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Evaluation of microwave remote sensing for monitoring live fuel moisture content in the Mediterranean region

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ABSTRACT

Live fuel moisture content (LFMC) is an important factor in fire risk management in the Mediterranean region. Drawing upon a large network of stations (the Réseau Hydrique) measuring LFMC for operational fire danger assessment in the south-eastern region of France, this study assesses the ability of several long-term passive microwave remote sensing indices to capture the LFMC temporal dynamic of various Mediterranean shrub species. Microwave remote sensing has a high potential for monitoring LFMC independently of several constraints (*e.g.*, atmospheric and cloud contamination effects) associated with optical-infrared and thermal remote sensing observations. The following four microwave-derived indices are considered: (1) the Essential Climate Variable near-surface soil moisture (ECV_SM); (2) the root-zone soil moisture (ECV_RZSM) derived from ECV_SM; (3) the microwave polarization difference index (MPDI) computed from five microwave frequencies (C, X, Ku, K and Ka-band corresponding to 6.9, 10.7, 18.7, 23.8 and 36.5 GHz respectively); and (4) the vegetation optical depth (VOD) at C- and X-band (from the Advanced Microwave Scanning Radiometer for the Earth observing system, AMSR-E). Firstly, an evaluation of the root-zone soil moisture ECV_RZSM against a network of soil moisture measurements (SMOSMANIA in southern France) gave satisfactory results. For most of the Réseau Hydrique sites, the present study found good agreement between LFMC and individual microwave indices, including root-zone soil moisture, VOD at X-band, and MPDI at X and Ku-bands, all averaged over the 15 days preceding the *in-situ* LFMC measurements. VOD at X-band showed the best agreement with the *in situ* LFMC data (median of correlation coefficients over all *in situ* sites = 0.43). Further comparisons between LFMC data and several optical indices computed from the Moderate Resolution Imaging Spectrometer (MODIS) data including normalized difference vegetation index (NDVI), soil adjusted vegetation index (SAVI), visible atmospheric resistant index (VARI), normalized difference water index (NDWI), normalized difference infrared index 6 (NDII6), normalized difference infrared index 7 (NDII7) and global vegetation moisture index (GVMI) were made. The comparisons showed that VARI and SAVI, as optical greenness indices, outperform the microwave indices and other optical indices with median of correlation coefficients of 0.66 and 0.65, respectively. Overall, this study shows that passive microwave indices, particularly VOD, are efficient proxies for LFMC of Mediterranean shrub species and could be used along with optical indices to evaluate fire risks in the Mediterranean region.

1. Introduction

Live fuel moisture content (LFMC), the mass of water contained within vegetation in relation to the dry mass, is an important parameter for determining fire risk because it is related to the probability of ignition and to the rate of spread of a fire (Chuvieco et al. 2002). Decreases in vegetation water content (VWC, the total aboveground water content in both the photosynthetic (foliar) and non-photosynthetic (woody) components of the vegetation stratum (kg/m^2)) that accompany the seasonal decrease in available soil moisture can lead to severe fire danger when low LFMC is combined with extreme meteorological drought (Dennison et al. 2003; Vicente-Serrano et al. 2004). In the Mediterranean region, where prolonged summer drought is a characteristic of the climate, shrub and grass species can exhibit particularly

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low LFMC (De Baets et al. 2008; Nolan et al. 2016). These species also possess a flammable structure and chemistry that readily allows live vegetation fuels to propagate wildfire (Dimitrakopoulos and Papaioannou 2001; Papió and Trabaud 1990). Therefore, monitoring LFMC can contribute to the identification of critical periods of high fire risk in Mediterranean regions.

LFMC is typically measured using field sampling, but it is difficult to extrapolate the values obtained to larger regions and longer periods. Remote sensing offers a relatively low-cost, rapid, and repeatable method for monitoring the spatial and temporal dynamics of LFMC. Regional assessments of LFMC have been largely dominated by the use of optical-infrared (IR) sensors (Chuvieco et al. 2004; Yebra et al. 2008) and associated optical greenness and wetness indices. Greenness Indices (*e.g.*, Normalized Difference Vegetation Index, NDVI) are sensitive to changes in vegetation chlorophyll absorption and leaf area index, which co-occur with changes in water content (Chuvieco et al. 2004; Hardy and Burgan 1999). Wetness indices such as the normalized difference water index (NDWI) are more directly sensitive to changes in the vegetation moisture content (Dennison et al. 2005; Peterson et al. 2008). Previous studies have also used canopy surface temperature measured by remote thermal sensors to predict LFMC from calibration equations (Chuvieco et al. 2004; García et al. 2008). In addition, the spatial resolutions of optical satellite instruments for estimating LFMC can be < 1 km (*e.g.*, Moderate Resolution Imaging Spectrometer, MODIS) (Yebra et al. 2013). However, all the optical indices mentioned above are based on the optical and thermal wavelengths that are known to be affected by clouds, smoke, and other atmospheric aerosol contamination.

Microwave remote sensing can detect changes in canopy structure, biomass, and soil and vegetation water content, and can thus provide an alternative for monitoring LFMC independently of many constraints of optical-IR and thermal remote sensing (Entekhabi et al. 2010a; Kerr et al. 2010; Wigneron et al. 2003). Due to their longer wavelength, the microwave remote sensing observations have low sensitivity to atmospheric and cloud contamination effects, and can thus provide global observations at a high temporal frequency (almost daily) (Al-Yaari et al. 2014a; Al-Yaari et al. 2016). Most of the previous studies using microwave observations have focused on the retrieval of soil moisture and less effort has been devoted to estimating vegetation water content indices such as LFMC.

Previous studies have found that the main effects of soil moisture deficit on plant condition are exerted through the plant water potential, which in turn affects the relative water content of plant tissue (Dorigo et al. 2017; Fan et al. 2015b; Jolly et al. 2014; Martin-StPaul et al. 2017; Porporato et al. 2001; Qi et al. 2012; Wang et al. 2007). This relationship between soil moisture and vegetation water content suggests that the microwave-derived soil moisture could be used to detect the temporal dynamic of LFMC. Recently, the Climate Change Initiative project has released a long-term near-surface soil moisture dataset (Essential Climate Variable soil moisture dataset, ECV_SM) based on a combination of multiple passive and active microwave remote sensing soil moisture data (An et al. 2016; Dorigo and de Jeu 2016; Dorigo et al. 2015; Fang et al. 2016; Liu et al. 2012). This provides an opportunity to explore the potential of soil moisture for the monitoring of LFMC over long periods. Furthermore, the root-zone soil moisture could be more appropriate for monitoring LFMC as it represents the reservoir of water available to the plant (González-Zamora et al. 2016). Previous studies have found that the root zone soil moisture can be accurately retrieved from near-surface soil moisture data due to their close relationship (Albergel et al. 2012; Albergel et al. 2008; de Jeu and Dorigo 2016; Griesfeller et al. 2016; Wagner et al. 1999).

As mentioned above, microwave observations are sensitive to vegetation water content. The vegetation optical depth (VOD) retrieved from passive microwave measurements is directly proportional to the water content of the total aboveground vegetation (Jackson and Schmugge 1991; Wigneron et al. 1993). Since the upper bound of vegetation water content scales with biomass, changes in VOD have previously been interpreted mostly in the context of vegetation phenology and biomass (Liu et al. 2015; Tian et al. 2016). Nevertheless, the seasonal dynamics of VOD also follow variations in the relative vegetation water content (Konings and Gentine 2017). This makes VOD a promising coarse spatial resolution proxy for LFMC, despite of some uncertainties in the VOD retrievals, particularly for pixels including open water bodies (Grant et al. 2016).

Land surface brightness temperatures (TB) measured from passive microwave sensors contain information on both the canopy and the soil surface emissions, which depend on their respective physical temperatures. The microwave polarization difference index (MPDI), a polarization ratios of the TB data, is independent of the surface temperature and is more strongly related to the water conditions of the soil and vegetation (Owe et al. 2008). Previous studies have documented the relationship between VOD, MPDI and vegetation water content (Owe et al. 2001a; Paloscia and Pampaloni 1988; Paloscia and Pampaloni 1992; Wen et al. 2005), implying that MPDI could be a potential variable for estimating LFMC.

Therefore, the objective of this study is to evaluate the potential of microwave remote sensing indices above-mentioned (surface and root-zone soil moisture, MPDI, VOD) for monitoring LFMC collected by the Réseau Hydrique network which was developed for preventing fire risk in Mediterranean regions. The Réseau Hydrique network, including > 30 sites in the south-eastern region of France, has been monitoring the summer dynamics of LFMC in Mediterranean shrub species for > 20 years. In the present study, several microwave remote sensing indices were evaluated against *in situ* LFMC data from the Réseau Hydrique network: MPDI and VOD data computed from the Advanced Microwave Scanning Radiometer - Earth Observing System (AMSR-E) measurements (Owe et al. 2001a), the remote sensing data for near-surface soil moisture (ECV_SM) (Liu et al. 2012), and the root-zone soil moisture data (ECV_RZSM) retrieved from ECV_SM using a recursive exponential filter approach (Albergel et al. 2008). Further comparisons between LFMC and several commonly used optical indices were made to compare the performance of the microwave and optical indices for monitoring the dynamics of *in situ* LFMC.

The microwave and optical indices used in this study are presented in Section 2, the computation of ECV_RZSM and the statistical methods used for the evaluation are explained in Section 3, and results are given in Section 4. Section 5 discusses the findings and the main conclusions are drawn in Section 6.

2. Datasets

2.1. *In situ data*

2.1.1. *In situ soil moisture*

ECV_SM and ECV_RZSM retrievals were evaluated against the Soil Moisture Observing System–Meteorological Automatic Network Integrated Application (SMOSMANIA) soil moisture datasets before investigating the relationships between LFMC, ECV_SM and ECV_RZSM. SMOSMANIA is a long-term soil moisture acquisition network in southern France (see Fig. 1) which was developed to evaluate remotely sensed and modeled soil moisture products (Albergel et al. 2008; Calvet et al. 2007). Twelve SMOSMANIA stations were activated in 2006 and nine more stations were installed along the Mediterranean coast at the end of 2008, so that data from all stations covering the whole annual cycle are available from 2009. This network has provided soil moisture profile measurements from the 21 automated weather stations at four different depths (5, 10, 20 and 30 cm) in units of m^3/m^3. The geographic location and soil properties (*e.g.*, soil porosity, soil organic matter, soil texture) of each station are described in Calvet et al. (2016). Data measured over the top 0–5 cm soil layer from 2009 to 2014 were used to evaluate the ECV_SM, and the weighted averages of soil moisture data for the 0–30 cm soil layer were used to calculate *in situ*