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Performance of five surface energy balance models for estimating daily evapotranspiration in high biomass sorghum

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ABSTRACT

Robust evapotranspiration (ET) models are required to predict water usage in a variety of terrestrial ecosystems under different geographical and agrometeorological conditions. As a result, several remote sensing-based surface energy balance (SEB) models have been developed to estimate ET over large regions. However, comparison of the performance of several SEB models at the same site is limited. In addition, none of the SEB models have been evaluated for their ability to predict ET in rain-fed high biomass sorghum grown for biofuel production. In this paper, we evaluated the performance of five widely used single-source SEB models, namely Surface Energy Balance Algorithm for Land (SEBAL), Mapping ET with Internalized Calibration (METRIC), Surface Energy Balance System (SEBS), Simplified Surface Energy Balance Index (S-SEBI), and operational Simplified Surface Energy Balance (SSEBop), for estimating ET over a high biomass sorghum field during the 2012 and 2013 growing seasons. The predicted ET values were compared against eddy covariance (EC) measured ET (ET_{EC}) for 19 cloud-free Landsat image. In general, S-SEBI, SEBAL, and SEBS performed reasonably well for the study period, while METRIC and SSEBop performed poorly. All SEB models substantially overestimated ET under extremely dry conditions as they underestimated sensible heat (H) and overestimated latent heat (LE) fluxes under dry conditions during the partitioning of available energy. METRIC, SEBAL, and SEBS overestimated LE regardless of wet or dry periods. Consequently, predicted seasonal cumulative ET by METRIC, SEBAL, and SEBS were higher than seasonal cumulative ET_{EC} in both seasons. In contrast, S-SEBI and SSEBop substantially underestimated ET under too wet conditions, and predicted seasonal cumulative ET by S-SEBI and SSEBop were lower than seasonal cumulative ET_{EC} in the relatively wetter 2013 growing season. Our results indicate the necessity of inclusion of soil moisture or plant water stress component in SEB models for the improvement of their performance, especially under too dry or wet environments.

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1. Introduction

The acreage of the cellulosic feedstocks is rapidly increasing globally. Although maize (*Zea mays* L.), switchgrass (*Panicum virgatum* L.), Miscanthus (*Miscanthus* × *giganteus*), sugarcane (*Saccharum officinarum* L.), and tree poplar (*Populus* spp.) are predominantly listed as potential bioenergy crops in the United States, high biomass sorghum (*Sorghum bicolor* L. Moench) is another promising dedicated cellulosic feedstock due to its high yield potential (Rooney et al., 2007). However, the increased deployment of dedicated cellulosic feedstocks has raised numerous environmental concerns, including the implications to water resources (Schnoor et al., 2008). Along with biomass/yield, several factors such as greenhouse gas mitigation and water usage should be considered when selecting suitable bioenergy crops (Hill et al., 2009; Somerville et al., 2010; Wagle and Kakani, 2014b; Zeri et al., 2013). Evapotranspiration (ET) is not only a key component of the hydrological cycle (Tateishi and Ahn, 1996), it also links several atmospheric, hydrological, and ecological processes (Pielke et al., 1998). Thus, quantifying ET in a variety of terrestrial ecosystems is necessary for a better understanding of terrestrial ecosystems, assessment of local to global water balances, and water management of agricultural lands (Tateishi and Ahn, 1996). Although the eddy covariance (EC) technique has been the most commonly used

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method for measuring ET at the ecosystem level in recent years, the cost and logistic requirements prohibit installation of EC systems in all places at all times. The EC-based ET (ET_{EC}) in high biomass sorghum is lacking until now (Wagle et al., 2016b). Furthermore, the EC technique is not applicable in heterogeneous terrain. Thus, robust ET models are required to predict water usage of high biomass sorghum under different geographical and agrometeorological conditions.

Satellite remote sensing complements the limited coverage of the land surface by ground-based observation networks. As a result, satellite remote sensing is being considered as the most promising tool to predict ET over large areas (Glenn et al., 2007; Gowda et al., 2008; Wagle et al., 2017). Remote sensing-based ET estimation methods fall broadly into two categories: simple empirical or statistical approaches based on satellite-derived vegetation index or climate data (Choudhury et al., 1994; Nagler et al., 2005; Wagle et al., 2016a, 2017) and relatively complex models based on the surface energy balance (SEB) equation (Gillies et al., 1997; Mallick et al., 2014). Simple empirical approaches can provide accurate estimates of ET over homogeneous areas with uniform vegetation (Nagler et al., 2005; Wagle et al., 2016a, 2017), but an accurate estimate of large-scale ET over heterogeneous areas by using empirical approaches is challenging. As a result, several remote sensing-based ET models have been developed in past two decades to estimate ET over large areas based on the SEB equation as shown below (Allen et al., 2007; Bastiaanssen et al., 1998; Roerink et al., 2000; Senay et al., 2013b; Su, 2002):

$$R_n = G + LE + H \tag{1}$$

where R_n is net radiation, G is soil heat flux, H is sensible heat flux, and LE is latent heat flux (unit is W m^{-2} for all energy terms). The LE is estimated as a residual:

$$LE = R_n - G - H \tag{2}$$

The SEB-based ET models convert remotely sensed radiances in satellite images into land surface and atmospheric variables, such as vegetation indices, albedo (α), surface emissivity (ε_o), and land surface temperature (T_s) to estimate ET. Among these variables, T_s is considered a key variable and is exploited in a typical SEB model (Duan et al., 2017). Although, several SEB models have shown reasonable accuracy for predicting ET in different parts of the world, comparison of their performance at the same site is rare because of varying levels of complexities associated with implementation of these models (Bhattarai et al., 2016). A thorough evaluation of numerous SEB models is necessary for adopting any single or combination of these models. In this study, we compared five widely used single-source SEB models - Surface Energy Balance Algorithm for Land (SEBAL) (Bastiaanssen et al., 1998), Mapping ET with Internalized Calibration (METRIC) (Allen et al., 2007), Surface Energy Balance System (SEBS) (Su, 2002), Simplified Surface Energy Balance Index (S-SEBI) (Roerink et al., 2000), and operational Simplified Surface Energy Balance (SSEBop) (Senay et al., 2013b) - at a high biomass sorghum field in the southern Great Plains (Chickasha, OK) of the United States. A recent study compared ET estimates from SEBAL, METRIC, and S-SEBI with ET from the water balance estimates for a grain sorghum field in Gezira Irrigation Scheme, Sudan (Al Zayed et al., 2016). To the best of our knowledge, none of these five SEB models have been evaluated to predict ET in rain-fed high biomass sorghum grown for biofuel production. Thus, the objective of this study was to compare the performance of five SEB models (SEBAL, METRIC, SEBS, S-SEBI, and SSEBop) to predict daily ET of high biomass sorghum using ET_{EC} data during the 2012 and 2013 growing seasons. This thorough evaluation of the commonly-used five SEB models helps to identify their strengths and weaknesses and ultimately to guide development of more robust SEB models.

2. Materials and methods

2.1. Site description, weather conditions, and crop growth

High biomass sorghum (*cv.* ES5200) was planted at 250,000 pure live seeds ha^{-1} (0.76 m row spacing) annually (May 18, 2012 and May 15, 2013) under no-till condition in an eight hectare plot (~275 m × 275 m) at Oklahoma State University, South Central Research Station, Chickasha, OK (35.04°N, 97.91°W). The site received 744 and 925 mm of annual rainfall in 2012 and 2013, respectively. The 30-year (1981–2010) mean annual rainfall at the site was about 900 mm. As compared to the 30-year mean, winter and spring 2012 were slightly warmer and wetter, but summer and fall 2012 were slightly warmer and drier. Summer 2013 was slightly cooler and wetter, but fall (August–September) 2013 was slightly warmer and drier compared to the 30-year average. Soil type is deep (>2 m) and well-drained, formed from weathered loamy alluvium (predominant soil series: Dale silt loam - a fine-silty, mixed, superactive, thermic Pachic Haplustoll). Seasonal patterns of soil moisture content (measured at 5 cm depth using two water content reflectometers) during the 2012 and 2013 growing seasons showed that soil moisture content was higher in 2013 than in 2012 during spring and summer, but similar during the August–September period (Fig. 1). Soil moisture content fluctuated between 0.13 and 0.48 m^3/m^3 in the 2012 growing season and between 0.15 and 0.48 m^3/m^3 in the 2013 growing season.

Canopy height reached a maximum of around 2.5 m in both years. The maximum leaf area index (LAI, measured using a plant canopy analyzer - LAI 2000, LI-COR Inc., Lincoln, NE, USA) was 5.7 and 5.2 m^2 m^{-2} in 2012 and 2013, respectively. The highest recorded aboveground dry biomass was about 3.0 kg m^{-2} (equivalent to 30 t ha^{-1}) in 2012 and about 1.3 kg m^{-2} in 2013. Water logging conditions in several parts in the field from seeding to mid-June and infestation of Johnson grass (*Sorghum halepense* L.) caused a significant reduction in biomass in 2013 compared to 2012. More details on crop growth and weather conditions are presented in our previous studies, which compared measured CO_2 fluxes (Wagle et al., 2015) and ET, ecosystem water use efficiency (EWUE, which relates biomass production or carbon gain to water use), and energy partitioning (Wagle et al., 2016b) between switchgrass and high biomass sorghum. Location of the study site and nearby Oklahoma Mesonet stations are shown in Fig. 2.

2.2. EC measurements

An EC system was set up at the north end of the sorghum plot facing south (i.e., prevailing wind direction) to continuously measure carbon dioxide (CO_2), water vapor (H_2O), and energy flux densities during the 2012 and 2013 growing seasons. The EC system comprised of an infrared gas analyzer (LI-7500, LI-COR Inc., Lincoln, NE, USA) and a three-dimensional sonic anemometer (CSAT3, Campbell Scientific Inc., Logan, UT, USA). We adjusted sensor heights throughout the growing season in relation to canopy heights to avoid flux measurements in roughness sub-layer. We also measured net radiation (R_n - NR-Lite, Kipp and Zonen, Delft, The Netherlands), photosynthetic photon flux density (*PPFD* – LI 190, LI-COR Inc., Lincoln, NE, USA), near surface (5 cm) soil temperature (TCAV-L, Campbell Scientific Inc., Logan, UT, USA), soil moisture (CS616, Campbell Scientific Inc., Logan, UT, USA), and soil heat fluxes (G - HFP01SC, Hukseflux Thermal Sensors B.V., The Netherlands).

2.3. Eddy flux data processing and gap filling for H_2O fluxes

The *EddyPro* software (LI-COR Inc., Lincoln, NE, USA) was used to compute 30-min average CO_2 and H_2O fluxes from 10 Hz