fire

Perspective

Live Fuel Moisture Content: The 'Pea Under the Mattress' of Fire Spread Rate Modeling?

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Abstract: Currently, there is a dispute on whether live fuel moisture content (FMC) should be accounted for when predicting a real-world fire-spread rate (RoS). The laboratory and field data results are conflicting: laboratory trials show a significant effect of live FMC on RoS, which has not been convincingly detected in the field. It has been suggested that the lack of influence of live FMC on RoS might arise from differences in the ignition of dead and live fuels: flammability trials using live leaves subjected to high heat fluxes (80–140 kW m^{-2}) show that ignition occurs before all of the moisture is vaporized. We analyze evidence from recent studies, and hypothesize that differences in the ignition mechanisms between dead and live fuels do not preclude the use of overall fine FMC for attaining acceptable RoS predictions. We refer to a simple theory that consists of two connected hypotheses to explain why the effect of live FMC on field fires RoS has remained elusive so far: H1, live tree foliage FMC remains fairly constant over the year; and H2, the seasonal variation of live shrubs' FMC correlates with the average dead FMC. As a result, the effect of live FMC is not easily detected by statistical analysis.

Keywords: laboratory and field fires; ignition mechanisms; flammability tests; heat flux

1. Introduction

Fire behavior modeling has been around for nearly a century [1]. Intuitively, one would expect that a complete understanding of the basic mechanisms driving fire propagation would have been achieved by now. That is not the case. For example, there is currently a dispute on how live fuel moisture content (FMC) impacts fire spread rate (RoS) [2]. As opposed to dead FMC, there seems to be no consensus on how live fuels should be accounted for to model RoS. Alternatively, live fuels could be treated as very wet dead fuels [3], their combustion mechanisms can be considered different from dead fuels [4], or they could simply be neglected [5]. FMC and wind speed are the most important factors determining RoS [6,7]. As a result, a lack in understanding the effect of live FMC on RoS hinders the development of prediction systems that are applicable to generic fuel complexes, which often are composed of mixed live and dead vegetation. More importantly, the process of accomplishing a physically correct detailed description of the mechanisms of fire spread would greatly benefit from fully confirmed guidance on the expected main factors influencing fire propagation and how they exert that influence. Thus, clarifying how live FMC influences RoS is decisive to advance fire behavior modeling, namely RoS prediction.

Here we briefly analyze the current laboratory and field-derived evidence of the effect of live FMC on fire behavior. There are studies confirming that ignition mechanisms differ between live and dead fuels [8–11]. We discuss the hypothesis that current research, including recent work [12,13], is sufficient to establish that those differences in the ignition process do not preclude RoS modeling from overall fine FMC (live and dead fuels) such that the resulting accuracy is acceptable for operational purposes.

2. The Sources of Uncertainty and a Unifying Theory

Out of convenience, the first attempts to physically describe fire spread mechanisms [14] were derived from laboratory tests over shallow dead fuel beds. The rationale for this option is quite obvious: near-natural litter fuel beds are relatively easy to reproduce in the laboratory, and fuels such as pine needles (which are very commonly used in indoors trials) are usually readily available in large amounts. The Rothermel RoS model [3], which has gained worldwide acceptance due to its versatility, was also primarily developed from laboratory experiments in homogeneous dead fuels. Although the model accounts for fire spread in mixed vegetation, weighing fuel properties by category (e.g., dead or alive) and size class, some issues have been raised regarding the weighing process methodology [15–17]. Nevertheless, live fuel was assumed as a very wet dead fuel [10]. Subsequent laboratory studies of fire spread in mixtures of live and dead fuels suggested that RoS is a function of overall FMC, both in no-wind and no-slope conditions [18,19], as well as in wind-assisted fire spread [20,21]. So, the effect of FMC on RoS was thought to be understood until the comprehensive review of field data carried out by Alexander and Cruz (2013) [2] failed to detect a statistically significant relationship between real-world RoS and live FMC. This somewhat surprising and counterintuitive conclusion shook the foundations of fire behavior modeling.

A simple reason for why field fires behave differently from the laboratory has been presented: real-world fires produce heat fluxes that are much higher than those obtained in laboratory experiments [2,22], e.g. peak radiative heat fluxes up to 150 kW m^{-2} have been measured in shrublands [23,24]). This explanation also seems to align with the results of flammability tests using live foliage [11] that is subjected to high heat fluxes (80–140 kW m^{-2}), which found no significant relationship between live FMC and time-to-ignition, with ignition occurring before all of the moisture was vaporized [8,9]. Gathering all of the evidence, it seemed that field fires spreading in mixed live and dead vegetation generated much higher heat fluxes than those observed in the laboratory, and fire would either percolate through dead fuels or ignite live fuels before their water content was fully removed, in such a way that RoS would not significantly depend on live FMC.

We will try to solve this "mystery" by following the quote of Sir Arthur Conan Doyle (the creator of Sherlock Holmes): "Once you eliminate the impossible, whatever remains, no matter how improbable, must be the truth." Rossa and Fernandes (2018) [13] reported RoS data for wind-assisted laboratory trials in shrub-like fuel beds (litter overlayered by live tree twigs, n = 45). Using the equations presented in Rossa and Fernandes (2018) [25] we can estimate the net horizontal heat flux through the fuel bed [3] in those trials, which yields an average of 76 kW m^{-2}, reaching a maximum of 121 kW m^{-2}. This range overlaps roughly with that used in the experimental apparatus of Fletcher et al. (2007) [11] (80–140 kW m^{-2}). Still, in the laboratory fire spread tests of Rossa and Fernandes (2018) [13], overall FMC was shown to be a good predictor for RoS. Thus, different heat flux magnitudes leading to distinct ignition mechanisms do not seem to explain the apparent conflict in the influence of live FMC on RoS between laboratory and field fires, and another explanation must be provided. Adding to the uncertainty, RoS was predicted from the overall FMC in recent field-tested RoS models for fire spread in no-wind and no slope-conditions [12] and wind-assisted propagation [13].

So why did Alexander and Cruz (2013) [2] not detect a significant relationship between field fires RoS and live FMC? Rossa and Fernandes (2017) [7] presented a simple theory, which consists of two connected hypotheses: H1, live tree foliage FMC remains fairly constant over the year (except under severe drought); and H2, the seasonal variation of live shrubs' FMC correlates with average dead FMC. As a result, the effect of live FMC is not easily detected by statistical analysis; this detection is further impaired by the dominant influence of wind on RoS and by intrinsic correlations between fuel metrics (e.g., FMC, fuel bed height, load, and density) [26] that dilute the effect of live FMC. H2 was tested by Rossa and Fernandes (2017) [7], through the detection of a correlation between FMC attenuation factors based on either dead FMC or overall FMC, for the shrubland fires in Anderson et al. (2015) [26]. Further support to this interpretation was obtained by Rossa (2018) [27] by developing a generic FMC attenuation factor that was built from dead and live FMC, and applicable to laboratory and real-world fire spread. It is important to notice that the explanation of Rossa and Fernandes (2017) [7] did not aim to invalidate previous RoS models based only on dead FMC. On the contrary, it attempted to reconcile laboratory and field-derived results, suggesting that empirical-based formulations [28] should work well without accounting for live FMC, as long as this variable does not significantly depart from the data that was used in model development. Yet, the applicability of these models will cease if live FMC drops below their implicitly assumed range of values, for example as a consequence of severe water deficit. Thus, disregarding the effect of live FMC can lead to a dramatic underprediction of RoS under drought conditions.

3. Need for a Different Approach in Field Experimentation?

Solid research exists showing differences in the ignition of live and dead fuels [8,9,11], which suggests that an accurate physical description of forest fuel combustion mechanisms should discriminate dead and live fuels [4,10]. Quantification of the impact of those different combustion mechanisms on RoS is yet to be assessed. Still, we believe that current evidence is also sufficient to establish that RoS modeling from overall FMC can yield fairly good results [12,13]. Even so, fire research would benefit from field experimental programs further confirming the influence of live FMC. Yet, most field experimental programs are usually limited in terms of the number of tests and amount of variables that are evaluated. For example, live FMC is seldom measured in field trials, except in partially-cured grass fuels, where overall FMC is often assessed [29]. This is understandable, since researchers want to focus on specific variables, maximizing the amount of retrieved data using their available resources. Still, it represents a great limitation when one wishes to establish a comprehensive dataset of field data from several sources [30].

To overcome this limitation, we would benefit from comprehensive field experimental programs to conduct well-documented trials, using fuel beds of similar structure in which both live and dead FMC vary as widely as possible and without being intrinsically correlated. For example, this could include conducting fires in shrublands of similar composition over the span of a year, combining times of year (allowing live FMC variation) and times of day (allowing dead FMC variation) such that experiments are conducted to cover a wide variety of combinations between live and dead FMC [31].

Unfortunately, carrying out comprehensive field trials spanning lengthy periods is hindered by funding issues (experimental field work is expensive) and time constraints (pressure to publish discourages researchers to plan for long, time-consuming activities). Perhaps the chance of accomplishing such an endeavor could be increased by collaborative efforts between research teams, sharing resources and manpower. Another option that could be explored is the analysis of RoS data from extreme wildfire events [32] under severe drought conditions (when live fuels are known to be below their "normal" FMC), for which live FMC data is available.

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