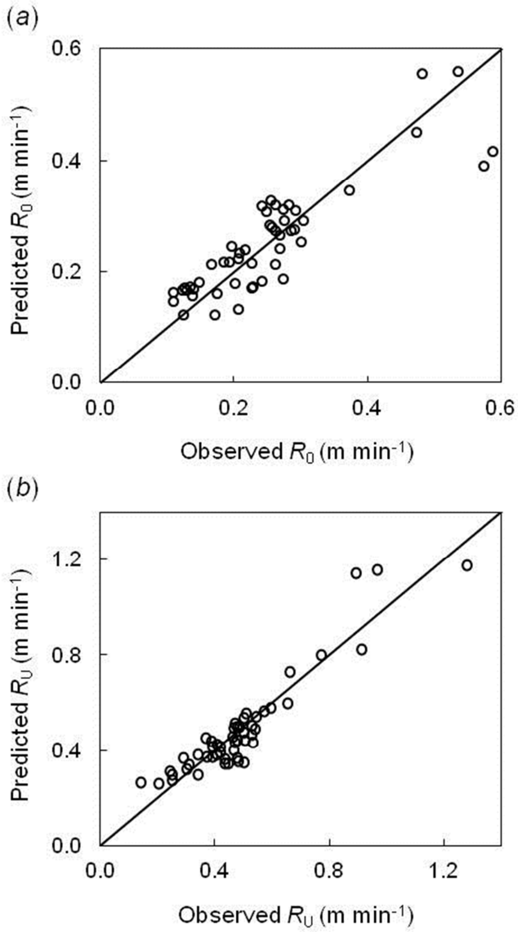

Fig. 3. Predicted basic fire spread rate (R_0) for constant fuel bed height (h = 0.33 m, experimental mean), wind-driven fire spread rate (R_U, U = 8 km h^{-1}) for constant foliar fuel bed density (ρ = 4.4 kg m^{-3}, experimental mean), and slope-driven fire spread rate (laboratory data of 50 tests in fuel beds of quasi-live vertical branches with a slope angle of 20º retrieved from Rossa et al. 2016, R_s = 8.98 $M^{-0.579}$, R^2 = 0.667), as a function of foliar fuel moisture content (M). Model equations, coefficients, and evaluation metrics for R_0 and R_U are in Table 4.

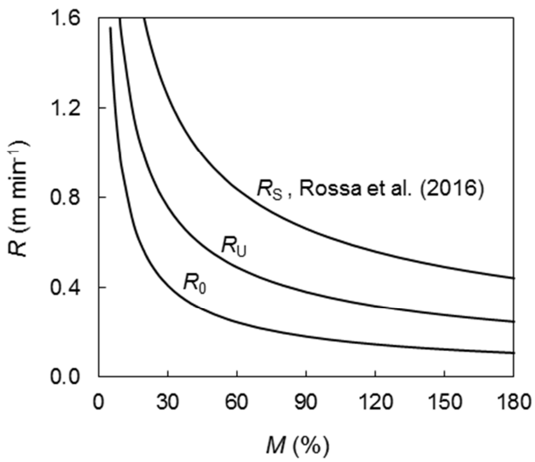

Fig. 4. Ratio between fuel bed height (*h*) and flame height (H_f) (measured from the base of the fuel bed) as a function of weighted foliar fuel moisture content (M_w). The solid line corresponds to the model equation whose coefficients and evaluation metrics are in Table 4.

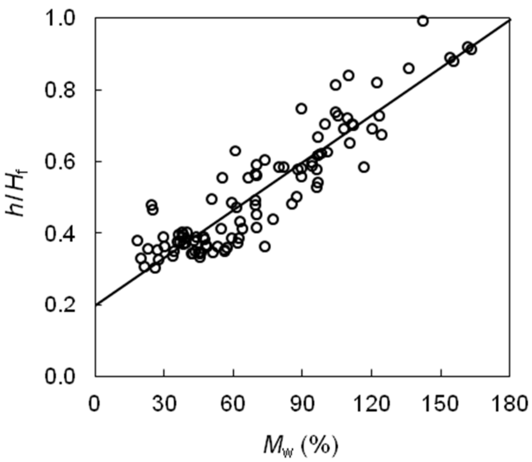

Fig. 5. Fraction of the total fuel load consumed by fire (f_{cs}) as a function of weighted foliar fuel moisture content (M_w). The solid line corresponds to the model equation whose coefficients and evaluation metrics are in Table 4.

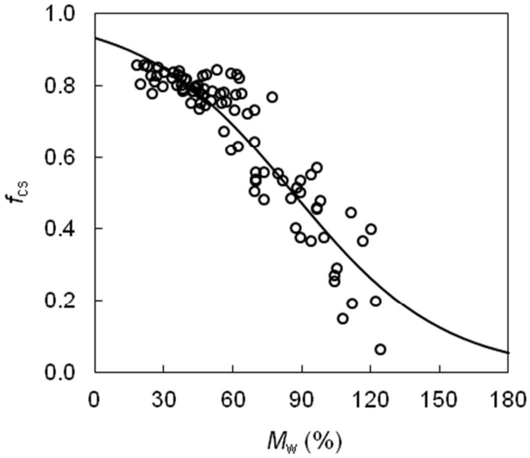

Fig. 6. Predicted *v.* observed mean post-fire terminal diameter of woody fuels (D_{wd}). The solid line corresponds to perfect agreement. Model equation, coefficients, and evaluation metrics are in Table 4.