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SHORT COMMUNICATION

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On the effect of live fuel moisture content on fire rate of spread

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Abstract

Aim of study: To reconcile the effects of live fuel moisture content (FMC) on fire rate of spread (ROS) derived from laboratory and field fires.

Methods: The analysis builds on evidence from previous fire-spread experimental studies and on a comparison between two functions for the FMC damping effect: one derived from field burns, based on dead FMC, and another derived from laboratory trials, based on a weighted FMC (dead and live fuels).

Main results: In a typical Mediterranean shrubland, laboratory and field-derived FMC damping functions are linearly related, which is explained by the correlation between monthly average live and dead FMC variation throughout the year. This clarifies why the effect of live FMC on real-world fires ROS has remained elusive, although in fact it has an influence.

Research highlights: By providing evidence that the most significant effect of FMC on ROS is independent of vegetation phenology (dead or live condition), and explaining why in specific situations dead FMC is sufficient to provide satisfactory ROS predictions, our results can assist future modelling efforts.

Additional keywords: fire behaviour; forest fuels; plant phenology; combustion.

Symbols used: f_d (fraction of dead fuels); M (fuel moisture content, %); M_d (dead fine fuel moisture content, %); M_l (live or quasi-live fine fuel moisture content, %); M_w (weighted fine fuel moisture content, %); R (fire rate of spread, m/s); U (wind speed, km/h).

Authors´ contributions: Both authors developed the analysis and wrote the manuscript.

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Introduction

The recognition of the significant influence of fuel moisture content (M) on fire rate of spread (R) is as old as fire research itself (*e.g.*, Show, 1919). The physical mechanisms underlying the substantial R decrease with the M-growth are quite simple to understand: as M increases so does the amount of energy and time necessary for water vaporization before ignition can be achieved, slowing down fire-spread.

Because natural mixed live and dead vegetation is difficult to reproduce indoors, laboratory studies have seldom been focused on fire spread in live fuel beds. The analysis of fire behaviour in fuel complexes including live components is usually derived from field studies. However, although counterintuitive, a review by Alexander & Cruz (2013) found no statistically significant relationship between field fires R and live fuel moisture content (M_l). Flammability tests on individual live fuel elements subjected to high radiative heat fluxes (up to 140 kW/m^2) suggest a weak relationship between M_l and time to ignition (Fletcher *et al.*, 2007) that occurs before all moisture is vaporized (Picket *et al.*, 2010). Not surprisingly, such findings support the belief that fire-spread mechanisms in live vegetation differ from those observed in dead fuels (Finney *et al.*, 2013). Another plausible explanation for the apparent lack of influence of M_l on R, which does not require *a priori* different spread mechanisms, would be that dead fuel elements allow fire front percolation through mixed live and dead vegetation.

In contrast, most laboratory studies find a relationship between R and M_l (*e.g.*, Rossa *et al.*, 2016; Weise *et al.*, 2016). As a consequence, R models derived from such studies are commonly based on a weighted fuel moisture content (M_w), computed from live and dead fuel mass fractions (*e.g.*, Marino *et al.*, 2012; Viegas *et al.*, 2013), whereas field-based models rely on dead fuel moisture content (M_d) alone (*e.g.*, Cruz *et al.*, 2015). Conclusions on the M_l effect derived from field and laboratory studies are thus conflicting.

Odds that the results from such an amount of high quality laboratory and fieldwork are somehow wrong are virtually null. Instead, we believe that the most viable explanation for this dispute is that all results are correct, but a unifying theory is lacking. This study discusses whether apparently different outcomes regarding the M_l effect on *R*, derived from either laboratory or field studies, are reconcilable.

Methods

Fuel moisture content effect

Shrublands are typically composed of a variable live and dead fuel mixture, and thus adequate to the present analysis. Anderson *et al.* (2015) developed an empirical *R* model from a comprehensive set of 79 field experiments of fire spread in shrublands worldwide. The *M*-effect was modelled as an exponential decay based only on dead fuels, given by exp(-0.0721 M_d). To obtain a measure of how the established important influence of wind speed (*U*) on *R* might hinder a proper field evaluation of the *M*-effect, we assessed the relative effects of *U* and M_d using daily *R* simulations for a two-year series (2015–2016) of meteorological observations recorded at 12:00 in Lousã, Central Portugal. M_d was estimated from the Fine Fuel Moisture Code (FFMC) of the Canadian Forest Fire Weather Index System (Van Wagner, 1987). We did not consider days with M_d >35% (because of unlikely fire spread) and used a bulk density of 1.8 kg m^{-3} (mean experimental value). *U* and M_d relative contributions to *R* were assessed using classification and regression trees (CART) analysis.

Rossa & Fernandes (2017) obtained an *M*-damping effect based on total fuel bed water content (live and dead fuels), given by $M_w^{-0.6253}$, using 51 fire spread laboratory tests in fuel beds composed of a litter layer (dead foliage) over-layered by vertically oriented quasi-live fuels, thus approaching the natural fuel structure. M_w can be obtained from:

$$M_w = f_d M_d + (1 - f_d) M_l \qquad [1]$$

where f_d is the mass fraction of dead foliar fuels. Because both the Anderson *et al.* (2015) field-based model and the Rossa & Fernandes (2017) laboratory-based model include fuel bed density and were derived from wind-driven fire spread, we assumed that the *M*-effect is comparable.

Fuel moisture content evolution throughout the year

We compared the laboratory and field-based *M*-damping effects for fire spread in a mixed *Calluna vulgaris* (L.) Hull and *Pterospartum tridentatum* (L.) Wilk. fuel complex, common in N-C Portugal shrubland, for the typical *M*-evolution throughout the year. We used monthly averages from a long term (1996–2012) *M*-assessment (Lopes, 2013) of a few selected fuel species, conducted in Lousã. M_d was obtained as the mean value between *Pinus pinaster* Ait. and *Eucalyptus globulus* Labill. litter, and M_l as the mean between live *C. vulgaris* and *P. tridentatum*, which assumes an equally distributed mixture. M_w was computed for f_d of, respectively, 0.2, 0.4, and 0.6 – *i.e.*, 20, 40, and 60% of fine dead fuels – and we assessed the significance (p<0.05) and strength (R^2) of the linear relationship between the two *M*-damping effects. The range in f_d for Anderson *et al.* (2015) model development was 0.14–0.91 (mean was 0.49), thus confirming that the selected values of f_d for analysis are realistic.

Results and discussion

Laboratory and field studies results

The *U* effect dominated over M_d, respectively explaining 61.9 and 38.1% of the variance in *R* predictions. The prevalence of such effect would probably be higher had we resorted to simulations based on hourly weather data, because of higher variation in *U* (Beck & Trevitt, 1989). In the year-round experimentally-assessed *M* evolution, M_d and M_l varied within 12.8–52.6% and 76.0–108.2% (Fig. 1). The linear relationship between laboratory and field-based *M*-damping effects (Fig. 2) approached significance for f_d=0.2 (p=0.06) and was highly significant for f_d=0.4 (p=0.004) and f_d=0.6 (p<0.0001). Likewise, R^2 increased markedly from 0.318 to 0.813 with the rise of f_d.

Laboratory testing allows the control and/or accurate monitoring of the main parameters influencing fire propagation. Rossa (2017) used data from 185 burns under windless conditions in the absence of slope, covering a wide diversity of fuel bed composition, arrangement and *M* (6–179%) conditions, showing that the *M*-effect on *R* does not depend on vegetation condition (live or dead). Extension of the results to real-world fires was confirmed by model validation against field fires. In the case of slope (*e.g.*, Rossa *et al.*, 2016) or wind-driven (*e.g.*, Marino *et al.*, 2012; Rossa & Fernandes, 2017) laboratory trials, *R* is limited by

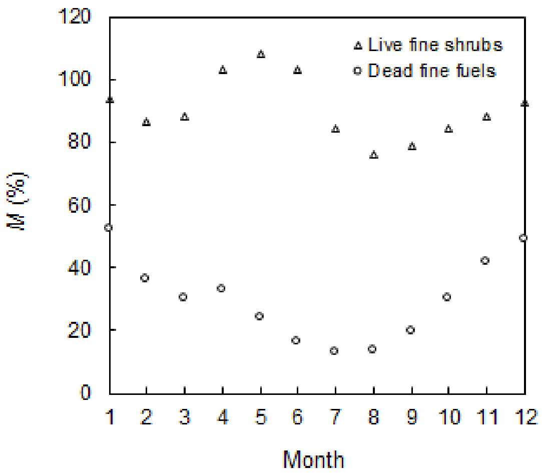

Figure 1. Mean monthly fuel moisture content (*M*) for dead fine fuels and live mixed *Calluna vulgaris* (L.) Hull and *Pterospartum tridentatum* (L.) Wilk. shrubs. These values were computed based on a long term *M*-assessment (1996–2012) of some selected Mediterranean fuel species, conducted in Lousã, Central Portugal (Lopes, 2013).

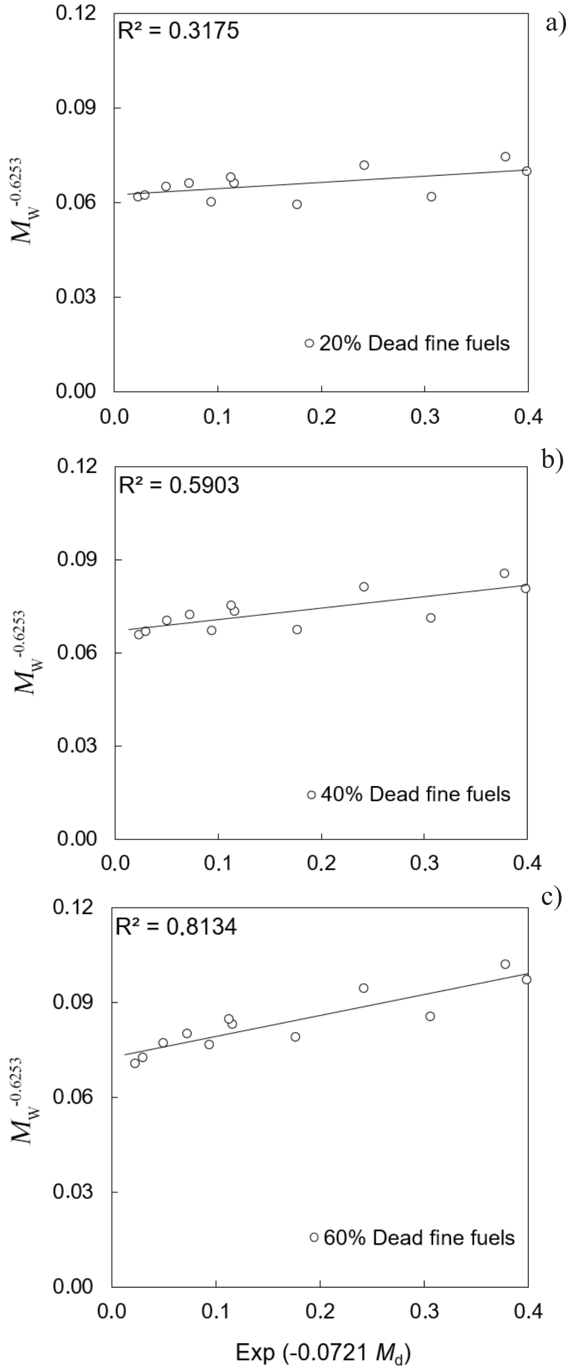

Figure 2. Linear relationships between fuel moisture content damping effects modelled as an exponential decay based on dead fine fuel moisture content (M_d) (Anderson *et al.*, 2015), and as a power law based on weighted fine fuel moisture content (M_w, Equation [1]) (Rossa & Fernandes, 2017), for wind-driven fire-spread in a shrubland with a percentage of dead fine fuels of: (*a*) 20% (R^2 = 0.318); (*b*) 40% (R^2 = 0.590); and (*c*) 60% (R^2 = 0.813).

the fire front width (Fernandes *et al.*, 2009). Still, these trials are representative of the initial stage of a point ignition field fire and the *M*-damping effect, as well as the independence from plant phenology, are expected to be independent of scale and hold under field conditions (Rossa *et al.*, 2016).

Outdoors experimental fires occur in real-world conditions. No fire behaviour model can be completely proven correct until it faces validation against field fires. Their use as a source of development data is also appealing because there are many fire-spread situations that cannot be reproduced in the laboratory without serious scaling limitations. Yet, this option is challenged by lack of control over environmental parameters, heterogeneity in fuel bed properties, and correlated fuel descriptors. These shortcomings have been fostering the dispute over the M_l influence on *R*, not clarifying if it is eluded by the difficulty in detecting specific effects, or if it is diluted by field-specific spread mechanisms. The latter remains to be verified only for the case of slope and wind-driven fires, since for no-wind or no-slope burns – which also approach backing fires (Rossa *et al.*, 2015) –, the accuracy of M_w-based *R* predictions was already tested against field fires, confirming the M_l influence (Rossa, 2017).

Unifying laboratory and field evidence

M_l will be approximately constant during a field experimental program in shrubland fuels conducted over a period of a few weeks, contrasting with M_d that will vary substantially in response to changes in air temperature, relative humidity and solar radiation (Anderson *et al.*, 2015). Other types of live vegetation, like evergreen mature tree foliage without severe soil water deficit, will even usually maintain an approximately constant

M_l over the year (Pook & Gill, 1993; Agee *et al.*, 2002). However, for the shrubs addressed by this study, the difference between minimum and maximum M_l was 32.1% for average monthly means (Fig. 1), a value similar to that observed for M_d (39.8%). Nevertheless, because of similar seasonal trends for M_l and M_d, which are evident in Fig. 1, M_d and M_w-based damping effects are correlated (Fig. 2).

Although the M_l evolution in Fig. 1 is not necessarily representative of a general shrubland, several year-round Mediterranean M_l assessments for a great number of shrub species (Piñol *et al.*, 1998; Pellizzaro *et al.*, 2007; Yebra *et al.*, 2008; Yebra & Chuvieco, 2009), report a similar seasonal pattern, with a M_l decrease between spring and summer, followed by an increase until winter. Because dry soils are frequently concurrent with meteorological conditions that yield low M_d values as well, the relationship between M_l and soil moisture content found by Qi *et al.* (2012) for a shrubland in Northern Utah (USA), also lends support to our hypothesis of correlated M_d and M_w damping effects.

Both cases of: (i) a year-round roughly constant M_l, or (ii) correlated M_d-M_w variations, explain why the M_l-effect is difficult to detect from the statistical analysis of field data, although laboratory studies systematically show that *R* is influenced by the total amount of water in the fuel complex, independently of vegetative condition. Dominance of *R* by *U* also adds to the challenge of properly assessing the *M*-effect based on field fires. The good agreement between the *M*-damping effects of field and laboratory-based *R* models also enlightens why the sole use of M_d is enough to provide a satisfactory *R* explanation in most fuel-dependent models (*e.g.*, Cruz *et al.*, 2015). Differences between the combustion mechanisms of live and dead fuels also do not necessarily lead to different *R*, because if all water is evaporated during the passage of the flame (before or after ignition) the net heat release sustaining fire-spread should approximately be the same (Rossa, 2017).

Conclusion

There is laboratory evidence that the main effect of *M* on *R* is a function of the total amount of water in the fuel bed and is independent of vegetative condition. The apparently different effects of M_l, assessed from either field or laboratory fires, are most likely a consequence of field-specific experimental features and the results from both approaches can easily be reconciled. In the absence of severe soil water deficit many types of mature live vegetation will maintain an approximately constant M_l over the year. Although that is not the case for the Mediterranean shrublands analysed in this work, their mean monthly M_l and M_d evolution trends are similar. As a result, the M_l-effect is very difficult to detect from field data. For the same reason, fuel-dependent *R* models provide satisfactory predictions relying on the sole use of M_d.

References

Agee JK, Wright CS, Williamson N, Huff MH, 2002. Foliar moisture content of Pacific Northwest vegetation and its relation to wildland fire behavior. Forest Ecol Manag 167 (1-3): 57-66. https://doi.org/10.1016/S0378-1127(01)00690-9

Alexander ME, Cruz MG, 2013. Assessing the effect of foliar moisture content on the spread rate of crown fires. Int J Wildland Fire 22 (4): 415-427. https://doi.org/10.1071/WF12008

Anderson WR, Cruz MG, Fernandes PM, McCaw L, Vega JA, Bradstock R, Fogarty L, Gould J, McCarthy G, Marsden-Smedley JB, *et al.*, 2015. A generic, empirical-based model for predicting rate of fire spread in shrublands. Int J Wildland Fire 24 (4): 443-460. https://doi.org/10.1071/WF14130

Beck JA, Trevitt AC, 1989. Forecasting diurnal variations in meteorological parameters for predicting fire behaviour. Can J For Res 19 (6): 791-797. https://doi.org/10.1139/x89-120

Cruz MG, Gould JS, Alexander ME, Sullivan AL, McCaw WL, Matthews S, 2015. Empirical-based models for predicting head-fire rate of spread in Australian fuel types. Aust Forest 78 (3): 118-158. https://doi.org/10.1080/00049158.2015.1055063

Fernandes PM, Botelho HS, Rego FC, Loureiro C, 2009. Empirical modelling of surface fire behaviour in maritime pine stands. Int J Wildland Fire 18 (6): 698-710. https://doi.org/10.1071/WF08023

Finney MA, Cohen JD, McAllister SS, Jolly WM, 2013. On the need for a theory of wildland fire spread. Int J Wildland Fire 22 (1): 25-36. https://doi.org/10.1071/WF11117

Fletcher TH, Pickett BM, Smith SG, Spittle GS, Woodhouse MM, Haake E, 2007. Effect of moisture on ignition behavior of moist California chaparral and Utah leaves. Combust Sci Technol 179 (6): 1183-1203. https://doi.org/10.1080/00102200601015574

Lopes S, 2013. Modelos de previsão do teor de humidade de combustíveis florestais. PhD thesis, University of Coimbra, Portugal.

Marino E, Dupuy JL, Pimont F, Guijarro M, Hernando C, Linn R, 2012. Fuel bulk density and fuel moisture content effects on fire rate of spread: A comparison between FIRETEC model predictions and experimental results in shrub fuels. J Fire Sci 30 (4): 277-299. https://doi.org/10.1177/0734904111434286

Pellizzaro G, Cesaraccio C, Duce P, Ventura A, Zara P, 2007. Relationships between seasonal patterns of live fuel moisture and meteorological drought indices for Mediterranean shrubland species. Int J Wildland Fire 16 (2): 232-241. https://doi.org/10.1071/WF06081

Pickett BM, Isackson C, Wunder R, Fletcher TH, Butler BW, Weise DR, 2010. Experimental measurements during combustion of moist individual foliage samples. Int J Wildland Fire 19 (2): 153-162. https://doi.org/10.1071/WF07121

Piñol J, Filella I, Ogaya R, Peñuelas J, 1998. Ground-based spectroradiometric estimation of live fine fuel moisture of Mediterranean plants. Agri For Meteo 90 (3): 173-186. https://doi.org/10.1016/S0168-1923(98)00053-7

Pook EW, Gill AM, 1993. Variation of live and dead fine fuel moisture in *Pinus radiata* plantations of the Australian Capital Territory. Int J Wildland Fire 3 (3): 155-168. https://doi.org/10.1071/WF9930155

Qi Y, Dennison PE, Spencer J, Riaño D, 2012. Monitoring live fuel moisture using soil moisture and remote sensing proxies. Fire Ecol 8 (3): 71-87. https://doi.org/10.4996/fireecology.0803071

Rossa CG, 2017. The effect of fuel moisture content on the spread rate of forest fires in the absence of wind or slope. Int J Wildland Fire 26 (1): 24-31. https://doi.org/10.1071/WF16049

Rossa CG, Fernandes PM, 2017. Fuel-related fire behaviour relationships for mixed live and dead fuels burned in the laboratory. Can J For Res 47 (7): 883-889. https://doi.org/10.1139/cjfr-2016-0457

Rossa CG, Davim DA, Viegas DX, 2015. Behaviour of slope and wind backing fires. Int J Wildland Fire 24 (8): 1085-1097. https://doi.org/10.1071/WF14215

Rossa CG, Veloso R, Fernandes PM, 2016. A laboratory-based quantification of the effect of live fuel moisture content on fire spread rate. Int J Wildland Fire 25 (5): 569-573. https://doi.org/10.1071/WF15114

Show SB, 1919. Climate and forest fires in northern California. J Forest 17 (8): 965-979.

Van Wagner CE, 1987. Development and structure of the Canadian Forest Fire Weather Index System. Canadian Forest Service, Petawawa Forest Experiment Station. Chalk River, Ontario. Forest Technical Report 35.

Viegas DX, Soares J, Almeida M, 2013. Combustibility of a mixture of live and dead fuel components. Int J Wildland Fire 22 (7): 992-1002. https://doi.org/10.1071/WF12031

Weise DR, Koo E, Zhou X, Mahalingam S, Morandini F, Balbi J, 2016. Fire spread in chaparral - A comparison of laboratory data and model predictions in burning live fuels. Int J Wildland Fire 25 (9): 980-994. https://doi.org/10.1071/WF15177

Yebra M, Chuvieco E, Riaño D, 2008. Estimation of live fuel moisture content from MODIS images for fire risk assessment. Agr For Meteo 148 (4): 523-536. https://doi.org/10.1016/j.agrformet.2007.12.005

Yebra M, Chuvieco E, 2009. Linking ecological information and radiative transfer models to estimate fuel moisture content in the Mediterranean region of Spain: Solving the ill-posed inverse problem. Remote Sens Environ 113 (11): 2403-2411. https://doi.org/10.1016/j.rse.2009.07.001