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Review

A global review of remote sensing of live fuel moisture content for fire danger assessment: Moving towards operational products

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ABSTRACT

One of the primary variables affecting ignition and spread of wildfire is fuel moisture content (FMC). Live FMC (LFMC) is responsive to long term climate and plant adaptations to drought, requiring remote sensing for monitoring of spatial and temporal variations in LFMC. Liquid water has strong absorption features in the near- and shortwave-infrared spectral regions, which provide a physical basis for direct estimation of LFMC. Complexity introduced by biophysical and biochemical properties at leaf and canopy scales presents theoretical and methodological problems that must be addressed before remote sensing can be used for operational monitoring of LFMC. The objective of this paper is to review the use of remotely sensed data for estimating LFMC, with particular concern towards the operational use of LFMC products for fire risk assessment. Relationships between LFMC and fire behavior have been found in fuel ignition experiments and at landscape scales, but the complexity of fire interactions with fuel structure has prevented linking LFMC to fire behavior at intermediate scales. Changes in LFMC have both direct (liquid water absorption) and indirect (pigment and structural changes) impacts on spectral reflectance. The literature is dominated by studies that have used statistical (empirical) and physical model-based methods applied to coarse resolution data covering the visible, near infrared, and/or shortwave infrared regions of the spectrum. Empirical relationships often have the drawback of being site-specific, while the selection and parameterization of physically-based algorithms are far more complex. Challenges remain in quantifying error of remote sensing-based LFMC estimations and linking LFMC to fire behavior and risk. The review concludes with a list of priority areas where advancement is needed to transition remote sensing of LFMC to operational use.

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1. Introduction

Fuel moisture content (FMC), the mass of water contained within vegetation in relation to the dry mass, is a critical variable affecting fire interactions with fuel. FMC is one of the primary variables in many fire behavior prediction models and fire danger indices, as it affects ignition, combustion, the amount of available fuel, fire severity and spread, and smoke generation and composition (Anderson & Anderson, 2010; Deeming et al., 1978; Finney, 1998; McArthur, 1967; Nelson, 2001; Plucinski et al., 2010; Viegas et al., 1992). FMC is usually separated into dead (DFMC) and live (LFMC) components. In many fire risk models, DFMC is empirically determined from weather variables, diameter of the material and biochemical compositions (Viney, 1991).

LFMC is much more difficult to estimate from meteorological indices than DFMC, because living plants have a variety of drought adaptation strategies (Viegas et al., 2001) and can draw upon moisture stored in the soil. The Keetch-Byram Drought Index (KBDI, (Keetch & Byram, 1968)) has been indirectly correlated with LFMC for some species (Dimitrakopoulos & Bemmerzouk, 2003; Xanthopoulos et al., 2006), while other species appear to be driven more by medium-term meteorological conditions or phenology (Castro et al., 2006; Pellizzaro et al., 2007; Zylstra, 2011a). Even though DFMC across a landscape is a determinant of landscape connectivity and therefore the potential area burnt (Caccamo et al., 2012a), the correlation of intense fire behavior with more persistent indicators such as deep soil dryness and/or extended heatwave conditions suggests that the moisture conditions of live fuels are also important determinants of fire behavior. For instance, the Black Saturday bushfires of February 2009 in Victoria, Australia, during which 173 people died and more than 3500 houses were destroyed, occurred after weeks of extreme record-breaking high temperatures, which dried many plants to critically low levels (Gellie et al., 2010). Drought had a major influence on the incidence of large bushfires ($\geq$1000 ha) in the Sydney Basin Bioregion, New South Wales, Australia, through drying of fuels over extended areas (Bradstock et al., 2009). The 2003 Sant Llorenç Fire in Catalonia, Spain, also occurred following a period where very hot, dry Saharan air produced critical moisture stress in plants (Oliveras et al., 2009). Very low LFMC and dry, warm, Santa Ana winds contributed to large bushfire events in southern California in 2003 and 2007 (Keeley, 2004; Keeley et al., 2009).

In grasses, live and dead fuel loads are variable through time as senescence converts live fuel to dead fuel. The proportion of herbaceous fuel that is dead is important in determining the probability of ignition and rate of spread (ROS) of wildfires (Cheney et al., 1998), which has led to the use of vegetation indices for estimation of dead versus live fuels proportion to compute fire danger potential (Burgan et al., 1998; Newnham et al., 2011).

Obtaining spatially comprehensive and temporally frequent estimates specifically for LFMC is more problematic. Field sampling and gravimetric methods (Lawson & Hawkes, 1989) are locally accurate but very costly. Furthermore, generalization of these measurements to landscape, regional, or global scales is not feasible from field sampling. Remotely sensed (RS) data provide the opportunity to estimate LFMC over large areas at fine spatial and temporal resolutions, but as illustrated in this review, these data require calibration and validation. The initial hypothesis behind satellite-based estimation of LFMC is that the impact of LFMC variation on the RS signal is strong enough to be discriminated from other factors affecting spectral variation such as the atmosphere, soil background, solar and sensor geometry, and other plant characteristics. Several studies have been published in recent years to test this hypothesis (Bowyer & Danson, 2004; Ceccato et al., 2001; Gillon et al., 2004; Riaño et al., 2005) and multiple methods have been developed to estimate LFMC from both coarse and fine spatial resolution remote sensors (e.g. Chuvieco et al., 2002; Peterson et al., 2008; Wang et al., 2013; Yebra et al., 2008b). However, despite the success of these methods few of the resulting products have been operationally integrated into wildfire danger systems to date.

The objective of this paper is to review the use of RS data for estimating LFMC to assess its potential, with the anticipation that these RS-based products will soon become useful for operational use. To address this objective we will cover the following aspects: (i) importance of estimating LFMC in the context of fire risk assessment (Section 2); (ii) methods of measuring vegetation water content and their relationships with LFMC (Section 3); (iii) field data collection challenges and recommendations (Section 4); (iv) models that have been developed to derive LFMC from RS data as well as a brief review of the physical bases for a RS based estimation of LFMC (Section 5); (v) challenges and developments in satellite-based estimation of this variable (Section 6); (vi) obstacles for the operational use of LFMC models and products (Section 7); and (vii) priorities for research and applications within this field (Section 8).

2. The importance of LFMC for fire risk assessment

The effects of LFMC on fire behavior are complex and not always easy to identify empirically. Elevation of fuel temperature to the combustion point requires loss of water through evaporation; thus, higher LFMC should increase the time to ignition and decrease the probability of ignition. LFMC has therefore been demonstrated to be a primary determinant of time to ignition across multiple species at low to moderate temperatures (Xanthopoulos & Wakimoto, 1993), exhibiting a geometrically decreasing effect as temperatures are raised (Zylstra, 2011a) until the effect is negligible at temperatures corresponding with the hottest parts of a flame (Fletcher et al., 2007). LFMC has also been shown to correlate negatively with flame length from burning leaves (Zylstra, 2011a).

The way in which these factors affect fire behavior and risk is complex and the subject of debate. Plucinski et al. (2010) found that in laboratory recreations of shrub fires, the most important factors for