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RESEARCH ARTICLE

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A generic fuel moisture content attenuation factor for fire spread rate empirical models

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Abstract

Aim of study: To develop a fuel moisture content (FMC) attenuation factor for empirical forest fire spread rate (ROS) models in general fire propagation conditions.

Methods: The development builds on the assumption that the main FMC-damping effect is a function of fuel ignition energy needs.

Main results: The generic FMC attenuation factor was successfully used to derive ROS models from laboratory tests (n = 282) of fire spread in no-wind and no-slope, slope-, and wind-aided conditions. The ability to incorporate the FMC attenuation factor in existing field-based ROS models for shrubland fires and grassland wildfires (n = 123) was also positively assessed.

Research highlights: Establishing *a priori* the FMC-effect in field fires benefits the proper assessment of the remaining variables influence, which is normally eluded by heterogeneity in fuel bed properties and correlated fuel descriptors.

Additional keywords: fire behaviour; fire management; live and dead fuels; experimental fires; wildfires.

Symbols used: a, b (fitted coefficients); c (specific heat, kJ kg^{-1} ºC^{-1}; subscripts: f, fuel; w, water); f_M (fuel moisture content attenuation factor); h (fuel bed height, m); M (fine fuel moisture content, %; subscripts: d, dead fuels; l, live fuels); Q (heat per unit mass of fuel needs, kJ kg^{-1}; subscripts: i, fuel ignition; w, water evaporation); R (fire spread rate, m min^{-1}; subscripts: 0, no-wind and no-slope; S, slope-driven; U, wind-driven); RH (relative humidity, %); S (slope angle, º); T (temperature, ºC; subscripts: a, air; f, fuel; i, ignition; v, vaporization); U (wind speed, km h^{-1}; subscript indicates measurement height, m); w (oven-dry fuel load, kg m^{-2}); ρ_b (fuel bed density, kg m^{-3}).

Authors´ contributions: CGR conceived the theoretical approach, analysed the data, and wrote the paper.

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Introduction

Although many fire spread metrics can be analysed in the field of forest fire behaviour modelling, such as fuel time to ignition (Madrigal *et al.*, 2011), flame residence time (Burrows, 2001), and flame geometry (Nelson & Adkins, 1988), spread rate (R) prediction is the focus of most studies. R estimates can be useful to assist fire management activities, such as prescribed burning (Fernandes *et al.*, 2009) or wildfire suppression (Finney, 1998).

R models can be obtained via two distinct methods (Van Wagner, 1971): a physical approach, *i.e.*, a mathematical description of the processes behind fire spread (Linn *et al.*, 2002), or an empirical approach, *i.e.*, the development of relationships between fuel and environmental parameters, derived from laboratory (Rossa *et al.*, 2015a) or field fires (Fernandes *et al.*, 2000). Nevertheless, because of key limitations associated with physical models (Cruz *et al.*, 2017), such as complexity and high computation time, support to fire management operations is and will continue to be based on empirically-based predictions for the foreseeable future (Sullivan, 2009).

Typical empirical R formulations (Cruz *et al.*, 2015) account for the fuel moisture content (M) effect through an M-damping function, hereafter called fuel content attenuation factor (f_M). Most frequently, f_M-functions are an exponential decay of the type exp(-b M) (Cheney *et al.*, 1993; Fernandes, 2001), but a power law of the type

$a\ M^{-b}$ is sometimes used (Cheney *et al.*, 2012), where a and b are fitted coefficients. Both functional forms have advantages and shortcomings. Exponential decay f_M vary between 0 ($M = \infty$) and 1 ($M = 0\%$) and allow obtaining a theoretical maximum R, *i.e.*, when fuel is moisture-free. However, because exponentials do not fit well to wide M-variations (Rossa & Fernandes, 2017a), extrapolations far outside the development M-range can be inaccurate. On the other hand, power law f_M provide a good fit to large M-intervals (Rossa, 2017), but do not offer reliable estimates for very low M-values because R tends rapidly to infinity when M approaches zero (Rossa & Fernandes, 2018a).

Although Rossa & Fernandes (2017a) show a very similar M-effect on R in no-wind and no-slope (R_0), slope- (R_S), and wind-driven (R_U) laboratory fires, currently, no f_M-function has been confirmed for the suitability to a general fire spread situation. In the present work, the hypothesis that a generic f_M can be used in empirical R models was tested. f_M was developed from the heat per unit mass of fuel requirements to ignite the fuel (Q_i) and does not have the above-mentioned constraints of exponential decay and power law functions. f_M was used to build R models from laboratory data and the ability to incorporate f_M in existing field-based models was also verified.

Methods

Fuel moisture content attenuation factor

Several factors beyond the heat needed to dry-out and ignite the fuel ahead of a flaming front have been attributed to the M-damping effect on R (Catchpole & Catchpole, 1991), such as the entrainment of moisture into the combustion zone and the attenuation of infra-red radiation by water vapour released from unburnt fuel. Still, not discarding those effects, in the present work Q_i will be assumed as the main responsible for slowing down fire spread. Q_i is given by (Rossa & Fernandes, 2018b):

$$Q_i = c_f\left(T_i - T_f\right) + \frac{M}{100}\left[c_w\left(T_v - T_f\right) + Q_w\right] \qquad [1]$$

where c_f, c_w, T_i, T_f, T_v, and Q_w, are, respectively, fuel specific heat, water specific heat, fuel igniting temperature, fuel initial temperature, water boiling temperature, and water latent heat of evaporation. In physically-based formulations (Thomas, 1971; Rothermel, 1972), Q_i is commonly used to account for the M-damping, as opposed to field-derived models. The relative M-effect on R, *i.e.*, f_M, results from dry-to-wet fuel ignition needs ratio:

$$f_M = \frac{\left(Q_i\right)_{M=0}}{Q_i} \qquad [2]$$

Although exponential decay or power law f_M-functions used in field-based R models are generally based solely on M, they implicitly account for the main variables determining the energy requirements to achieve ignition, *i.e.*, T_f and M (Eq. [1]). But because T_f and M are correlated for dead fuels, and dead fuels are present in most real-world fuel beds, specific f_M-factors work fine without explicitly accounting for T_f. This does not apply if f_M is based on Q_i. As a result, defining the numerator of Eq. [2] requires establishing T_f for which M will become 0%. Otherwise, predicted f_M will be systematically above real f_M values, causing an over-prediction bias. I assumed that fuel will attain moisture-free conditions at $T_f = 100$ ºC, which is water vaporization temperature and also roughly the temperature recommended to oven dry fuel samples (Matthews, 2010). If we consider the physical constants in Eq. [1] to be $c_f = 1.72$ kJ kg^{-1} ºC^{-1} (Balbi *et al.*, 2014), $c_w = 4.19$ kJ kg^{-1} ºC^{-1}, $T_i = 320$ ºC, $T_v = 100$ ºC, and $Q_w = 2260$ kJ kg^{-1} (Catchpole & Catchpole, 1991), we obtain:

$$f_M = \frac{378.4}{1.72\left(320 - T_f\right) + \frac{M}{100}\left[4.19\left(100 - T_f\right) + 2260\right]} \qquad [3]$$

Because it is not easy to measure or estimate T_f, air temperature (T_a) was used as a surrogate. f_M can theoretically vary between 0 and 1, as in the case of an exponential decay. Throughout the remainder of the paper f_M is Eq. [3], unless otherwise stated.

The M-effect on R will be restricted to fine fuels, which are responsible for 'carrying the fire' (Catchpole *et al.*, 1993). M represents fuel bed overall water content and, hence, is obtained by weighing dead (M_d) and live (M_l) fuel moisture contents based on mass fractions in fuel beds composed of dead and live fuels (Rossa & Fernandes, 2017b). Usually, fuel bed $M < 20\%$ is achieved when vegetation is composed only of dead fuels, which respond to T_a variations. As M_d gets closer to zero, lowering its value requires an exponential T_a increase. On the other hand, fuel bed $M >$ 20-30% is typically attained when vegetation also contains live fuels, whose M_l is insensitive to T_a. To obtain a continuous plot of f_M as a function of M, I considered an exponential T_f decrease between 100 ºC for $M = 0\%$ and an arbitrary value of 15 ºC for $M = 20\%$, and constant $T_f = 15$ ºC for $M > 20\%$.

Laboratory data

A total of 282 laboratory fires were retrieved from several sources (Table 1). R_0 tests ($n = 181$) compiled in Rossa & Fernandes (2018a) include experiments from

Table 1. Data sources and summary of fuel bed, ambient, and fire spread metrics.

Data type	Model no.	Reference of data compilation	Fire spread type	Fuel bed	n	w (kg m^{-2})	h (m)	T_a (ºC)	M (%)	R (m min^{-1})
Laboratory fires	1	Rossa & Fernandes (2018*a*)[A]	No-wind and no-slope	Litter, slash, and shrub-like fuel beds	181	0.45-3.50	0.020-0.508	13.0-37.7	6.0-161.7	0.025-1.301
	2	Rossa *et al.* (2016)	Slope-driven (S = 20º)	Shrub-like fuel beds	50	1.00-1.74	0.500-0.550	12.9-26.8	12.9-179.3	0.294-2.000
	3	Rossa & Fernandes (2017*a*)	Wind-driven (U = 8 km h^{-1})	Shrub-like fuel beds	51	0.66-2.43	0.292-0.406	14.7-26.8	18.0-163.0	0.143-1.285
Field fires (experimental)	4	Anderson *et al.* (2015)[B]	Wind-driven (U_2 = 2-25 km h^{-1})	Shrublands	100	0.32-5.22	0.210-4.800	7.0-33.0	26.8-101.9	0.800-43.90
Wildfires	5	Cheney *et al.* (1998)[C]	Wind-driven (U_{10} = 27-55 km h^{-1})	Grasslands	23	-	-	34.0-43.0	2.6-4.2	66.67-383.4

Variables used were: S, slope angle; U, wind speed (subscript indicates measurement height); w, fuel load; h, fuel bed height; T_a, air temperature; M, fuel bed fine fuel moisture content (live and dead fuels); R, fire spread rate. [A]Includes data from: Rossa (2009), Oliveira (2010) and Rossa & Fernandes (2018a). [B]Includes data from: Catchpole (1987), Vega *et al.* (1998), Fernandes (2001), Vega *et al.* (2006), Anderson (2009), and Cruz *et al.* (2010). [C]Includes data from: McArthur *et al.* (1982), Rawson *et al.* (1983), Keeves & Douglas (1983), Noble (1991), Maynes & Garvey (1985), McArthur (1966), Finocchiaro *et al.* (1970), Douglas (1970), and Cheney *et al.* (1998).

Rossa (2009) and Oliveira (2010), and pertain to fire spread in litter, slash, and shrub-like fuel beds, *i.e.*, vertically placed tree branches with or without a surface litter layer. Fuel beds were built using quasi-live, *i.e.*, collected live with M decreasing as a function of storage time, and dead vegetation of several species (*Pinus pinaster* Ait., *Eucalyptus globulus* Labill., *Eucalyptus obliqua* L'Her., *Acacia mangium* Willd., *Quercus robur* L., *Pinus resinosa* Sol. ex Ait.).

R_S burns (n = 50) with slope angle (S) set to 20º were retrieved from Rossa *et al.* (2016). Fuel beds were made of vertically positioned quasi-live shrub and tree branches of four species: *Acacia dealbata* Link., *Cytisus striatus* (Hill) Rothm., *P. pinaster*, and *E. globulus*. In the *A. dealbata* tests, air-dried leaves had contracted folioles, because they fold inward when branches are cut from the plant and surface-to-volume ratio is greatly diminished, attaining a fire behaviour similar to the remaining fuel species.

The R_U experiments (n = 51) from Rossa & Fernandes (2017a) were carried out under constant wind speed (U) of 8 km h^{-1} wind in shrub-like fuel beds, composed of vertically placed quasi-live tree branches over a dead litter layer. *P. resinosa* and *P. pinaster* needles were over-layered by *P. pinaster* branches, and *E. globulus* leaves were over-layered by *E. globulus* branches. In all laboratory trials (R_0, R_S, R_U), only the foliar fuel component was considered for computing oven-dry fuel bed load (w) and density (ρ_b) in vegetation containing woody elements.

Experimental field fires and wildfires data

The applicability of f_M to real-world fire spread was tested based on 123 outdoors fires (experimental and wildfires). A comprehensive data set (n = 100), representative of global shrubland fire behaviour, was retrieved from Anderson *et al.* (2015), which compiled data from Catchpole (1987), Vega *et al.* (1998), Fernandes (2001), Vega *et al.* (2006), Anderson (2009), and Cruz *et al.* (2010).

Wildfires in fully cured grasslands (n = 23), compiled by Cheney *et al.* (1998), were used to test f_M for fire spread in very low M conditions, seldom attained in experimental fires. Data provenance was Cheney *et al.* (1998) own observations, McArthur (1966), Finocchiaro *et al.* (1970), Douglas (1970), McArthur *et al.* (1982), Rawson *et al.* (1983), Keeves & Douglas (1983), Maynes & Garvey (1985), and Noble (1991). Fuel beds were undisturbed, cut or grazed, and eaten-out pastures. Because Cheney *et al.* (1998) did not report M, the Noble *et al.* (1980) equation describing the McArthur (1977) model: $M_d = (97.7 + 4.06\,RH) / (T_a + 6.0) - 0.00854\,RH$, where RH is relative humidity, was used to obtain M estimates.

Data analysis and modelling

f_M was used to develop R_0, R_S, and R_U models from the laboratory fire spread data. In the Rossa & Fernandes (2018a) R_0 formulation based on fuel bed height (h) and M, the h-exponent is close to unity. So, for the sake of simplicity, a linear h-effect was assumed. The present R_0 model was obtained by linear fitting R_0 to $h\,f_M$. In the case of R_S and R_U data, structural fuel bed metrics of most trials were close to the experimental mean, despite some variation between observed minimum and maximum h and w values. Also, both S and U were kept constant. As a result, M was the parameter with most influence on R_S and R_U, and both models were obtained by establishing a linear relationship between R and f_M.

Both studies where field fires were compiled (Cheney *et al.*, 1998; Anderson *et al.*, 2015) provide R models accounting for the M-effect through an exponential decay f_M, which, like Eq. [3] f_M, varies in the 0–1 range. Thus, the concept of using a generic f_M-function was tested by using the original R models, substituting their original (specific) f_M by the proposed generic f_M. In mixed live and dead fuel complexes, this exchange can only be done if the specific f_M-function accounts for both M_d and M_l, as in Anderson *et al.* (2015). Specific f_M were plotted against generic f_M-values and predictions using both f_M-functions were evaluated for comparison.

Goodness of fit of linear regressions was assessed based on the coefficient of determination (R^2). All predictions (laboratory and field fires) were evaluated using deviation measures: root mean square error (RMSE), mean absolute error (MAE), mean absolute percentage error (MAPE), and mean bias error (MBE) (Willmott, 1982).

Results

Both in the laboratory (6.0–179.3%) and outdoors (2.6–101.9%) fires the M-range was very wide (Table 1). Wildfires allowed testing f_M for extreme fire spread conditions with U_{10} (measured at a 10-m height) up to 55 km h^{-1} and an impressive R of 383.4 m min^{-1} (23 km h^{-1}). As expected, f_M evolution with M (Fig. 1) resembles the M-damping plots obtained using power law f_M-functions (Rossa, 2017), which are able to describe the M-effect well over wide ranges.

All laboratory R relationships yielded a good fit to the data (Fig. 2) with R^2 between 0.651 and 0.9. Model evaluation (Table 2) confirms these figures, with MAE and MAPE, respectively, in the range 0.06–0.19 m min^{-1} and 16.2–28.9%. f_M testing with field fires showed highly significant correlations (p<0.0001) between specific and generic f_M-derived values (Fig. 3), respectively of 0.457 for shrubland and 0.995 for grassland fires. The lower correlation for shrubland suggests a diminished sensitivity of the generic f_M to M. Nevertheless, generic f_M produced accurate predictions of all field data (Fig. 4) and, in fact, allowed for an overall improvement in model performance, for example with a decrease in MAPE from 70.6 to 63.4% in shrubland fires and 26.7 to 24.8% in grassland wildfires. Of course, the quality of predictions is mostly dictated by the original R formulation and these results only demonstrate that the proposed generic f_M is a reasonable surrogate for the specific f_M.

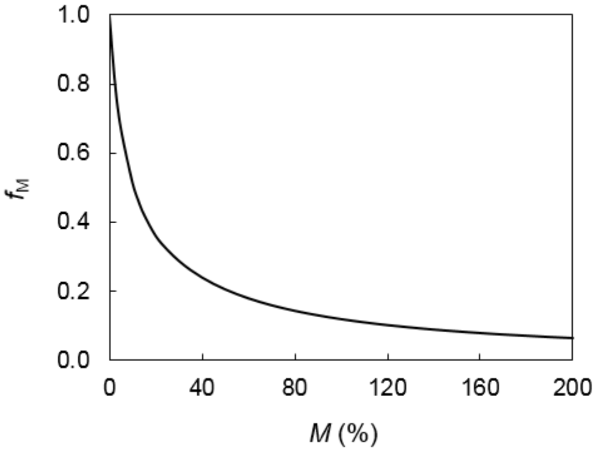

Figure 1. Fuel moisture content attenuation factor (f_M, Eq. [3]) as a function of fuel bed moisture content (M). f_M was computed considering an exponential fuel temperature (T_f) decrease between 100 ºC for M = 0% and 15 ºC for M = 20%; T_f = 15 ºC was assumed for M > 20%. See the 'Methods' section for details.

Discussion

f_M performance and applicability

Laboratory-based R models built with the generic f_M showed good agreement with data. They yielded R^2 slightly below those obtained using the original power law f_M-based models (0.667–0.947), but significantly above the 0.566 and 0.665 values obtained for the R_S and R_U models using exponentials (Rossa *et al.*, 2016; Rossa & Fernandes, 2017a, 2018a). Despite a small decrease in accuracy, when compared with the use of power laws, the generic f_M provides important benefits, such as not becoming extremely sensible at very low M-values and allowing extrapolation to moisture-free conditions. The generic f_M allowed improved prediction ability in relation to the specific f_M-functions used in existing field-based models for shrubland experimental fires and grassland wildfires.

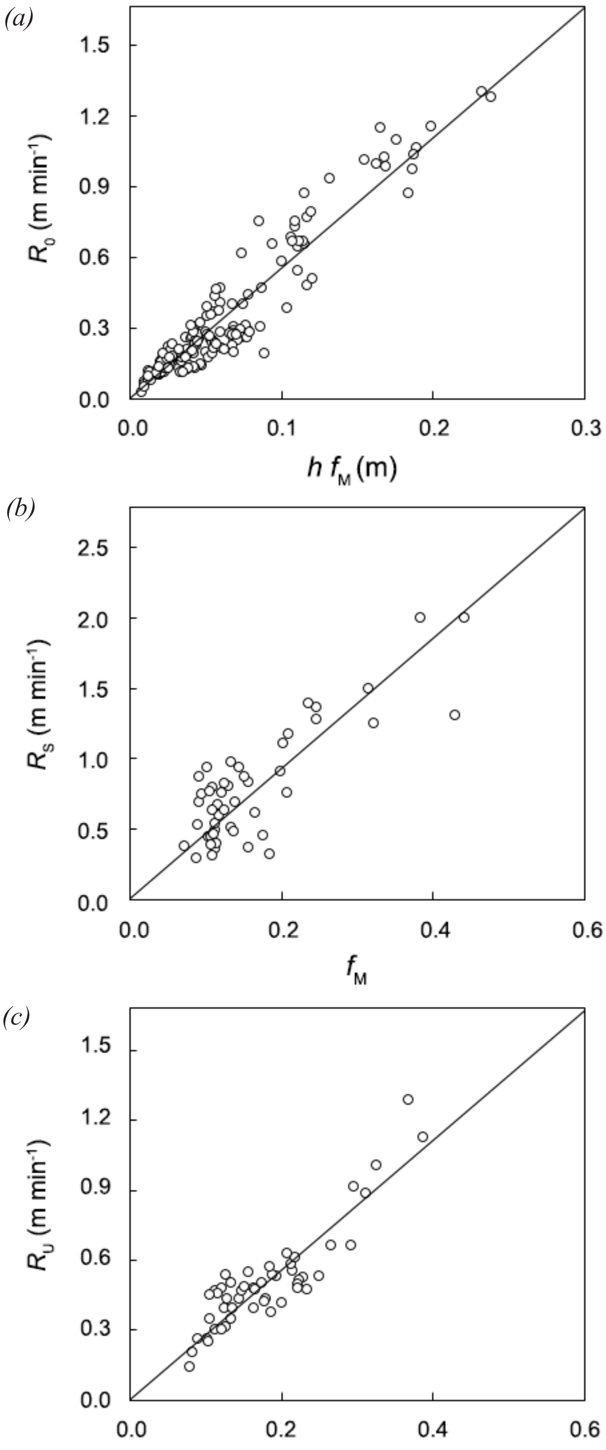

Figure 2. Laboratory-derived fire spread rate (R) models based on fuel moisture content attenuation factor (f_M, Eq. [3]) for: (*a*) no-wind and no-slope spread (R_0) in litter, slash, and shrub-like fuel beds, h is fuel bed height, linear fit is model 1 in Table 2 ($R^2 = 0.900$); (*b*) slope-driven spread (R_S) in shrub-like fuel beds, linear fit is model 2 in Table 2 ($R^2 = 0.651$); and (*c*) wind-driven spread (R_U) in shrub-like fuel beds, linear fit is model 3 in Table 2 ($R^2 = 0.795$). All regressions were significant at $p < 0.0001$. See Table 1 for data sources.

Laboratory data included a great number of tests in several fire spread conditions over a wide M-range, and fuel beds were very diverse in terms of species and structure. R_0 laboratory tests are representative of field R_0 and a reasonable surrogate for backing fires R (Rossa, 2017; Rossa & Fernandes, 2018a). That is not the case of slope and wind-driven laboratory trials, in which R is limited by the fire front width (Fernandes *et al.*, 2009). Shrubland and grassland outdoors fires enabled the positive testing of f_M in R_U conditions free of scaling issues. There is no apparent reason for f_M not to hold for slope-driven field fires as well. Not excluding the need of further assessing f_M with additional field data, its overall performance in all tested fire spread situations lends strong support to its ability of successfully incorporating empirically-based R models in generic fire spread conditions.

If Eq. [3] were developed without assuming that moisture-free conditions will be attained at $T_f = 100$ ºC, *i.e.*, with the numerator becoming $1.72\ (320 - T_f)$ instead of 378.4, using the generic f_M in the field-derived R models would yield MBE of 3.92 and 41.7 m min^{-1}, respectively for shrubland and grassland fires. The arising of this substantial over-prediction bias lends support to the supposition that f_M-functions based only on M implicitly account for T_f. In other words, this means that in a hypothetical situation of fire spread through a dry fuel bed at, for example, $T_f = 20$ ºC, predicted R using typical empirical field-based models would be higher than observed because the M-functions were fitted in conditions where the decrease in M is concurrent with increasing T_f. As a result, estimated f_M attains its maximum, *i.e.*, fire spread attenuation is minimum, although fuel conditions will delay fuel ignition more than expected in an extrapolation to $M = 0\%$, where T_f was supposed to grow concomitantly with diminishing M. It is important to notice that this rationale was derived from results using a limited field data set, hence further testing with additional data would benefit its confirmation.

Advantages and limitations

M_d of field fuels is easy to sample. Overall M determination requires measuring both M_d and M_l (Rossa *et al.*, 2015b), as well as assessing dead and live fuel mass fractions, which may be problematic in very heterogeneous fuel complexes. This is a limitation of using the generic f_M, when compared to f_M-functions accounting for only the M_d-effect. Most empirical fuel-dependent models rely on the sole use of M_d (Cruz *et al.*, 2015) to provide a satisfactory R explanation, which restricted the data available to test the specific f_M-function proposed in the present work. Field-based

Table 2. Model evaluation metrics (see Table 1 for details on fire spread data).

Model	f_M	RMSE (m min^{-1})	MAE (m min^{-1})	MAPE (%)	MBE (m min^{-1})
(1) $R_0 = 5.53\ h f_M$	Eq. [3]	0.0864	0.0624	23.7	0.0044
(2) $R_S = 4.63 f_M$	Eq. [3]	0.2352	0.1891	28.9	-0.0340
(3) $R_U = 2.79 f_M$	Eq. [3]	0.0966	0.0773	16.2	-0.0036
(4) $R_U = 6.42\ U_2^{0.994}\ h^{0.372} f_M$	exp(-0.0761 M_d - 0.00313 M_l)	6.3070	4.5524	70.6	1.3627
	Eq. [3]	6.2379	4.5075	63.4	-0.3927
(5) $R_U = (a + b\ (U_{10} - 5\ ))^{0.844} f_M$	exp(-0.108 M_d)	56.483	43.964	26.7	0.9197
	Eq. [3]	58.824	43.955	24.8	-6.534

Variables used were: f_M, fuel moisture content attenuation factor; R, fire spread rate (subscripts indicate: 0, no-wind & no-slope; S, slope-driven; U, wind-driven); h, fuel bed height; U, wind speed (subscript indicates measurement height); M, fine fuel moisture content (subscripts indicate: d, dead fuels; l, live fuels); a, b, fitted coefficients dependant on grassland type (Cheney *et al.*, 1998). Models 4 and 5 were evaluated using their original f_M and the one proposed in Eq. [3].

models based only on M_d work well because, usually, M_l is either constant or correlated with M_d for a given fuel complex (Rossa & Fernandes, 2017b).

Nevertheless, especially for experimental programs composed of a limited number of tests, possible difficulties in assessing overall M might pay-off in terms of the advantages of using a generic f_M. The use of experimental outdoors fires as a source of development data is appealing because of the strong resemblance to real-world fire-spread. However, this option is often challenged by heterogeneity in fuel bed properties and correlated fuel descriptors, which elude the correct quantification of specific effects (Rossa & Fernandes, 2017b). Establishing *a priori* the M-effect through the use of f_M significantly simplifies the proper assessment of the remaining influent variables.

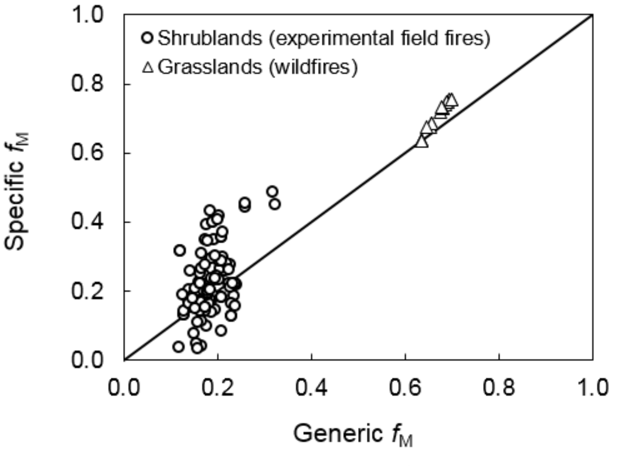

Figure 3. Specific *vs.* generic fuel moisture content attenuation factor (f_M) for shrubland fires and grassland wildfires. Specific f_M are given in Table 2; generic f_M is Eq. [3]. Solid line is perfect agreement; correlation between variables is 0.457 for shrubland fires and 0.995 for grassland wildfires ($p < 0.0001$). See Table 1 for data sources.

Conclusion

A generic f_M-function for empirical R models was developed based on the assumption that the main M-damping effect is a function of Q_i. f_M was successfully used to derive R models from laboratory

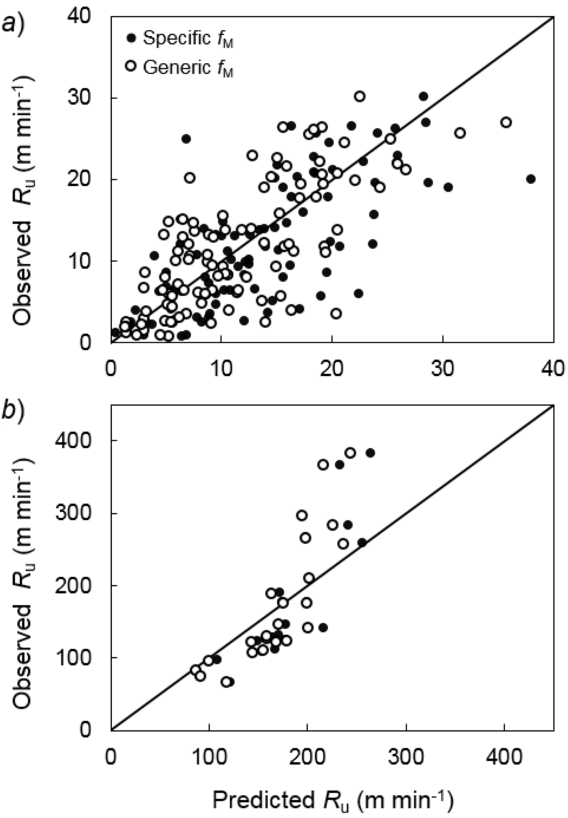

Figure 4. Observed *vs.* predicted wind-driven fire spread rate (R_U) using the specific fuel moisture content attenuation factor (f_M) (Table 2) and the generic f_M (Eq. [3]) for: (*a*) shrubland fires; and (*b*) grassland wildfires. Solid lines are perfect agreement. See Table 1 for data sources.

fire spread in no-wind and no-slope, slope-, and wind-aided conditions. The ability to incorporate f_M in existing field-based models was also positively assessed. Possible difficulties in assessing overall M due to fuel complex heterogeneities, might pay-off in terms of the advantages of using a tested generic f_M. For example, establishing *a priori* the M-effect benefits the proper quantification of the remaining variables influence. Not excluding the need of further assessing f_M with additional field data, its overall performance in all tested fire spread situations lends strong support to its ability of successfully incorporating empirically-based R models in generic fire spread conditions.

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