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Evaluating a satellite-based seasonal evapotranspiration product and identifying its relationship with other satellite-derived products and crop yield: A case study for Ethiopia

Tsegaye Tadesse[a,*], Gabriel B. Senay[b], Getachew Berhan[c], Teshome Regassa[d], Shimelis Beyene[e]

[a] National Drought Mitigation Center, School of Natural Resources, University of Nebraska-Lincoln, 816 Hardin Hall, 3310 Holdrege Street, P.O. Box 830988, Lincoln, NE 68583-0988, USA
[b] U.S. Geological Survey (USGS) Earth Resources Observation and Science (EROS) Center, 47914 252nd Street, Sioux Falls, SD 57198, USA
[c] Addis Ababa University, P.O. Box 1176, Addis Ababa, Ethiopia
[d] Department of Agronomy and Horticulture, University of Nebraska-Lincoln, USA
[e] Institute for Ethnic Studies, Department of Anthropology, University of Nebraska-Lincoln, USA

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ABSTRACT

Satellite-derived evapotranspiration anomalies and normalized difference vegetation index (NDVI) products from Moderate Resolution Imaging Spectroradiometer (MODIS) data are currently used for African agricultural drought monitoring and food security status assessment. In this study, a process to evaluate satellite-derived evapotranspiration (ETa) products with a geospatial statistical exploratory technique that uses NDVI, satellite-derived rainfall estimate (RFE), and crop yield data has been developed. The main goal of this study was to evaluate the ETa using the NDVI and RFE, and identify a relationship between the ETa and Ethiopia's cereal crop (i.e., teff, sorghum, corn/maize, barley, and wheat) yields during the main rainy season. Since crop production is one of the main factors affecting food security, the evaluation of remote sensing-based seasonal ETa was done to identify the appropriateness of this tool as a proxy for monitoring vegetation condition in drought vulnerable and food insecure areas to support decision makers. The results of this study showed that the comparison between seasonal ETa and RFE produced strong correlation ($R^2 > 0.99$) for all 41 crop growing zones in Ethiopia. The results of the spatial regression analyses of seasonal ETa and NDVI using Ordinary Least Squares and Geographically Weighted Regression showed relatively weak yearly spatial relationships ($R^2 < 0.7$) for all cropping zones. However, for each individual crop zones, the correlation between NDVI and ETa ranged between 0.3 and 0.84 for about 44% of the cropping zones. Similarly, for each individual crop zones, the correlation (R^2) between the seasonal ETa anomaly and de-trended cereal crop yield was between 0.4 and 0.82 for 76% (31 out of 41) of the crop growing zones. The preliminary results indicated that the ETa products have a good predictive potential for these 31 identified zones in Ethiopia. Decision makers may potentially use ETa products for monitoring cereal crop yields and early warning of food insecurity during drought years for these identified zones.

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1. Introduction

Recent studies have shown the importance of remotely sensed data in improving drought and vegetation monitoring for risk management (Tadesse et al., 2014; Rojas et al., 2011; Mishra and Singh, 2011; Meze-Hausken, 2004). Given the repeat coverage and spatially continuous measurements over a large area, satellite-based remote sensing plays a vital role in monitoring drought on a more local scale. In addition, advanced satellite technology products with high temporal resolution are cost effective and may serve to detect the onset of a drought and its duration and magnitude, which is critical information for risk management and food security. Monitoring crop production to provide early warning of production shortfalls during extreme climate events such as drought is a key objective of many governments. Thus, satellite information and

* Corresponding author. Tel.: +1 402 472 3383.
E-mail addresses: ttadesse2@unl.edu (T. Tadesse), senay@usgs.gov (G.B. Senay), getachewb1@yahoo.com (G. Berhan), tregassa2@unl.edu (T. Regassa), sbeyene2@unl.edu (S. Beyene).

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products are expected to help in decision making for countries with a wide diversity of crops, ecosystems, and production systems.

Food production and water scarcity are long-standing issues in Ethiopia, exacerbated by periodic drought and an ever-increasing population (Tadesse et al., 2014; Meze-Hausken, 2004). Agriculture continues to be a predominant sector of the economy and an important sector that provides food to the fast-growing population. Generally, food insecurity typically results from a combination of climate events and societal vulnerabilities. In rainfed agriculture, availability of water is the most critical factor for sustaining crop productivity and food security. Recent droughts have illustrated the need for improved monitoring and enhanced decision support systems to deliver timely and reliable information products to decision makers at many levels (Tadesse et al., 2008). Several methods and approaches for drought monitoring and risk management have been developed in the last few decades (Tadesse et al., 2008; Panu and Sharmat, 2002). However, there is still an increasing demand to improve, test, and integrate existing satellite-derived products using integrated remote sensing and ground observation of climate data to address food production issues that arise from water scarcity and drought (Vicente-Serrano et al., 2012; Rojas et al., 2011; Mishra and Singh, 2011). In addition, the development of new tools that provide timely, detailed spatial-resolution drought information is essential for improving drought preparedness and response (Brown et al., 2008). Recent state-of-the-art drought monitoring tools, such as the vegetation drought response index (VegDRI) (Brown et al., 2008), Vegetation Outlook (VegOut) (Tadesse et al., 2010), and Atmosphere-Land Exchange Inverse (ALEXI) (Anderson et al., 2007) were developed to address vegetation stress using satellite and remote sensing data. Among these, drought and vegetation monitoring tools, only a few (e.g., ALEXI) are focused on the use of evapotranspiration (ET) data as a proxy for vegetation condition monitoring.

Bastiaanssen et al. (2005) and Senay et al. (2011) indicated that ET's dependence on land cover and soil moisture, and its direct relationship with carbon dioxide assimilation in plants, makes it an important variable to monitor and estimate crop yield and biomass for decision makers interested in food security. ET is the combined process of water surface evaporation, soil moisture evaporation, and plant transpiration. In the environmental system, ET is an important and primary component of the hydrologic budget because it expresses the exchange of mass and energy between the soil–water–vegetation system and the atmosphere. ET comprises two sub-processes: evaporation and transpiration. Evaporation occurs on the surfaces of open water bodies, vegetation, and bare ground. Transpiration involves the withdrawal and transport of water from the soil/aquifer system through plant roots, stems, and eventually an evaporation process from the interior of the plant leaves into the atmosphere (Senay et al., 2007, 2011). Prevailing weather conditions influence potential and reference ET through forcing variables such as radiation, temperature, wind, and relative humidity (Senay et al., 2011).

Since 2000, actual ET (ETa) data from the Moderate Resolution Imaging Spectroradiometer (MODIS) have been produced by the U.S. Geological Survey (USGS) Famine Early Warning Systems Network (FEWSNET) using the operational simplified surface energy balance (SSEBop) model (Senay et al., 2013). The SSEBop setup is based on the simplified surface energy balance (SSEB) approach (Senay et al., 2007, 2011) with unique parameterization for operational applications. The ETa may be used to show the current vegetation condition as compared to the long historical records. This comparison has the potential to help identify vegetation stress in time and space (Senay et al., 2013). For example, the ETa anomaly for a given period expresses the surplus or deficit of ETa as compared to the same period historically. FEWSNET (2014) noted that knowledge of the rate and amount of ETa for a given location is an essential component in the design, development, and monitoring of agricultural and environmental systems. Across the crop or rangeland areas, ETa anomalies are assumed to show (i) surplus or deficit in soil moisture during the non-growing season and (ii) surplus or deficit of crop water use in the growing season, which is directly related to crop condition and biomass. Thus, positive ETa anomalies expected to indicate relatively higher biomass, and negative ETa anomalies show less biomass as compared to the long historical record (median value) for the same period. Based on this assumption, ETa products are used for 8-day cumulative, monthly, and seasonal ET anomalies for Africa to monitor agricultural drought and food security status assessment (FEWSNET, 2014).

Despite the general consensus in using ETa anomalies for drought monitoring and food security assessment, a comprehensive model evaluation has not yet been done. Moreover, methodologies for evaluating drought and food security models are limited. Taking these gaps into account, this research has focused on developing a model evaluation method specifically applicable to drought and food security models using crop yield data. The specific objectives are to (1) develop a process to evaluate satellite-derived evapotranspiration anomalies using satellite-derived rainfall estimate (RFE), normalized difference vegetation index (NDVI), and crop yield data, (2) evaluate the potential use of ETa products in estimating the main cereal crops during the long rainy season (Kiremt) using the correlation between seasonal ETa anomaly and crop yield anomaly data, and (3) identify crop growing zones in Ethiopia that could potentially use the ETa products for monitoring crop yields to support risk management and food security.

2. Materials and methods

2.1. Study area selection for model evaluation

Ethiopia occupies a total area of 1,100,000 km^2 and is divided into 72 administrative zones (Fig. 1). The areas of these zones range from about 300 km^2 (Hareri zone) to 45,000 km^2 (Bale zone) (GeoHive, 2014). The average area of all zones is about 15,000 km^2. The global land cover map produced by the European Space Agency (ESA) was used to identify the cropland zones in Ethiopia. The ESA's global land cover map (GlobCover LC v2) is based on Medium Resolution Image Spectrometer (MERIS) sensor data with a spatial resolution of 300 meters (ESA, 2008). The geographic distribution of the cropland in Ethiopia and the crop growing zones are shown in Fig. 1. For this study, 41 crop growing zones that have about eleven years of historical records of yield data (2000–2010) were selected (Fig. 1).

2.2. The crop growing seasons and estimating crop yield in Ethiopia

The two main rainy seasons in Ethiopia are locally known as Kiremt (June–September) and Belg (February–May) (Diro et al., 2008; Gissila et al., 2004). Kiremt is the main rainy season across most parts of Ethiopia, except the extreme south and southeast part of the country (Gissila et al., 2004). The onset and withdrawal as well as the amount and distribution of precipitation during Kiremt have a greater impact on crop production than Belg (Evangelista et al., 2013). In addition, the Kiremt season yield accounts for 90–95% of the annual crop production of Ethiopia (Seifu, 2004; FEWSNET, 2003). Thus, this study focused on a crop yield anomaly for the Kiremt growing season.

Cereals are the major food crops in terms of area planted and volume of production in the selected zones (CSA, 2014). Cereals are also produced in greater volumes compared with other crops because they are the principal staple crops in these zones. The CSA

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