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, \(\text{kJ kg}^{-1} \text{°C}^{-1}\); subscripts: \(f\), fuel; \(w\), water);
- \(f_{\text{ai}}\) (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, \(\text{kJ kg}^{-1}\); 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, °);  
- \(T\) (temperature, °C; 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\(^{-2}\)); \(\rho_{i}\) (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 \(f_{\text{ai}}\). Most frequently, \(f_{\text{ai}}\)-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 $M^a$ is sometimes used (Cheney et al., 2012), where $a$ and $b$ are fitted coefficients. Both functional forms have advantages and shortcomings. Exponential decay $f_{M^b}$ 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 $f_{M^a}$ 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 ($R_i$), slope- ($R_s$), and wind-driven ($R_w$) laboratory fires, currently, no $f_{M^b}$-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 ($Q$) 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 infrared 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):

$$Q_i = c_i (T_i - T_f) + \frac{M}{100} [ c_{w, f} (T_i - T_f) + Q_{w, f} ]$$  \hspace{1cm} [1]

where $c_i$, $c_{w, f}$, $T_i$, $T_f$, $T_{w, f}$, and $Q_{w, f}$ 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., $f_{M^b}$, results from dry-to-wet fuel ignition needs ratio:

$$f_M = \frac{(Q_i)_M}{Q_i}$$  \hspace{1cm} [2]

Although exponential decay or power law $f_{M^a}$ 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., $T_i$ and $M$ (Eq. [1]). But because $T_i$ and $M$ are correlated for dead fuels, and dead fuels are present in most real-world fuel beds, specific $f_{M^a}$-factors work fine without explicitly accounting for $T_i$. This does not apply if $f_{M^a}$ is based on $Q$. As a result, defining the numerator of Eq. [2] requires establishing $T_i$ 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 $T_i = 100 \degree C$, 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 $c_i = 1.72$ kJ kg$^{-1}$ °C$^{-1}$ (Balbi et al., 2014), $c_{w, f} = 4.19$ kJ kg$^{-1}$ °C$^{-1}$, $T_i = 320 \degree C$, $T_f = 100 \degree C$, and $Q_{w, f} = 2260$ kJ kg$^{-1}$ (Catchpole & Catchpole, 1991), we obtain:

$$f_M = \frac{378.4}{\frac{1.72 (320-T_f) + \frac{M}{100} [ 4.19 (100-T_f) + 2260 ]}{100}}$$  \hspace{1cm} [3]

Because it is not easy to measure or estimate $T_f$, air temperature ($T_f$) 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 $T_i$ variations. As $M_d$ gets closer to zero, lowering its value requires an exponential $T$ 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 $T_i$. To obtain a continuous plot of $f_M$ as a function of $M$, I considered an exponential $T_i$ decrease between 100 °C for $M = 0\%$ and an arbitrary value of 15 °C for $M = 20\%$, and constant $T_i = 15$ °C for $M > 20\%$.

#### Laboratory data

A total of 282 laboratory fires were retrieved from several sources (Table 1). $R_i$ tests ($n = 181$) compiled in Rossa & Fernandes (2018a) include experiments from
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 $20^\circ$ 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 $R_w$ 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 ($R_w$, $R_s$, $R_v$), only the foliar fuel component was considered for computing oven-dry fuel bed load ($w$) and density ($\rho_v$) 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), Noble (1991), Maynes & Garvey (1985), McArthur (1966), Finocchiaro et al. (1970), Douglas (1970), and Cheney et al. (1998).

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) | $T_a$ ($^\circ$C) | $M$ (%) | $R$ (m min$^{-1}$) |
|-------------------------------|-----------|--------------------------------|------------------|---------------------------------------|-----|-----------------|--------|-----------------|--------|-------------------|
| Laboratory fires              | 1         | Rossa & Fernandes (2018a)$^a$ | No-wind and      | Litter, slash, and shrub-like fuel beds | 181 | 0.45-3.50       | 0.020-0.508 | 13.0-37.7       | 6.0-161.7 | 0.025-1.300       |
|                               | 2         | Rossa et al. (2016)            | Slope-driven ($S = 20^\circ$) | 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 (2017a)      | 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 ($U_w = 2-25$ 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 ($U_w = 27-55$ 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).
Data analysis and modelling

$f_M$ was used to develop $R_g$, $R_s$, and $R_{vs}$ models from the laboratory fire spread data. In the Rossa & Fernandes (2018a) $R_g$ 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 $R_g$ model was obtained by linear fitting $R_g$ to $h f_M$. In the case of $R_s$ and $R_{vs}$ data, structural fuel bed metrics of most trials were close to the experimental mean, despite some variation observed between 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 $R_g$ and $R_{vs}$, 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], 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 $M_f$ and $M_d$ 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 $f_M$.

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 $R_g$ and $R_{vs}$ 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.
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 $R_f$ and a reasonable surrogate for backing fires ($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 $T_f = 100 ^\circ$C, 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, $T_f = 20 ^\circ$C, 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

![Figure 2](image_url). 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.
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) $R_0 = 4.63 \ f_M$ | Eq. [3] | 0.2352 | 0.1891 | 28.9 | -0.0340 |
| (3) $R_0 = 2.79 \ f_M$ | Eq. [3] | 0.0966 | 0.0773 | 16.2 | -0.0036 |
| (4) $R_0 = 6.42 \ U_2^{0.094} h^{0.72} f_M$ | exp(-0.0761 $M_d$ - 0.00313 $M_l$) | 6.3070 | 4.5524 | 70.6 | 1.3627 |
| (5) $R_0 = (a + b (U_{10} - 5))^{0.44} f_M$ | exp(-0.108 $M_l$) | 56.483 | 43.964 | 26.7 | 0.9197 |

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].

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 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 influential 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.

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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