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Evapotranspiration partitioning and water use efficiency of switchgrass and biomass sorghum managed for biofuel

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ABSTRACT

Switchgrass (*Panicum virgatum* L.) and biomass sorghum (*Sorghum bicolor* L. Moench) are two candidate bioenergy crops for the US Southern Great Plains region. In this water-limited region, there is a need to partition evapotranspiration (ET) and to determine the water use efficiency (WUE) of these potential feedstocks. Both crops were grown in a field plot experiment at Stillwater, OK. Soil water content measurements were made by neutron probe every two weeks to a depth of 2.0 m in 0.2-m intervals over the course of three growing seasons. Growing season ET was estimated as the difference between growing season precipitation and change in root zone soil water storage. Evapotranspiration was partitioned by measuring canopy interception using interception trays and estimating soil evaporation using the FAO-56 dual crop coefficient method. Transpiration was calculated as ET minus soil evaporation and canopy interception. Transpiration was the largest component of ET; however, soil evaporation and canopy interception accounted for 28% of growing season ET for switchgrass and 42% for biomass sorghum. Although the non-productive losses were greater from biomass sorghum, WUE values of 9–49 kg ha^{-1} mm^{-1} based on ET and 22–83 kg ha^{-1} mm^{-1} based on transpiration were observed for biomass sorghum, which were greater than the WUE values of switchgrass, 8–21 kg ha^{-1} mm^{-1} based on ET and 12–28 kg ha^{-1} mm^{-1} based on transpiration. These results demonstrate that biomass sorghum is a candidate feedstock with potential to achieve greater WUE than switchgrass at this location; however, other factors such as economics and ecosystem services should also be considered.

1. Introduction

Continuing interest in producing cellulosic ethanol from plant biomass is driven by rising oil prices, concerns about climate change, and energy security issues. In the US Southern Great Plains, bioenergy cropping systems for cellulosic ethanol are being explored with both switchgrass (a native C4 perennial grass; McLaughlin et al., 2002) and biomass sorghum (a highly productive annual; Rooney et al., 2007) considered as candidate bioenergy crops. There is a need for a clearer understanding of the dependency of these candidate bioenergy crops on water availability and of the potential impacts of these cropping systems on the hydrology of the region. Due to the sub-humid to semi-arid nature of the climate, the majority of the precipitation in the region returns to the atmosphere as ET. For instance, from field experiments in Oklahoma involving switchgrass, mixed grasses, and biomass sorghum, Yimam et al. (2014) reported ≥79% of the annual precipitation, which ranged from 625 to 836 mm, being used for ET by these cropping systems. Thus, identifying sustainable bioenergy cropping systems requires understanding the ET dynamics and the efficiency with which these crops translate ET into harvestable biomass.

Evapotranspiration includes non-productive losses (i.e. water losses not associated with biomass production) such as evaporation from the soil surface, from the external plant surfaces, and from residues; as well as productive transpiration through plant stomata. Evapotranspiration has been used as an indicator of plant growth and yield. However, the relationship between yield and ET is not robust due largely to the varying contribution of non-productive losses to the total ET (Shideed, 2005). Hence, partitioning ET between plant canopy interception, soil evaporation, and transpiration is necessary to relate biomass yield to transpiration and to accurately parametrize these components in the crop growth and hydrological models.

The interception component of ET is the amount of rainfall (or irrigation) retained by and evaporated from the plant canopy and plant residue. Interception can significantly reduce the amount of water reaching the soil surface for infiltration. Therefore, it

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is important to consider interception separately from total ET (Savenije, 2004). The majority of studies on interception have been concentrated on tree species, and only a limited number of reports are available for grasses and row crops. Gilliam et al. (1987) reported a mean interception of 38% of precipitation for unburned tallgrass prairies and 19% for annually burned tallgrass prairies in Kansas receiving approximately 820 mm year^{-1} of precipitation. For switchgrass in England, Finch et al. (2004) measured rainfall interception of 47–54% for rainfall events of $\leq$10 mm during the late growing season. A study of rainfall interception by another candidate bioenergy crop, miscanthus (*Miscanthus* × *giganteus*), was performed by Finch and Riche (2010) at the same site in England. They found an interception loss of ~25% of the rainfall from June to January, a period in which rainfall totals ranged from 391 to 643 mm. Clearly rainfall interception can be a significant component of ET. However, we are not aware of any published reports on interception by switchgrass or biomass sorghum managed as bioenergy feedstocks.

Another significant non-productive loss of soil water occurs through soil evaporation, which can account for 20–30% of growing season ET for annual crops (Allen, 2011). Garofalo and Rinaldi (2013) estimated 10–44% of growing season water use being lost as soil evaporation under drip-irrigated biomass sorghum receiving 275–415 mm of irrigation and 67–92 mm of rainfall. They used the ratio of the intercept and slope of the linear regression between ET and above-ground dry biomass as their estimate of soil evaporation. These relatively large soil evaporation values highlight the importance of accurately quantifying this component of ET for accurate representation of the soil water balance. However, we are not aware of any other detailed studies on soil water evaporation under switchgrass or biomass sorghum.

Soil evaporation under crops is highly dependent on net radiation, surface soil water content, crop growth stage, and leaf area index (Wang and Liu, 2007). Under constant atmospheric demand, evaporation from the soil occurs in two discrete stages (Ritchie, 1972). The first stage, known as the constant rate stage, occurs when the soil is sufficiently wet, and the water from the soil evaporates at the rate of potential evaporation. In this stage the evaporation rate is controlled by the available energy at the surface. Stage one continues until the ability of the soil to provide water drops below the potential evaporation rate. Stage two, the falling-rate stage, is limited by the hydraulic properties of the soil and soil water content.

Water use efficiency (WUE), the ratio of carbon assimilated or biomass produced to the amount of water used, is an important indicator which can be used to evaluate how efficiently bioenergy crops utilize available water. The WUE can be defined based on carbon dioxide assimilation, above-ground biomass, or crop yield; and the water consumption can be represented as transpiration, ET, or total water input for the system. Moreover, the time scale for calculating WUE can be instantaneous, daily, or seasonal (Sinclair et al., 1984). In part because of these varying definitions, previous studies on the WUE of switchgrass have produced a wide range of results. Byrd and May (2000) estimated values ranging between 43 and 85 kg ha^{-1} of total biomass (root plus shoot) per mm of water transpired in an outdoor pot experiment for different cultivars of switchgrass grown under varying water and N regimes. Xu et al. (2006) determined the WUE of switchgrass seedlings in a growth chamber. They calculated the WUE as total biomass per mm of water transpired and found values of 52 kg ha^{-1} mm^{-1} for dry and 55 kg ha^{-1} mm^{-1} for wet conditions. They also found values of 15 and 18 kg ha^{-1} of shoot (i.e. above-ground) biomass per mm of water transpired in dry and wet conditions, respectively. Kiniry et al. (2008) simulated WUE values for switchgrass between 30 and 50 kg ha^{-1} of above-ground biomass per mm of water transpired using the ALMANAC model, significantly higher than the values estimated by Xu et al. (2006). From the above-mentioned WUE studies, it is evident that the range of reported values for switchgrass WUE is wide and the WUE on an above-ground biomass basis is particularly uncertain.

The majority of studies on the WUE of sorghum cultivars have focused on yield response to different irrigation amount and frequencies. Aishah et al. (2011) calculated the WUE of forage sorghum in their study of yield response to salinity and irrigation frequencies in Malaysia. They obtained values ranging between 59 and 69 kg ha^{-1} of dry forage yield per mm of water applied through irrigation. Saeed and El-Nadi (1998), working in Sudan, reported WUE values from 65 to 86 kg ha^{-1} of dry forage yield per mm of ET. Garofalo and Rinaldi (2013), in a Mediterranean environment, reported WUE values of biomass sorghum between 40 and 85 kg ha^{-1} of above-ground dry biomass per mm of ET under different irrigation regimes. In Texas, Hao et al. (2014) reported WUE values at different irrigation levels for photoperiod-sensitive sorghum ranging from 30 to 47 kg ha^{-1} of above-ground dry biomass per mm of ET. The widely varying WUE estimates for sorghum have been attributed to differences in atmospheric vapor pressure deficit, evaporative demand, phenological stages, and other factors (Garofalo and Rinaldi, 2013). There are limited reports on WUE values for biomass sorghum under rainfed conditions, and we are not aware of any prior estimates of WUE for biomass sorghum based on transpiration.

In the existing literature, there is significant uncertainty regarding the WUE of switchgrass and biomass sorghum and little information about the underlying ET partitioning. Therefore, the main objectives of this study were (1) to partition ET by switchgrass and biomass sorghum between transpiration, interception, and soil evaporation; and (2) to quantify and compare the seasonal WUE of these crops when managed for bioenergy feedstock production.

2. Materials and methods

2.1. Study site and experimental design

A plot scale study was conducted from 2010 through 2013 at the Oklahoma State University, Efaw Research Farm (36.13° N, 97.10° W) near Stillwater, OK. The soil is a deep and well-drained Easpur loam (fine-loamy, mixed, superactive, thermic Fluventic Haplustoll). The area has an average annual precipitation of 880 mm, and the average daily minimum and maximum temperatures are 8.6 °C and 21.9 °C (Oklahoma Climatological Survey, 2014). 'Alamo' switchgrass and 'ES5200' biomass sorghum were established in the spring of 2010 in a randomized complete block design with three replications. Biomass sorghum was planted at a row spacing of 0.19 m. Similarly, switchgrass was initially planted at 0.19 m row spacing; however, when it matured the rows were no longer evident. The study period comprises three growing seasons from 2011 to 2013. Growing seasons are from greening of switchgrass or planting of biomass sorghum to harvest. Greening of switchgrass occurred between mid-March and mid-April, while biomass sorghum was planted between April 20 and May 12. Harvest of both crops occurred between November 16 and December 4. Urea ammonium nitrate (UAN) solution was applied in a band at a rate of 84 kg N ha^{-1} to all plots. Additional soil and agronomic information for the site was reported by Yimam et al. (2014).

2.2. Measurement and estimation of ET components

Growing season ET was determined from 2011 to 2013 using the soil water balance approach based on measurements of precipitation and change in soil water storage in the root zone. Soil water storage to 2-m depth was determined every two weeks