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A semi-mechanistic model for predicting the moisture content of fine litter

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ABSTRACT

The moisture content of vegetation and litter (fuel moisture) is an important determinant of fire risk, and predictions of dead fine fuel moisture content (fuel with a diameter <25.4 mm) are particularly important. A variety of indices, as well as empirical and mechanistic models, have been proposed to predict fuel moisture, but these approaches have seldom been validated across temporally extensive datasets, or widely contrasting vegetation types. Here, we describe a semi-mechanistic model, based on the exponential decline of fuel moisture content with atmospheric vapor pressure deficit, that predicts daily minimum fuel moisture content. We calibrated the model at one site in New South Wales, Australia, and validated it at three contrasting ecosystem types in California, USA, where 10-h fuel moisture content was continuously measured every 30 min over a year. We found that existing drought indices did not accurately predict fuel moisture, and that empirical and equilibrium models provided biased estimates. The mean absolute error (MAE) of the fuel moisture content predicted by our model across sites and years was 3.7%, which was substantially lower than for other, commonly used models. Our model's MAE dropped to 2.9% when fuel moisture was below 20%, and to 1.8% when fuel moisture was below 10%. Our model's MAE was comparable to instrumental MAE (3.1–2.5%), indicating that further improvement may be limited by measurement error. The simplicity, accuracy and precision of our model makes it suitable for a range of applications, such as operational fire management and the prediction of fire risk in vegetation models, without the need for site-specific calibrations.

1. Introduction

Wildfires require four factors: (1) an ignition source; (2) 'fire weather' (favorable temperature, wind and relative humidity), (3) fuel load (sufficient combustible material to sustain fire); and (4) low fuel moisture (Bradstock, 2010). The moisture content of fine fuel, which is generally defined as litter and woody debris with a diameter less than 25.4 mm (Scott et al., 2014; Viney, 1991), is a particularly critical consideration in fire danger rating systems (Bradshaw and Deeming, 1983; McArthur, 1966; van Wagner, 1987). In turn, fire danger ratings are often used to make short-term decisions on staffing, movement of resources (from low to high risk areas) and restriction of activities (e.g: barbecues in wildland areas or operation of machinery). Dead fine fuel moisture is also an important component of basic fire science and ecological research, which require estimates that can be readily applied at large temporal and spatial scales using remote sensing or other techniques for scaling and, preferably, independent of site-specific calibrations.

A model of dead fine fuel moisture needs to provide accurate and precise estimates across ecosystem types, while maintaining simplicity with respect to input data and computation. Current methods for predicting fine fuel moisture can be broadly classified as drought indices, empirical models and mechanistic models. It is important to note that drought indices were not necessarily developed as dead fine fuel moisture models *per se*, though they are nonetheless used by agencies worldwide as indicators of fuel moisture. Dead fine fuel moisture is an important aspect for fire

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risk and fire propagation, and drought indices are therefore used as surrogates of dead fine fuel moisture.

Viney (1991) and Matthews (2013) reviewed 37 published models for predicting dead fine fuel moisture. A common theme across the reviewed models was a focus on hourly time scales and a paucity of models that operate at daily time steps, as well as a lack of long-term or multiple site validation (Slijepcevic et al., 2013). Studies on fire behaviour or propagation may require hourly model predictions, whereas daily values are required for most other operational and scientific purposes.

Here we test the applicability in the field of a novel, semi-mechanistic model of fuel moisture content that operates at daily time scales, and that is simple with respect to both inputs and computation. The model was designed to predict the daily minimum dead fuel moisture, as this is a key determinant of fire. The model is based on the diffusion of water vapor between hygroscopic dead plant tissue and the atmosphere. Model development and parameterization were performed at a temperate forest in SE Australia. The model was then tested with data from three contrasting Mediterranean ecosystem types in California (Table 1). The development of the model was originally motivated by the observation that drought indices and empirical models led to poor predictions of dead fine fuel moisture, and that mechanistic models are too complicated for many uses.

2. Methods

2.1. Model development

We developed a deterministic, steady-state model of minimum daily dead fine fuel moisture (FM) that operates at 24 h time-steps. The model assumes that: (1) fuel-to-air vapor pressure deficit (D_f, the difference between the saturation vapor pressure at the temperature of the evaporating surface of the fuel and the vapor pressure of the air) is the main driver of FM; (2) that the relationship between FM and D_f in the field is exponential; and (3) that equilibrium between FM and D_f is reached within one day:

$$FM_{Df} = FM_0 + FM_1 e^{(-mD_f)} \quad (1)$$

where FM_0 is the minimum measured fuel moisture, $FM_0 + FM_1$ the maximum measured fuel moisture, and m defines the rate of moisture decay with increasing D_f (Motulsky and Christopoulos, 2003; Motulsky and Ransnas, 1987). We are interested in minimum daily fuel moisture; D_f indicates the maximum daily fuel-to-atmosphere vapor pressure deficit, and FM_{Df} indicates the minimum daily fuel moisture modelled from D_f.

Fuel particles with diameters of 25.4 mm or less typically have a time-lag (time to reach 1/e of the final response) of 10 h or less (Viney, 1991), and so we assume that temporal auto-correlations between FM and D_f will be of less than one day. We further tested this assumption by examining the lagged correlation between field values of FM and vapor pressure deficit measured every 30 min.

Under field settings, an uncoupling between D_f and D could occur if the temperature at the evaporating site (fuel surface) is different from air temperature. To circumvent this problem, and to avoid needing to know the surface temperature, we followed Monteith (1965), where:

$$D_f = D + s(T_f - T_a) \quad (2)$$

with s, T_f and T_a indicating the slope of the saturation curve, and fuel and air temperatures, respectively. The difference in fuel to air temperature depends on the ratio between the sensible heat flux

Table 1
Site descriptions.

Site name	Dominant vegetation	Latitude (°)	Longitude (°)	Elevation (m)	Long-term			During data collection			
					Mean annual rainfall (mm)	Mean maximum temperature (°C)	Mean minimum temperature (°C)	Year	Duration of longest dry spell (days)	Maximum rain event (mm)	Maximum temperature (°C)
Cumberland Plains	Eucalypt and Melaleuca	−33.6153	150.7237	25	801	29.0	3.0	2013	38	109.8	45.5
SCCG Sonoran desert	Desert perennials and annuals	33.6518	−116.3721	275	129	28.8	12.9	2008	295	20.3	47.7
SCCG Pinyon/Juniper Woodland	Pinyon and Juniper	33.6049	−116.4547	1280	313	23.6	8.0	2007	109	28.5	35.6
SCCG desert Chaparral	Desert Shrubland	33.6100	−116.4502	1300	313	23.6	8.0	2007	89	44.4	38.2