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L-band vegetation optical depth seasonal metrics for crop yield assessment

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ABSTRACT

Attenuation of surface microwave emission due to the overlying vegetation is proportional to the density of the canopy and to its water content. The vegetation optical depth (VOD) parameter measures this attenuation. VOD could be a valuable source of information on agroecosystems, especially at lower frequencies for which greater portion of the vegetation canopy contributes to the observed brightness temperature. In the past, visible-infrared indices have been used to provide yield estimates based on measuring the photosynthetic activity from the surface canopy layer. These indices are affected by clouds and apply only in the presence of solar illumination. In this study we instead use the L-band microwave radiometer on board of the SMAP mission that provides VOD estimates in all weather and regardless of illumination. This study proposes a series of L-band VOD metrics for crop yield assessment using the first annual cycle of SMAP data (April 2015 to March 2016) over north-central United States. Maps of yield and crop proportion from the US Department of Agriculture are compared to VOD retrieved from SMAP with the Multi-Temporal Dual Channel Algorithm (MT-DCA). The yield-VOD relationship is explored using principal components regressions. Results show that 66% of yield variance is explained over the whole region by the first principal component (PC1). In corn-soy crops, PC1 explains 78% of yield amount, and maximum, standard deviation, and range of VOD capture the yield spatial patterns. Mixture of crops and scene heterogeneity reduced the unique relationships between VOD metrics and yield for specific crops. Hence, in wheat and mixed crops, PC1 explains 43% of yield variance. Results suggest that complementary information on maximum biomass, growth rate, and VOD amplitude can provide robust yield estimates, and that the uncertainty of these estimates depends on crop composition and heterogeneity. This study provides evidence that L-band VOD metrics can potentially be used to enhance crop yield forecasts.

1. Introduction

Agriculture represents the most commonly occurring human land use in the world, occupying ~38% of continental land. During the last fifty years, concurrently to the doubling of human population, the global crop production has increased substantially (Foley et al., 2011). In particular, most main grains have tripled (e.g., wheat and rice) or quadrupled (e.g., corn) their stocks (Godfray et al., 2010; FAO, 2017). Nevertheless, total consumption can exceed production when adverse weather conditions occur (Becker-Reshef et al., 2010a). The possible increase of adverse weather for crop production due to climate change may result in decline of most grain yields (Deryng et al., 2014; Asseng et al., 2015; Zhao et al., 2017). Furthermore, the population is growing, and there is a need for increased food supply in the coming decades, at least until the middle of this century. Additionally, agriculture has important environmental impacts: the increase of deforestation which reinforces climate change, biodiversity loss, or land and water degradation (Foley et al., 2005). In this context, agriculture faces a remarkable challenge: to fulfil the raising food demands improving food security, while reducing the environmental impacts. Present and future Earth Observation (EO) missions are key to help achieving this goal, and close the so-called 'yield gaps' (i.e. reduce the difference between the potential and the real yield on croplands; Godfray et al., 2010; Foley et al., 2011; Tilman et al., 2011).

Agricultural monitoring and yield forecasts are essential to mitigate the impacts of shortages in crop production. Information on crop status and yield are needed to be updated timely and regularly during the crop season. Satellite remote sensing can provide this information worldwide with reasonable costs. The complementarity between remote sensing tools and high quality survey data eases the development and

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calibration of remote sensing based crop yield models (e.g., Becker-Reshef et al., 2010a). Satellite data is the only means to obtain this information for developing countries were ground-based surveys are most needed but least available (Atzberger, 2013).

Studies on crop phenology and crop yield forecasting from satellite information have been focused mainly on vegetation indices from the visible and the near-infrared spectral regions. These indices measure the amount of photosynthetic active vegetation, which depends on the biotic and abiotic conditions that affect crop status and, ultimately, determine final yield. In particular, the Normalized Difference Vegetation Index (NDVI) is the most widely used index for crop yield forecast (Rembold et al., 2013; Alemu and Henebry, 2013). The Enhanced Vegetation Index (EVI), in turn, has also been shown useful for this purpose, with the advantage of being less sensitive than NDVI to atmosphere and soil effects (Huete et al., 2002). A variety of yield modelling studies covering different crop types and regions have used these two indices (e.g., Quarmby et al., 1991; Maselli et al., 1993; Doraiswamy and Cook, 1995; Mika et al., 2002; Weissteiner and Kühbauch, 2005; Wall et al., 2008; Becker-Reshef et al., 2010a; Son et al., 2014; Mosleh et al., 2016). Also, they are the basis for global operational agricultural monitoring systems such as the Global Agricultural Monitoring project (GLAM; Becker-Reshef et al., 2010b) or the European Commission's Monitoring Agricultural Resources (MARS; European Commission, 2017).

Despite the common use of visible-infrared indices, they present several limitations: (i) clouds and aerosols as well as seasonal decreases in solar light in high latitudes limit the global coverage and the accuracy of the indices; (ii) these indices saturate for dense crops with high leaf area index (LAI) values; (iii) they are limited to monitor the top of the vegetation canopy; and (iv) the photosynthetic activity is not always the main factor conditioning the final yield (Liu et al., 2011, 2013; Jones et al., 2012). Alternatively, microwave remote sensors can be used to overcome the above-mentioned limitations (Ulaby et al., 1981, pp. 1–5). In active systems, radar backscattering allows to obtain microwave vegetation indices (MVIs), which provide information on vegetation status and characteristics (see recent reviews of Vereecken et al., 2012 and McNairn and Shang, 2016). In passive systems, the attenuation of soil emissivity through vegetation is accounted for with the vegetation optical depth (VOD), which is directly proportional to the vegetation water content (VWC; Ulaby et al., 1986, pp. 1551–1596; Jackson and Schmugge, 1991). VOD is sensitive to the amount of living biomass, in both woody and leafy components, as well as to the amount of water stress experienced by the vegetation (Momen et al., 2017). VOD from passive microwave sensors at C- and X-bands has been applied to study biomass, carbon balance (Liu et al., 2011, 2013, 2015), and isohydricity on forests (Konings and Gentine, 2017), to analyse vegetation phenology (Jones et al., 2011, 2012; Guan et al., 2014), and vegetation dynamics in drylands (Andela et al., 2013; Tian et al., 2016). Related to agriculture monitoring, VOD at C- and X-bands retrieved from the Advanced Microwave Scanning Radiometer (AMSR-E) has been studied as a predictor of yield in the United States, showing highest correlation for summer months, when the peak of season occurs. Still, this VOD dataset showed less predictive capacity for yield than EVI and NDVI (Mladenova et al., 2017; Guan et al., 2017). Interestingly, Guan et al. (2017) have found that VOD at X-band in the United States Corn Belt is linked not only to biomass, but also to environmental stresses driving yield in the region, providing essential information to improve crop yield predictability. Hence, VOD is a promising tool in vegetation studies and particularly in crop phenology and yield assessment. Nevertheless, three main limitations must be stressed in the latter sense. Firstly, VOD coarse (9 to 36 km) resolution ideally requires relatively homogenous cropland regions to avoid the impact of fragmented landscapes in the VOD signal. Even so, major crop areas in the world with a crucial role in food supply are prone to be target regions for crop studies using VOD (e.g., the US Corn Belt, the Sahel region, central Eurasia, or India, among others). Secondly, the presence of standing water or bare land in agricultural fields (e.g., due to irrigation or crop rotation) may have an important impact on the VOD signal and subsequent crop analysis. The most significant case is rice fields when flooded, where standing water leads to a sharp decrease in VOD that impedes tracking the rice phenology (Piles et al., 2017). Thirdly, VOD is a variable directly related to biomass, but indirectly related to crop grain yield.

The sensitivity of VOD to vegetation water content and biomass depends on the frequency, with lower frequencies being more sensitive to deeper vegetation canopy layers (Ulaby et al., 1986, pp. 1551–1596). Consequently, L-band (1 to 2 GHz) is expected to be more appropriate to derive vegetation information from VOD than C- (4 to 8 GHz), X- (8 to 12 GHz), and Ku-bands (12 to 18 GHz). Hence, there is an increasing interest in recent L-band measurements, since they can potentially provide further insight to vegetation studies. At present, L-band radiometers are on board the ESA's Soil Moisture and Ocean Salinity (SMOS) satellite (launched on November 2009; Kerr et al., 2010), and the NASA's Soil Moisture Active Passive (SMAP) mission (launched on January 2015; Entekhabi et al., 2010). They have a revisit time of ~3 days and a resolution (half-power or −3 dB definition) of approximately 40 km. Additionally, L-band VOD measurements were retrieved also from the Aquarius mission, with coarser resolution (~100 km) and larger revisit time (~7 days; Le Vine et al., 2010). Aquarius ceased operations on 2015. These missions were specifically designed to retrieve soil moisture (SMOS and SMAP) and ocean salinity (SMOS and Aquarius). In the case of the soil moisture retrieval algorithms for SMOS and SMAP missions, they are based on the τ-ω emission model, which accounts for vegetation extinction (i.e. VOD; also represented by the symbol τ) and scattering (i.e. albedo; ω) effects. The need to account for optical depth estimates has led to VOD products from both satellites (Wigneron et al., 2017).

The SMOS retrieval algorithm is based on a multi-angular and dual-polarization approach obtaining simultaneous information of soil moisture and VOD (Kerr et al., 2012). The performance of SMOS-derived VOD in the field of agriculture research has been assessed in previous studies showing that, despite of the presence of instrumental noise limits detecting short-term changes, long-term and seasonal trends on SMOS VOD can be used to provide crop phenology and crop yield information. In that sense, Lawrence et al. (2014) found that SMOS VOD followed the increase of vegetation indices during the growing season, and their decrease during the crop senescence. The peak of VOD lagged the peaks of visible-infrared vegetation indices, which can be explained by the fact that maximum greenness precedes maximum biomass. Similarly, Hornbuckle et al. (2016) found that the SMOS VOD followed the corn development in the region, and that the VOD peak corresponded to a specific development stage of this crop (i.e., the milk stage, when the maximum water content is reached). Furthermore, the relationship between the SMOS VOD and yield in Iowa was investigated by Patton and Hornbuckle (2013). They found that the increase of VOD during the crop season explained ~60% of yield variability in the region. Additionally, a new SMOS VOD product -the SMOS-IC- is now available. It has shown improved correlation with NDVI than the standard L3 SMOS VOD, and its application to vegetation studies is promising (Fernández-Morán et al., 2017).

The SMAP radiometer measures terrestrial emission at single-look angle configuration and provides brightness temperatures (TB) at ~40 km resolution (Entekhabi et al., 2010). The SMAP single-look angle configuration limits the possibility to extract soil moisture and VOD information with just one acquisition using a single-channel approach. Consequently, the SMAP single-channel baseline algorithm retrieves only soil moisture at every acquisition and relies on auxiliary information of VOD, albedo, and roughness. In particular, VOD is estimated from NDVI climatology, and albedo and roughness are fixed parameters per land-cover (Chan, 2013). In contrast, the SMAP dual-channel baseline algorithm (SMAP-DCA) provides simultaneous retrievals of VOD and soil moisture. Konings et al., 2015 introduced the