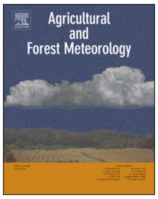
Agricultural and Forest Meteorology 259 (2018) 141–153

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet



Integrated remote sensing approach to global agricultural drought monitoring

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A R T I C L E I N F O

Keywords:
Agricultural drought
Soil moisture
SMOS
MODIS

A B S T R A C T

This study explores the use of the Soil Moisture Agricultural Drought Index (SMADI) as a global estimator of agricultural drought. Previous research presented SMADI as a novel index based on the joint use of remotely sensed datasets of land surface temperature (LST) and normalized difference vegetation index (NDVI) from the Moderate Resolution Imaging Spectroradiometer (MODIS) together with the surface soil moisture (SSM) from the Soil Moisture and Ocean Salinity (SMOS) mission. This study presents the results of applying SMADI at the global scale with a spatial resolution of 0.05° every 15 days. The period of the study spanned from 2010 to 2015. Three spatial scales (local, regional and global) were used to compare the agricultural drought events captured by SMADI against existing agricultural drought indices, as well as reported occurrences of drought events from dedicated databases.

Results show that SMADI had good consistency with two agricultural indices in the center of the Iberian Peninsula at the local and regional scales, depicting 2012 and 2014 as the driest years in the area. A comparison of SMADI across the United States of America with the impact and intensity maps of drought from the US Drought Monitor (USDM) revealed a reasonable match with the temporal and spatial extent of the affected areas, detecting the most intense drought events. Finally, a comparison at the global scale with documented events of drought world-wide showed that SMADI was able to recognize more than 80% of these events for more than 50% of their duration.

The calculation of the SMADI is simple and fast, and it relies on data that are readily available, thereby providing a rapid overview of drought-prone conditions that could enhance the present capabilities of early warning systems.

1. Introduction

Agricultural drought involves a deficit in plant-available water that could compromise the crop yields. A vast suite of approaches has been developed to monitor and characterize agricultural drought, as based on either climatic ground-based data or a variety of remote-sensing drought proxies. Indices based on ground measurements are usually derived from meteorological variables such as precipitation and temperature, and their applicability at local or regional scales primarily depends on the density and spatial distribution of the ground station networks (Rhee et al., 2010).

Remote sensing-based indices are an effective tool for large-scale drought monitoring because they naturally integrate soil moisture or vegetation information into agricultural drought indicators (Kogan, 1995; Martínez-Fernández et al., 2016; Aadhar and Mishra, 2017), which are otherwise difficult to gather through direct field observations. Despite an increasing number of studies that utilize soil moisture as the basis for agricultural drought assessments (Sridhar et al., 2008; Carrão et al., 2015; Martínez-Fernández et al., 2016), the use of remotely sensed soil moisture is far from being generalizable. This limitation is likely because the first two satellite-based missions that were specifically launched to measure soil moisture were just recently launched. They are the Soil Moisture and Ocean Salinity mission (SMOS, from the European Satellite Agency), which was launched in 2009; and the Soil Moisture Active Passive mission (SMAP, from the National Aeronautics and Spatial Agency), which was launched in 2015. In contrast, vegetation indices and land surface temperatures from satellites with long-term deployments (e.g., Landsat or the

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https://doi.org/10.1016/j.agrformet.2018.04.022
Received 18 July 2017; Received in revised form 24 March 2018; Accepted 30 April 2018

Moderate Resolution Imaging Spectroradiometer, MODIS) have been widely applied for drought estimations under very diverse environmental conditions (Asoka and Mishra, 2016).

Among remote sensing-based methods, a great number of studies are based on the so-called condition indices (Kogan, 1995; Bayarjargal et al., 2006; Bhuiyan et al., 2006; Zambrano et al., 2016; Zhang et al., 2017), several versions of them (Sandholt et al., 2002; Wan et al., 2004; Zhang et al., 2013a) or a synthetic integration of them (Du et al., 2013; Sánchez et al., 2016b). Such condition indices consist on the normalization of the remotely sensed variable from 0 to 1, based on its absolute minimum and maximum temporal values for each pixel (Zhang et al., 2017). Condition indices have been proposed for vegetation variables (usually derived from the Normalized Difference Vegetation Index, NDVI), such as the Vegetation Condition Index, or VCI (Kogan, 1990); for the surface temperature, such as the Temperature Condition Index, or TCI (Kogan, 1995); and for the soil moisture, e.g., the Soil Moisture Condition Index, or SMCI (Zhang and Jia, 2013). In addition, a condition index using precipitation from the Tropical Rainfall Measuring Mission (TRMM), the Precipitation Condition Index (PCI), was proposed by Zhang and Jia (2013).

It should be noted that the application of a single indicator across a varying range of climate and specific environmental conditions is both challenging and ambitious. In fact, most comparative drought studies are generally focused on specific geographical regions that are prone to drought (Zhang et al., 2017), such as the continental United States (Brown et al., 2008; Yao et al., 2010; Jiao et al., 2016), Australia (Caccamo et al., 2011), China (Zhang et al., 2013a), Brazil (Anderson et al., 2016) or different countries in Africa (Rojas et al., 2011; Enenkel et al., 2016; Klisch and Atzberger, 2016).

Some pioneering research is also available on drought indices that have been applied at a global scale. For example, Kogan (1997) and Mu et al. (2013) produced global drought indices using MODIS-derived evapotranspiration and NDVI, and Hao et al. (2014) embedded remote sensing observations in global model simulations. Yet, in these studies the results were evaluated at a regional scale and the comparisons were primarily qualitative. This finding reveals the two primary problems associated with the application of drought indices at the global scale. First, the lack of standardized global drought databases as well as the different definitions of agricultural (or any other type) drought make global validation difficult. This difficulty leads to the need to test database performance using proxies of drought representatives from regional to global scales. Second, there is a need for a multi-criteria validation exercise to gather real drought data or equivalent climatic/agronomic proxies.

Apart from several examples of comparisons using agricultural impacts derived from local crop yields databases (Anderson et al., 2016; Schroeder et al., 2016) or reported drought events (Rojas et al., 2011), validation of drought indices is mostly performed using meteorological indicators such as the Standardized Precipitation Index (SPI) owing to its ease of use and availability as well as its ease of interpretation (Rhee et al., 2010; Caccamo et al., 2011; Zhang and Jia, 2013; Zambrano et al., 2016). However, little agreement is typically found when the NDVI-derived VCI and other satellite-derived drought indices are compared to station-based drought indices (Bayarjargal et al., 2006).

In spite of this complexity, several efforts have been made to define and/or distribute global drought data. It is likely that the paramount initiative for developing and disseminating information about the condition of major food crops at a global scale is the FAO-United Nations Global Information and Early Warning System on Food and Agriculture (GIEWS) (www.fao.org/giews) (Cumani and Rojas, 2016) together with the Famine Early Warning Systems Network (FEWSNET) (www.fews.net/) by the US Agency for International Development. With a broader objective, the Centre for Research on the Epidemiology of Disasters (CRED) hosts the Emergency Events Database (EM-DAT), which contains core data on the occurrence and effects of drought (Guha-Sapir et al., 2017). From a climatic perspective, the Global Drought Map from NOAA (https://gis.ncdc.noaa.gov/maps/ncei/drought/global) provides global maps of the SPI (McKee et al., 1993) and rainfall data, and the Standardized Precipitation-Evapotranspiration Index (SPEI) monitor initiative (Vicente-Serrano et al., 2010) provides global real-time drought monitoring data at 0.05° (http://spei.csic.es/index.html). The above-mentioned organizations provide drought data with very different purposes but also with a variety of spatial extents, ranging from point measurements to regional/country estimations, and an extremely variable temporal resolution, ranging from daily measurements to annual events.

The Soil Moisture Agricultural Drought Index, or SMADI (Sánchez et al., 2016a), was chosen for this study. SMADI is scalable over space and time and can integrate remote sensing datasets on land surface temperature (LST), vegetation indices (e.g., the NDVI) and surface soil moisture (SSM). Previous experiments with SMADI were based in the Iberian Peninsula and showed good potential for agricultural drought monitoring, and in the United States (Sánchez et al., 2017), where it was compared to the Vegetation Drought Response Index, VegDRI (Brown et al., 2008), with encouraging results.

The objective of this study is to evaluate the potential use of SMADI, a simple and intuitive index solely based on remote sensing observations, as a global indicator of agricultural drought. To this end, global daily products of LST and NDVI from MODIS together with SMOS SSM were integrated into a global SMADI product of 0.05° spatial resolution covering years 2010 to 2015. The assessment was performed at three spatial scales (from local to global) and two quantitative criteria using climatic-agricultural indices together with registered drought occurrences. To ensure representativeness of results, the analysis includes a selection of target areas covering a wide range of biomes and climate conditions.

The study is presented as follows. Section 2 introduces the index rationale and data processing. Section 3 details the validation strategy. In Section 4, the results are analyzed in accordance with the two validation perspectives, and a discussion of the results is presented. A section with the summary and conclusions closes the article.

2. Rationale and global data sets for SMADI

After SMADI was tested at a high spatial resolution (500 m) over the Iberian Peninsula with very satisfactory results (Sánchez et al., 2016a), the next step was to assess the suitability of SMADI at a global scale, with a broader and more manageable spatial resolution. With this aim, the following global MODIS products were selected: the daily MODIS/Terra LST (MOD11C1 v.6) and the daily reflectance (MOD09CMG v.6), from which NDVI was computed. Regarding LST, owing to the conclusions of previous work, only the daytime was selected (Sánchez et al., 2016a). Both products are available on a global 0.05° latitude/longitude grid. Regarding SSM, the daily SMOS BEC L3 soil moisture data v2.0 (which corresponds to the latest SMOS L2 v.620) was resampled into the MODIS global 0.05° regular grid using bilinear interpolation. The LST, NDVI and SSM products were subsequently time-averaged into biweekly series using the 14 antecedent days. The study period spans from June 2010 to December 2015.

All the daily input data were masked before applying time averaging by using a land-use map at 0.05° derived from the 2012 MODIS/Terra Land Cover Types map (MOD12C1). The mask includes grassland and cropland/natural vegetation mosaic classes as representatives of the primary agro-ecosystems (Fig. 1). The aim of this clustering was to ensure that the study was focused on crop areas in which water availability strongly limits vegetation growth (Enenkel et al., 2016).

SMADI is based on the inverse relationship between the soil temperature status (LST) and the vegetation response (NDVI), both of which are closely related to soil moisture. In fact, LST and NDVI variations have been frequently applied to indirectly retrieve the soil moisture status (Sandholt et al., 2002; Carlson, 2007). The inclusion of soil moisture in the index rationale is essential, as agricultural drought