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How well do meteorological drought indices predict live fuel moisture content (LFMC)? An assessment for wildfire research and operations in Mediterranean ecosystems

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ABSTRACT

Live Fuel Moisture Content (LFMC) is a critical variable affecting fire ignition, behavior and severity in many ecosystems. Although the use of meteorological drought indices as proxies for LFMC is a straightforward and widespread approach, it is largely unknown whether it can provide reliable estimates of LFMC, either for local or spatial applications. We address this issue by evaluating the capacity of drought indices to predict LFMC quantitative variations and critical values. LFMC observations used for reference were measured on six different Mediterranean shrub species for 15 years in 20 different sites in Southern France. Six drought indices were evaluated: the Duff Moisture Code (DMC) and Drought Code (DC) of the Canadian Forest Fire Weather Index System, the Keetch-Byram Drought Index (KBDI), the Nesterov Index (NI) and the Relative Water Content (RWC) of the soil derived from a forest water balance model for low (80 mm) and high (160 mm) field capacities. The species were classified in two groups according to their seasonal variability: high and low responding species. We found large differences in the capacity of drought indices to predict LFMC, with indices that simulate long-term drought dynamics (DC, RWC and KBDI) generally performing better than others (NI and DMC). Once calibrated at stand scale, drought indices showed a good potential for predicting LFMC of high responding species, although large variations between sites were observed. In contrast, spatial predictability was limited with a RMSE and R^2 on the order of 20% and 0.3, respectively (for high responding species). Our results suggest that drought indices should therefore be used with caution for spatial applications in wildfire research and operational fire management. Because they can explicitly consider environmental (soil, climate) and biological (species traits related to dehydration) factors, mechanistic indices have a great potential to improve LFMC predictions.

1. Introduction

Live Fuel Moisture Content (LFMC), the mass of water contained within living vegetation in relation to the dry mass, is a critical variable affecting fire interactions with fuel (Chandler et al., 1983). In a number of fuel types present in the Mediterranean biomes, fire spreads through living plants and LFMC has been identified as a determinant factor of fire ignition, behavior and severity in these ecosystems (Dennison and Moritz, 2009; Chuvieco et al., 2009; Nolan et al., 2016; Ruffault et al., 2018). Recent experimentsconfirm this importance in laboratory, showing that there is no difference between the effect of LFMC and dead fuel moisture content (DFMC) on the fire rate of spread (Marino et al., 2012; Rossa and Fernandes, 2017). Accordingly, LFMC is incorporated in some widely-used fire behavior models (Jolly, 2007; Andrews et al., 2008) and is also monitored during the fire season by some fire agencies (such as the French Forest Service) to adjust fire hazard levels for fire suppression planning and resource allocation (Weise et al., 1998; Martin-StPaul et al., 2018; Yebra et al., 2018). The response of LFMC to increasing drought conditions is also one of the key factors of future fire regime in a context of climate changes (Abatzoglou and Williams, 2016).

Despite a growing need for reliable LFMC estimations in wildfire research and management, obtaining comprehensive and reliable time series of LFMC remains problematic. One main reason for this difficulty is that the dynamics of moisture in live fuels remains poorly understood and predicted, in particular when compared to DFMC. Indeed, DFMC is essentially determined by the short-term weather conditions (Resco de Dios et al., 2015), whereas LMFC is driven by dynamic and nonlinear interactions between weather conditions, soil properties and plant physiological processes, the latter including plant response to drought

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and dry mass changes associated with phenology (Jolly et al., 2014; Fares et al., 2017; Jolly and Johnson, 2018). As a consequence, field measurement remains a reference method to provide reliable LFMC point estimations. This method, however, requires the collection of multiple vegetation samples that must be weighed fresh, oven-dried during several hours and weighed dry (Countryman and Dean, 1979). Besides, its extension to landscape or regional scales is not feasible, particularly in areas where climatic and/or land cover heterogeneity are important such as the Mediterranean. Alternatively, remotely sensed data provide LFMC estimations over large areas (Dennison et al., 2003; Chuvieco et al., 2004a,b; Peterson et al., 2008; Caccamo et al., 2012; Jurdao et al., 2012; Fan et al., 2018; Yebra et al., 2018), but this method require extensive calibration and validation (see a review in Yebra et al., 2018) and its application, which is limited by the availability of spectral indices, is restricted to LFMC monitoring and to mid-term historical reconstructions.

As a result of these limitations, the use of empirical relationships between meteorological drought indices and LFMC remains a straightforward and widely-used approach. These indices are based on daily weather data (air temperature, air humidity, wind speed and precipitation) that can be easily derived from weather datasets, and therefore provide historical or projected time series of LFMC predictions at locations of interest. The most popular are the Drought Code (DC) and Duff Moisture Code (DMC) of the Fire weather index (Van Wagner, 1987) and the Keetch-Byram Drought Index (KBDI, Keetch and Byram, 1968). While none of these drought indices were initially designed to model foliage moisture, they have often been used to predict LFMC in Mediterranean ecosystems (Viegas et al., 2001; Castro et al., 2003; Dimitrakopoulos and Bemmerzouk, 2003; Pellizzaro et al., 2007). More generally, drought indices are also frequently related to various fire metrics, either by being explicitly mentioned as LFMC proxies (Ruffault and Mouillot, 2015, 2017) or used in a more indirect way, as indicators of fuel aridity or dryness as a whole (*e.g.* Thonicke et al., 2010; Pausas and Paula, 2012; Abatzoglou and Kolden, 2013; Gudmundsson et al., 2014; Ruffault et al., 2016; Littell et al., 2016).

To date, very little effort has been devoted to evaluating the genericity/generality of this approach. Yet, this question is all the more relevant that these relationships are applied for operational or research purposes in highly heterogeneous environments. One notable exception is the statistical model developed in Castro et al. (2003), that includes several climatic variables and drought indices which increase model spatial generality. This model, however, applies to a single species and was calibrated on a limited number of sites and years.

The recently published "Réseau hydrique" database (Duché et al., 2017) provides more than 20,000 multispecies and multisites LFMC measurements of several shrub species in Mediterranean France (Martin-StPaul et al., 2018). This dataset therefore offers a good opportunity to undertake a thorough evaluation of meteorological drought indices for LFMC estimation regarding both theoretical and operational purposes. In the present paper, we estimated daily values of several drought indices and compared them to LFMC measurements of a selection of species in different sites. The objectives of the study were (i) to evaluate the performance of some widespread meteorological drought indices for LFMC predictions in Mediterranean ecosystems, (ii) to discriminate the relative influence of site and species on these relationships and (iii) to suggest some improvements to improve LFMC predictions.

2. Material and methods

2.1. Background: description of drought indices

In this subsection, we describe the six drought indices that were evaluated against LFMC data in this study. All indices are based on daily temperature and precipitation and some of them also relied on additional variables, namely relative humidity and global radiation. They include carry-over effects over time, as they were designed to represent empirically the water dynamic in soil or duff reservoir.

The two first indices were the Duff Moisture Code (DMC) and the Drought Code (DC), which are both sub-components of the widespread Canadian Fire Weather Index. These indices are logarithmic functions of respectively duff and soil moisture, that differ in the quantity and depth of duff or soil layers considered (Van Wagner, 1987). The DMC was originally designed to estimate the moisture availability of a loosely-compacted-duff layer with a depth of 3 in. (76.2 mm). It combines a set of empirical functions that describe the dynamics of a single water reservoir that fills and empties according to daily rainfall, temperature, relative humidity and day length. The DC was initially developed to estimate the soil water content of deep and compacted duff (over 10 in. of soil). The DC differs from the DMC in the soil horizon considered -which is shallower in DMC- and in the more mechanistic description of the water balance, which includes a Thornthwaite-type evapotranspiration function (Turner, 1972).

The third index was the Keetch-Byram Drought Index (KBDI; Keetch and Byram, 1968). KBDI intends to describe moisture deficit in deep duff and upper soil layers. it was developed to measure the cumulative soil water deficit of forested ecosystems for a layer of 8 in. (202.3 mm) from daily temperature and precipitation. An interesting aspect of KBDI lies in the fact that it indirectly accounts for density of transpiring vegetation by weighting the daily moisture deficit by the annual rainfall of the location of interest.

The fourth index was the Nesterov index (NI, Nesterov, 1949). NI uses the mid-day and dew-point temperature, as well as the number of days since last rainfall heavier than 3 mm. Daily values are cumulated as long as no rainfall heavier than 3 mm happens. Values below 300 usually indicate days with minimal fire potential, while the fire potential is likely and very likely above 1000 and 10,000 respectively. NI is also used as a proxy of fuel aridity by some fire modules embedded in dynamic global vegetation models (*e.g.* SPITFIRE, Thonicke et al., 2010).

Finally, the last two indices were used to represent the Relative Water Content of the soil (RWC), *i.e.* the ratio of actual soil water content (S) over the water content at field capacity (FC). RWC was calculated by using the simplified bucket type water balance model with a limited storage capacity initially suggested by Linacre (1973). This model was applied and validated against soil water content measurements in southern France by Lavoir et al. (2011). The basic principle is to calculate the daily change in soil water content as the difference between rainfall input (minus deep drainage) and actual evapotranspiration (AET) outputs. Deep drainage occurs when soil water content exceeds FC. AET is a function of potential evapotranspiration (PET) using the following equation:

$$AET = \min\left[\beta\left(\frac{S}{FC}\right)^2, PET\right] \tag{1}$$

PET was calculated with the Priestley-Taylor formulae. β was set to 5.5 according to Lavoir et al. (2011). During summer drought, AET is therefore progressively downregulated as RWC declines, mimicking the stomatal control of transpiration.

Two different RWC indices were computed in this study, corresponding to high (180 mm; RWC_H) and low (90 mm; RWC_L) water content at field capacity. These values encompass the range of field capacities encountered in the study area (Ruffault et al., 2013).

2.2. LFMC data

We used the live fuel-moisture database of the French "*Reseau Hydrique*" (Duché et al., 2017) described in details in Martin-StPaul et al. (2018). This database consists of LFMC measurements that have been performed on shoots of various shrubs from different sites of the French Mediterranean area (Fig. 1) during the fire season (June to