Remote Sensing of Environment 174 (2016) 82–99

Contents lists available at ScienceDirect

Remote Sensing of Environment

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

The Evaporative Stress Index as an indicator of agricultural drought in Brazil: An assessment based on crop yield impacts

Martha C. Anderson [a,*], Cornelio A. Zolin [b], Paulo C. Sentelhas [c], Christopher R. Hain [d], Kathryn Semmens [e], M. Tugrul Yilmaz [f], Feng Gao [a], Jason A. Otkin [g], Robert Tetrault [h]

[a] USDA-ARS, Hydrology and Remote Sensing Laboratory, Beltsville, MD
[b] Embrapa Agrosilvopastoral, P.O. Box 343, 78550-970, Sinop–MT, Brazil
[c] Department of Biosystems Engineering, ESALQ, University of São Paulo, Piracicaba, SP, Brazil
[d] Earth System Science Interdisciplinary Center, University of Maryland, College Park, MD
[e] Nature Nurture Center, Easton, PA
[f] Middle East Technical University, Civil Engineering Department, Water Resources Division, Ankara, Turkey
[g] Cooperative Institute for Meteorological Satellite Studies, University of Wisconsin-Madison, Madison, WI
[h] USDA Foreign Agricultural Service, Washington, DC

ARTICLE INFO

Article history:
Received 30 March 2015
Received in revised form 20 November 2015
Accepted 24 November 2015
Available online 17 December 2015

ABSTRACT

To effectively meet growing food demands, the global agronomic community will require a better understanding of factors that are currently limiting crop yields and where production can be viably expanded with minimal environmental consequences. Remote sensing can inform these analyses, providing valuable spatiotemporal information about yield-limiting moisture conditions and crop response under current climate conditions. In this paper we study correlations for the period 2003–2013 between yield estimates for major crops grown in Brazil and the Evaporative Stress Index (ESI) – an indicator of agricultural drought that describes anomalies in the actual/reference evapotranspiration (ET) ratio, retrieved using remotely sensed inputs of land surface temperature (LST) and leaf area index (LAI). The strength and timing of peak ESI-yield correlations are compared with results using remotely sensed anomalies in water supply (rainfall from the Tropical Rainfall Mapping Mission; TRMM) and biomass accumulation (LAI from the Moderate Resolution Imaging Spectroradiometer; MODIS). Correlation patterns were generally similar between all indices, both spatially and temporally, with the strongest correlations found in the south and northeast where severe flash droughts have occurred over the past decade, and where yield variability was the highest. Peak correlations tended to occur during sensitive crop growth stages. At the state scale, the ESI provided higher yield correlations for most crops and regions in comparison with TRMM and LAI anomalies. Using finer scale yield estimates reported at the municipality level, ESI correlations with soybean yields peaked higher and earlier by 10 to 25 days in comparison to TRMM and LAI, respectively. In most states, TRMM peak correlations were marginally higher on average with municipality-level annual corn yield estimates, although these estimates do not distinguish between primary and late season harvests. A notable exception occurred in the northeastern state of Bahia, where the ESI better captured effects of rapid cycling of moisture conditions on corn yields during a series of flash drought events. The results demonstrate that for monitoring agricultural drought in Brazil, value is added by combining LAI with LST indicators within a physically based model of crop water use.

1. Introduction

To meet the food supply needs of the world's growing population, global food production will need to roughly double by 2050 (e.g., Global Harvest Initiative, 2014). This increased production must be accomplished within the constraints of a non-uniform distribution of freshwater resources, an amplifying climate cycle, and concern for the environmental impacts of agriculture (Foley et al., 2011). To make significant strides in improving the production capacity and resiliency of global agricultural systems, we must better understand the regional distribution of factors currently limiting production: where crops are most vulnerable to climate extremes, where expansion and intensification can occur with minimal environmental costs, and where infusions of technology in water and land management are likely to significantly improve yields (Lobell et al., 2008; van Ittersum & Cassman, 2013; Zaitchik et al., 2012). Robust early warning indicators highlighting regions with developing crop stress and degrading canopy conditions due to drought

* Corresponding author at: 10300 Baltimore Ave, Beltsville, MD 20705, USA.
E-mail address: martha.anderson@ars.usda.gov (M.C. Anderson).

http://dx.doi.org/10.1016/j.rse.2015.11.034
0034-4257/Published by Elsevier Inc.

or other stressors are needed to improve within-season yield forecasts and to more effectively mobilize humanitarian response to regional crop failures (Brown, 2008). With an ever-expanding network of earth observing satellites providing free and open data access, remote sensing provides new potential to supply global geospatial information for effective assessments of yield and yield-limiting factors with serviceable spatial and temporal detail.

Remote sensing indicators of agricultural drought convey spatially explicit information regarding variability in water supply (primarily precipitation for rainfed crops), plant available water (soil moisture), crop water requirements and actual water use (evapotranspiration; ET), light-harvesting capacity (green biomass), and crop progress and vegetation health (Basso, Cammarano, & Carfagna, 2013; Rembold, Atzberger, Savin, & Rojas, 2013; Wardlow, Anderson, & Verdin, 2012). An effective large-scale crop monitoring program will require a suite of indicators, because yield limiting factors vary spatially and from year-to-year, and no single indicator will capture all factors. In addition, routine access to multiple indicators facilitates actionable response to drought detection – particularly at the global scale. A convergence of evidence of crop stress emerging in multiple independent yet related indicators leads to greater confidence that the signals are real and that action should be taken. In some cases, one might expect a staged progression of signals through different indicators; for example, a decrease in rainfall leading to crop stress and reductions in ET, and finally manifesting in a degradation in green canopy cover.

One metric of performance for operational drought indicators is a demonstrated linkage to observed impacts on the ground. For agricultural drought, impacts may be most notably manifested in terms of yield reductions. Studies conducted in many countries have investigated correlations between crop yields and spectral vegetation indices (VIs) such as the Normalized Difference Vegetation Index (NDVI; e.g., Becker-Reshef, Vermote, Lindeman, & Justice, 2010; Esquerdo, Júnior, & Antunes, 2011; Fernandes, Rocha, & Lamparelli, 2011; Kogan, Gitelson, Zakarin, Spivak, & Lebed, 2003; Mkhabela, Bullock, Raj, Wang, & Yang, 2011; Mkhabela, Mkhabela, & Mahinini, 2005), the Enhanced Vegetation Index (EVI; Gusso, Ducati, Veronez, Arvor, & da Silveira, 2013; Kouadio, Newlands, Davidson, Zhang, & Chipanshi, 2014), or biophysical parameters like Leaf Area index (LAI; Doraiswamy et al., 2005; Rizzi & Rudorff, 2007; Zhang, Anderson, Tan, Huang, & Myneni, 2005), and fraction of absorbed photosynthetically active radiation (fAPAR; Lobell, Ortiz-Monasterio, Addams, & Asner, 2002; López-Lozano et al., 2015) – all measures of vegetation amount. In addition, landsurface temperature (LST) retrieved from thermal infrared (TIR) remote sensing provides information about temperature extremes encountered during crop development (Gusso, Ducati, Veronez, Sommer, & da Silveira, 2014), as well as stress-induced stomatal closure resulting in elevated canopy temperatures (Jackson, Idso, Reginato, & Pinter, 1981; Moran, 2003). VI- and LST-based indicators have also been combined for yield estimation; with a weighting factor as in the Vegetation Health Index (VHI; Kogan, 1995, 1997; Kogan, Salazar, & Roytman, 2012; Liu & Kogan, 2002; Salazar, Kogan, & Roytman, 2007), through multi-variable regression, decision tree analysis, or other merging criteria (Doraiswamy, Akhmedov, Beard, Stern, & Mueller, 2007; Gusso et al., 2014; Johnson, 2014; Prasad, Chai, Singh, & Kafatos, 2005), or through surface energy balance retrievals of evapotranspiration (ET) – an indicator of vegetation health and soil moisture availability (Bastiaanssen & Ali, 2003; Mishra, Cruise, Mecikalski, Hain, & Anderson, 2013; Tadesse, Senay, Berhan, Regassa, & Beyene, 2015; Teixeira, Scherrer-Warren, Hernandez, Andrade, & Leivas, 2013; Zwart & Bastiaanssen, 2007). Key findings from representative studies comparing VI- and LST-based indicators to crop yields are summarized in Table 1. Other remotely sensed indicators used for yield assessment include solar-induced fluorescence measurements (Guan et al., in press) and microwave retrievals of surface soil moisture (Bolten, Crow, Zhan, Jackson, & Reynolds, 2010).

These studies have investigated both the strength and timing of peak correlations between remote sensing time series and ground-based yield estimates. Advance signals of anomalous production are beneficial to agricultural producers and commodity markets, and globally for early warning of food insecurity; therefore, earlier peak yield correlations with satellite indicators are a desirable feature. In some climates, responsiveness to rapidly changing conditions is an advantage, such as during rapid onset – or "flash" – drought events. Vegetation health can deteriorate very quickly if moderate precipitation deficits are accompanied by intense heat, strong winds, and sunny skies, as the enhanced evaporative demand quickly depletes root zone moisture (Mozny et al., 2012; Otkin et al., 2013). The ability to pinpoint periods of stress in space and time has motivated assimilation of remote sensing indicators into crop models, which are sensitive to timing of stress within the growing cycle (Ines, Das, Hansen, & Njoku, 2013; Launay & Guerif, 2005; Nearing et al., 2012).

This study assesses the remotely sensed Evaporative Stress Index (ESI) as an indicator of agricultural drought in terms of the timing and magnitude of peak correlations with spatially distributed yield observations. The ESI depicts anomalies in the actual-to-reference ET ratio retrieved via energy balance using remote sensing inputs of LST and LAI (Anderson et al., 2013; Anderson, Hain, Wardlow, Mecikalski, & Kustas, 2011; Anderson, Norman, Mecikalski, Otkin, & Kustas, 2007b). The energy balance scheme incorporates key meteorological variables that drive flash drought, and in the U.S. the ESI has been shown to provide early warning of deteriorating crop moisture conditions in comparison with precipitation or VI-based indices (Anderson et al., 2011, 2013; Otkin et al., 2013; Otkin, Anderson, Hain, & Svoboda, 2014).

The study focuses on the utility of the ESI in explaining regional yield variability in major crops grown in Brazil, which has been identified as an area where significant gains in agricultural production can be achieved, both in terms of expansion and intensification (FAO, 2003). Brazil is a major exporter of several key agricultural products (including soybean, corn, cotton, coffee, sugar and ethanol from sugarcane, and orange juice), and fronts of land use conversion to agriculture continue to expand in the northeast, the central savanna regions (Cerrado), and rainforest transition zones. The north and northeastern states of Maranhão, Tocantins, Piauí and Bahia (the so-called "MATOPIBA" region), for example, are considered a major frontier for new agribusiness investment. However, decisions regarding reasonable expansion are complex and must be informed by analyses of regional climate vulnerability and sustainability of existing ecosystem services. Major droughts in the past decades have severely impacted yields and water availability in some regions of Brazil, particularly in the northeast, pointing to the need for improved drought preparedness in the most climatically vulnerable regions (Gutiérrez, Engle, De Nys, Molejón, & Martins, 2014). This need has led to the recent development of a Northeast Brazil Drought Monitor {http://monitordesecas.ana.gov.br/; \De Nys, 2015 #1142} following the convergence of evidence approach adopted by the U.S. Drought Monitor (Svoboda et al., 2002).

This paper builds on a prior study (Anderson et al., 2015) which compared cross-correlations in ESI with satellite-based precipitation and LAI retrievals and anomalies over Brazil, and their relative behaviors over rainforest vs. agricultural (farm and pasture) land cover classes. Here, these same satellite indicators are compared with a decade of yield data from Brazil, collected between 2003 and 2013. First, the indices are correlated with state-level data for corn, soybean and cotton from the National Food Supply Agency (CONAB), which provides yield estimates discriminated by cropping season (e.g., early vs. late season corn crops). Next, we examine patterns in yield-index correlations at higher spatial resolution using yield estimates at the municipality level from the Brazilian Geographical and Statistical Institute (IBGE). An overarching goal of this study was to evaluate the relative value of different classes of satellite indicators for integration into ongoing drought monitoring, crop modeling and yield estimation efforts in Brazil. We also evaluate the value added by combining LAI – indicative of the VI class of agricultural indicators – with LST in a physically based model of ET, and in comparison with precipitation anomalies