Title: Evapotranspiration Partitioning and Water Use Efficiency of Switchgrass and Biomass
Sorghum Managed for Biofuel

Authors: Yohannes Tadesse Yimam, Tyson E. Ochsner, and Vijaya Gopal Kakani

Institution: Department of Plant and Soil Sciences, Oklahoma State University, 368
Agricultural Hall, Stillwater, OK 74078

Corresponding author and address:

Tyson E. Ochsner, 368 Agricultural Hall, Stillwater, OK 74078

Email: tyson.ochsner@okstate.edu

Phone: (+1) 405-762-0357

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.

Key Words: soil evaporation, canopy interception, transpiration, non-productive losses, switchgrass, biomass sorghum

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 $\geq 79\%$ 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 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 yr⁻¹ of precipitation. For switchgrass in England, Finch et al. (2004) measured rainfall interception of 47-54% for rainfall events of ≤ 10 mm during the late growing season. A study of rainfall interception by another candidate bioenergy crop, miscanthus (*Miscanthus x 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 to 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, Efav Research Farm (36.13° N, 97.10° W) near Stillwater, OK. The soil is a deep and well-drained Easpor 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 during the growing season using neutron probe measurements (CPN 503 HydroProbe, InstroTek Inc., Raleigh, NC) in 0.2-m intervals. The count ratios from the neutron probe readings were converted to volumetric soil water content values using a calibration equation developed for the site (Yimam et al., 2014). The summation of the product of the soil water content value at each depth and the corresponding 0.2-m layer thickness resulted in the total soil water storage in the 2-m soil profile for each measurement date. Precipitation data were obtained from a nearby Oklahoma Mesonet station (McPherson et al., 2007) and a nearby National Oceanic and Atmospheric Administration (NOAA) station. For our study site, from 2011-2013, Yimam et al. (2014) estimated deep drainage totals of less than 1% of total precipitation by using the Darcian method of deep drainage estimation (Nimmo et al., 2005) and assuming a unit gradient at the bottom of the root zone. In addition, using the online version of Water Erosion Prediction Project (WEPP) (Frankenberger et al., 2011), average annual runoff for the study site was estimated to be less than 2% of average annual precipitation (data not shown). Hence, in this study deep drainage and runoff were assumed to be negligible. Growing season ET was determined as the difference between growing season precipitation and change in profile soil water storage in the root zone between greening and harvest for switchgrass and between planting and harvest for biomass sorghum.

The interception component measured in this study was canopy interception. Residue interception was not measured. These crops were grown and managed for biofuel feedstock production, and during harvest the majority of above-ground biomass was collected, thus residue

181 accumulation was limited. Finch et al. (2004) observed negligible stem flow for switchgrass with
182 values usually < 1% of the total rainfall. Hence, stem flow was not measured in this study.
183 Measurements of throughfall were collected using interception trays. The interception tray
184 design of Brye et al. (2000) was used in this study with some modifications. Loaf pans 305 mm
185 in length, 114 mm in width, and 64 mm in depth (#NLP-12, Winco, Lodi, NJ) were used as
186 interception trays. The interior of each tray was covered, just below the top of the tray wall, with
187 thin styrene foam to reduce evaporation. The styrene foam was fixed to the interior wall of the
188 tray with a gentle slope, leaving only a small space at one end for the water to drain into the
189 bottom of the tray. Above the styrene foam, wire mesh with 6 mm square openings was added to
190 reduce the entrance of litter into the tray. Three to four trays were randomly placed in each plot
191 to account for spatial variability. The long axis of the tray was systematically aligned
192 perpendicular to the rows in the biomass sorghum plots. The throughfall collected in the trays
193 was measured using a measuring cylinder within 18 hours of each rain event (Brye et al., 2000).
194 Canopy interception was estimated by subtracting throughfall from precipitation.

195 Measured throughfall was used to estimate canopy interception for rainfall events
196 between 2 and 30 mm during the growing season, when the canopy cover (measurements
197 described below) was >85% for switchgrass and >35% for biomass sorghum. Our field
198 observations indicated that for these conditions: 1) throughfall was distributed more uniformly
199 than for periods with smaller precipitation totals, 2) tray depth was adequate to capture all the
200 throughfall without overflowing, and 3) plant heights were large enough to allow the trays to be
201 placed underneath the canopy. From the measured throughfall values in this range, linear
202 relationships between precipitation and canopy interception ($r^2 = 0.67$ for switchgrass and $r^2 =$
203 0.47 for biomass sorghum) were created to gap fill missing throughfall measurements. The

averages of the four largest interception estimates for each crop were used as the interception estimates for rainfall events > 30 mm. For rainfall events of < 2 mm, the rainfall was multiplied by canopy cover to estimate interception. During the 2011 to 2013 growing seasons, the percentage of rainfall which fell during events with totals < 2 mm was 3%, while 51% of the precipitation fell during events with totals of 2 – 30 mm, and 46% fell in events with totals > 30 mm.

To determine green canopy cover and total canopy cover, we used downward-facing digital images taken at about 1-m height above the canopy. Four images per plot were taken every two weeks during the growing season. The pictures were analyzed using SamplePoint software (Booth et al., 2006) to estimate the percentage of green canopy and total canopy cover.

The Food and Agricultural Organization of the United Nations (FAO) Irrigation and Drainage paper No. 56 (FAO-56; Allen et al., 1998) dual crop coefficient method of calculating ET was used to estimate soil evaporation. Weather data, surface soil physical properties, plant height and canopy cover were used as inputs to the model. The FAO- 56 model estimates soil evaporation (E_s) on a daily time step using

$$E_s = K_e ET_o \quad [1]$$

where K_e is the evaporation coefficient and ET_o is the reference evapotranspiration. In this study, ET_o was estimated using the FAO-56 Penman-Monteith equation for a hypothetical grass reference surface (Allen et al., 1998). When there is vegetation present,

$$K_e = K_r (K_{c \max} - K_{cb}) \leq f_{ew} K_{c \max} \quad [2]$$

where K_{cb} is the basal crop coefficient, $K_{c\ max}$ is the maximum value of K_c following rain or irrigation, K_r is a dimensionless evaporation reduction coefficient [0-1], and f_{ew} is the fraction of the soil surface from which most of the evaporation occurs. As defined in the FAO-56 dual crop coefficient model, f_{ew} is the fraction of the soil surface that is exposed both to drying and wetting events near solar noon (Allen et al., 1998).

The K_{cb} curve for the growing season was divided into three regions ($K_{cb\ ini}$, $K_{cb\ mid}$, and $K_{cb\ late}$) depending on the green canopy cover as described in Allen et al. (1998). The K_{cb} values for switchgrass and biomass sorghum are not currently available in the literature. For this study, the K_{cb} values for sweet sorghum (*Sorghum bicolor* L. Moench) were used for biomass sorghum. The K_{cb} values for sudangrass [*Sorghum bicolor* (L.) Moench ssp. *Drummondii* (Nees ex. Steud.) de Wet and Harlan] were used for switchgrass because, among the forages with listed K_{cb} values in the FAO-56 tables, the maximum crop height specified for sudangrass (1.2 m) was closest to the observed height of switchgrass. Growing season soil evaporation totals were relatively insensitive to K_{cb} values. Increasing or decreasing the K_{cb} values by 0.1 led to changes in cumulative growing season soil evaporation of ± 3 mm.

Water for E_s mostly comes from near the soil surface down to a maximum depth of about 0.10 m for coarse soil or 0.15 m for fine soil (Allen et al., 2005). The total evaporable water (TEW) from this top evaporation ‘slab’ can be calculated as

$$TEW = (\theta_{FC} - 0.5 \theta_{WP})Z_e \quad [3]$$

where θ_{FC} and θ_{WP} are the volumetric water content in $m^3\ m^{-3}$ at field capacity and permanent wilting point, respectively, and Z_e is the thickness of the effective surface layer that is dried by evaporation. In this study, Z_e was set equal to 150 mm because the soil at the site is not coarse-

246 textured. Using a value of 100 mm would have resulted in a 10-12% reduction in E_s under the
247 conditions of our experiment.

248 The cumulative depth of E_s at the end of stage one evaporation, readily evaporable water
249 (REW, mm), was calculated from the surface soil texture (Ritchie et al., 1989) as follow:

250
$$REW = 20 - 0.15Sa \text{ for } Sa > 80 \quad [4a]$$

251
$$REW = 11 - 0.06Cl \text{ for } Cl > 50 \quad [4b]$$

252
$$REW = 8 + 0.08 Cl \text{ for } Sa < 80 \text{ and } Cl < 50 \quad [4c]$$

253 where Sa and Cl are the percentages of sand and clay in the soil.

254 The $K_{c \max}$ value was calculated as follow

255
$$K_{c \max} =$$

$$\max \left\{ 1.2 + \right.$$

$$\left[0.04(u_2 - \right.$$

$$2) -$$

$$0.004(RH_{\min} -$$

$$45)] \left(\frac{h}{3} \right)^{0.3} \left. \right\},$$

$$(K_{cb} +$$

$$0.05) \left. \right)$$

256
$$[5]$$

257 where u_2 is the daily average wind speed at 2 m, $RH_{\min}$ is the daily minimum relative humidity,
258 and h is the mean vegetation height. For our study, the plant height was measured every two
259 weeks at four random locations per plot.

K_r was proportional to the amount of water remaining in the surface soil layer when the soil water depletion from the surface to depth Z_e on the previous day ($D_{e, i-1}$) was $> REW$.

$$K_r = \min \left[\frac{TEW - D_{e,i-1}}{TEW - REW}, 1.0 \right]$$

[6]

K_r is 1 during stage one evaporation (i.e. $D_{e, i-1} < REW$)

Using the daily water balance, $D_{e, i}$ was calculated as

$$D_{e,i} = \min \left\{ D_{e,i-1} - [(1 - f_b) * P_i + f_b * P_{i+1}] + \frac{E_i}{f_{ew}}, TEW \right\}$$

[7]

where $D_{e,i-1}$ and $D_{e,i}$ are the cumulative depletion at the end of time step $i-1$ and i , P_i and P_{i+1} are the precipitation on date i and $i+1$, f_b is the fraction of precipitation during a day that contributes to soil evaporation during the same day (0.5 was used for this study), and E_i is soil evaporation during day i . All calculations were performed in Matlab (R2013b, The MathWorks, Inc., Natick, MA, USA) including linear interpolation of green canopy cover, f_{ew} , and crop height to allow continuous daily soil evaporation estimates.

Finally, transpiration was estimated from ET, soil evaporation, and canopy interception as follows:

$$\text{Transpiration} = ET - \text{canopy interception} - E_s$$

[8]

2.3. Calculation of WUE

Several previous WUE studies for switchgrass defined WUE as mg of total biomass produced (both shoot and root) per g of water transpired. But for our purposes, we are interested in the harvestable biomass only. Hence, in this study, calculations of WUE were made using kg ha⁻¹ of above-ground dry biomass per mm of ET (WUE_{ET}) and also per mm of transpiration (WUE_T). In the center of each plot, biomass in a 45-m² area was cut using a pull type swather (model 630, Deere and Company, Moline, IL, USA) at 10-15 cm stubble height, baled with a round baler (model 568, Deere and Company, Moline, IL, USA), and weighed. The bales were weighed with a load cell suspended from a front-end loader. Subsamples of biomass harvested at the center of the plots were oven dried at ~70°C to determine the biomass moisture content. The moisture content varied depending on species and year. The average moisture content in 2011, 2012 and 2013, for sorghum was 58, 51 and 48%, while it was 35, 23 and 18% for switchgrass, respectively. The wet weight of the bale was adjusted for moisture content to derive the bale dry weight.

The SAS Proc MIXED procedure was employed for the analysis of data using a randomized block design model and the Least Significant Difference was used to compare the mean values. Global ANOVA, considering year, was created to test the effect of year, cropping system, and year x cropping system interactions on ET, biomass yield, soil evaporation, transpiration, interception, WUE_{ET} and WUE_T.

3. RESULTS AND DISCUSSION

3.1. Weather

Monthly anomalies of air temperature and precipitation relative to 50-yr means for the site reflect the diverse weather conditions during the study period (Fig. 1). Monthly average air temperatures were above the long-term means for June–August 2011 and March–July 2012. In contrast, April 2013 was colder than the long-term mean. At Stillwater, the long term (50-yrs.) annual average precipitation is 880 mm. The annual precipitation was 590 mm in 2011, 572 mm in 2012, and 918 mm in 2013. The study period included severe growing season drought in 2011, with precipitation below average March–October. There was also a growing season drought in 2012 with precipitation below average May–December, but the impact of this drought was moderated by above average precipitation in the preceding dormant season (February–April). Growing conditions were most favorable in 2013 with above average precipitation April–July.

3.2. Canopy Cover and Biomass

There was great year-to-year variation in the amount and timing of canopy cover (Fig. 2). In the 2011 growing season, switchgrass canopy development was slightly delayed relative to the canopy development in 2012 and 2013 (Fig. 2) due to below average rainfall (Fig. 1), but switchgrass still reached >90% cover in June because of adequate initial plant available water (Table 1). The maximum canopy cover for biomass sorghum in 2011 was only 70% (Fig. 2) because of the severe drought, indicated by higher than average temperatures and lower than average rainfall after biomass sorghum planting in May (Fig. 1). In 2012, switchgrass showed rapid early growth with >95% cover in April (Fig. 2) due to above average precipitation and temperature in March and April (Fig. 1). Biomass sorghum reached >90% cover in June 2012 and had about two months delay relative to switchgrass to reach the maximum cover. In 2011 and 2012, drought induced senescence was observed in both crops beginning in July. In 2013, 100% canopy cover was observed by June for switchgrass and July for biomass sorghum. Water

was not a limiting factor in 2013, hence senescence of switchgrass was not observed until late September. We did not measure cover of biomass sorghum after August 2013 because the plants were >3 m in height, and we assumed 100% canopy cover. In summary, there was greater year-to-year variation in the timing of canopy development for switchgrass than for biomass sorghum, but there was greater year-to-year variation in the maximum canopy cover for biomass sorghum than for switchgrass. These differences in amount and timing of canopy cover impacted the ET components (see section 3.3).

Due to the severe drought in 2011, switchgrass and biomass sorghum yields were low, ~4.3 Mg ha⁻¹ and were not significantly different. Under moderate drought in 2012 yields were higher, ~13 Mg ha⁻¹ and again not significantly different between cropping systems. However, with good growing conditions in 2013, yield of biomass sorghum was much greater than that of switchgrass (Table 1). Biomass sorghum produced an above-ground dry biomass of 32.5 Mg ha⁻¹, while switchgrass produced only 14.4 Mg ha⁻¹. The maximum yield of biomass sorghum in this study was higher than the yield reported by Hao et al. (2014), who obtained a maximum yield of 24 Mg ha⁻¹ under full irrigation in western Texas where the growing season rainfall was between 78 and 227 mm. However, our maximum yield of biomass sorghum was within the range of 18-41 Mg ha⁻¹ reported by Garofalo and Rinaldi (2013) for different irrigation regimes in a Mediterranean environment. These results show that yield of biomass sorghum was strongly influenced by seasonal water supply, which is consistent with previous observations (Hao et al., 2014; Garofalo and Rinaldi, 2013).

In contrast, switchgrass yield was not as sensitive to water availability. This finding is consistent with those of Wullschlegel et al. (2010). They found no strong correlation between yield and growing season precipitation totals for either upland or lowland switchgrass ecotypes,

although growing season precipitation totals <600 mm did appear to limit maximum potential yield. The timing of rainfall, however, may play a critical role in determining switchgrass yield. Although growing season rainfall was nearly identical for switchgrass in 2011 and 2012 (Table 1), March and April precipitation totaled only 61 mm in 2011 but 254 mm in 2012. This greater early season rainfall in 2012 contributed to switchgrass above-ground dry biomass being ~9 Mg ha⁻¹ greater in 2012 than in 2011. Similarly, Lee and Boe (2005) found that early growing season precipitation amount explained >90% of the variation in biomass production for switchgrass in South Dakota. Our switchgrass yields in 2012 and 2013 were within the range of yields reported by Fuentes and Taliaferro. (2002), who observed average Alamo switchgrass yields of 12.8 Mg ha⁻¹ at Chickasha, OK and 17 Mg ha⁻¹ at Haskell, OK.

3.3. Evapotranspiration components

Growing season ET ranged from 521 to 786 mm for switchgrass and from 446 to 683 mm for biomass sorghum (Table 2). Total growing season ET varied significantly with year and cropping system, but not with the interactions. The ET was significantly greater for switchgrass than biomass sorghum in 2011 and 2012 growing seasons; whereas, it was similar in 2013, when rainfall was above average. Likewise, Yimam et al. (2014) observed similar ET by annual and perennial bioenergy crops only when rainfall was above average. The ET data presented here are a subset of the data from Yimam et al. (2014). Our growing season ET values for switchgrass were higher than the 480-610 mm of growing season ET previously reported for tallgrass prairie in north-central Oklahoma (Burba and Verma, 2005). The difference might be due to the 84 kg N ha⁻¹ input in our experiment. Garofalo and Rinaldi (2013) reported growing season ET of 566-891 mm for irrigated biomass sorghum in southern Italy, which was greater than our growing season ET values for biomass sorghum grown solely under rainfed conditions. Our results were

within or greater than the range of 324-517 mm growing season ET reported by Hao et al. (2014) for irrigated biomass sorghum in Texas, where the growing season rainfall ranged from 78 to 227 mm.

Transpiration was the predominant component of growing season ET with totals ranging from 366 to 546 mm for switchgrass and from 181 to 417 mm for biomass sorghum (Fig. 3 and Table 2). Kiniry et al. (2008) simulated switchgrass transpiration values ranging from 290 to 399 mm using the ALMANAC model for four locations in the central US, a range which was exceeded by the 2012 and 2013 switchgrass transpiration totals in our study. We are not aware of any attempts to estimate growing season transpiration in a field experimental setting for switchgrass and biomass sorghum using the soil water budget and evapotranspiration partitioning approaches. In our study, we observed transpiration to ET ratios ranging from 0.70 to 0.76 for switchgrass and from 0.40 to 0.70 for biomass sorghum indicating that the non-productive losses from biomass sorghum were higher than from switchgrass. During the growing seasons, interception was greater than soil evaporation for both crops, except in 2011 for biomass sorghum, which failed to exceed 70% canopy cover. Moreover, the differences between interception and soil evaporation were greater for switchgrass than biomass sorghum.

The difference in non-productive losses between switchgrass and biomass sorghum was mainly due to soil evaporation (E_s), even though it was the smallest component of ET. Growing season soil evaporation ranged from 28 to 69 mm for switchgrass and from 53 to 153 mm for biomass sorghum. Soil evaporation was significantly higher under biomass sorghum compared with switchgrass each season (Table 2). The E_s/ET ratio for switchgrass ranged from 0.05 to 0.09, while for biomass sorghum it ranged from 0.11 to 0.34. Le et al. (2011) used a simulation model to estimate ET partitioning for switchgrass and predicted that soil evaporation would

account for 6% of the total ET, an estimate consistent with ours. For biomass sorghum, Garofalo and Rinaldi (2013) estimated 10 to 44% of seasonal water use being lost as E_s , and our results fall in that range.

Most of the soil evaporation was observed during the early growing season, when percent canopy cover was relatively low and energy was available for evaporation at the soil surface (Fig 3). After canopy cover reached 80%, soil evaporation was minimal. This result is consistent with many other studies which have shown the importance of canopy cover in determining the amount of soil evaporation during the growing season (e.g. Denmead et al., 1996; Todd et al., 1991; Wang and Liu, 2007). For switchgrass, the percentage of total growing season soil evaporation which occurred during the first month after greening was 39% in 2011, 72% in 2012, and 83% in 2013. For biomass sorghum, the percentage of total growing season soil evaporation which occurred during the first month after planting was 62% in 2011, 73% in 2012, and 80% in 2013. These differences across the years mainly depended on crop growth conditions, canopy development, and surface moisture conditions.

Growing season interception losses ranged from 103 to 171 mm for switchgrass and from 99 to 160 mm for biomass sorghum (Table 2). Since switchgrass canopy cover developed earlier than that of biomass sorghum, the amount of canopy interception by switchgrass was greater than that of biomass sorghum two out of three growing seasons (Table 2). The percentage of growing season rainfall intercepted by switchgrass ranged from 25 to 31%, and biomass sorghum intercepted 27-45% of growing season rainfall. The switchgrass interception in our study was greater than the 66 mm predicted in the simulations of Le et al. (2011) but similar to the results of Finch and Riche (2010), who reported interception loss of 24-25% for miscanthus in England. For rainfall events of less than 10 mm, Finch et al. (2004) observed 47-54% of the precipitation

being intercepted by switchgrass. Similarly, we found 43-51 % of rainfall intercepted by switchgrass for rainfall amounts of less than 10 mm (data not shown). These relatively high percentages are expected because the smaller the rainfall event, the larger the percentage lost to interception (Thurow et al., 1987). We are not aware of any prior reports of rainfall interception for biomass sorghum. Bui and Box (1992) demonstrated that stem flow can be high for grain sorghum, and biomass sorghum may also have generated stem flow which was not measured in this study. If so, then our interception estimates for biomass sorghum may be somewhat inflated.

3.4. Evapotranspiration and Transpiration Water Use Efficiencies (WUE_{ET} and WUE_T)

The seasonal WUE expressed as above-ground dry biomass per unit ET (WUE_{ET}) ranged from 8 to 21 kg ha⁻¹ mm⁻¹ for switchgrass and from 9 to 49 kg ha⁻¹ mm⁻¹ for biomass sorghum (Fig. 4). Seasonal WUE expressed as above-ground dry biomass per unit transpiration (WUE_T) ranged from 12 to 28 kg ha⁻¹ mm⁻¹ for switchgrass and from 22 to 83 kg ha⁻¹ mm⁻¹ for biomass sorghum (Fig. 4). The difference between WUE_{ET} and WUE_T was due to the non-productive losses (interception and soil evaporation). Since the non-productive losses from biomass sorghum were higher than from switchgrass, we observed a larger difference between WUE_{ET} and WUE_T for biomass sorghum than for switchgrass.

Both WUE_{ET} and WUE_T varied significantly with cropping systems, years, and cropping systems x year interactions. Comparison of WUE values between the two cropping systems within a year showed the existence of a significant difference only in the 2013 growing season, when rainfall was above average (Fig. 4). In that season the WUE values for biomass sorghum were 2 to 3 times greater than the WUE values for switchgrass.

The difference in WUE values within a cropping system among years was mainly due to the influence of climatic conditions on ET, transpiration, and especially on biomass production. Switchgrass had significantly smaller WUE_{ET} and WUE_T in 2011 compared with 2012 and 2013. However, there was no significant difference in WUE values between 2012 and 2013. In 2011, switchgrass was in its 2nd year of establishment; hence, it may have allocated a relatively large portion of assimilated carbon to its roots; whereas, in 2012 and 2013, the switchgrass stand had reached maturity and may have reduced the share of assimilated carbon allocated to the root system. This reduction of root to shoot ratio for switchgrass as it matures was described in the review of switchgrass physiology by Zegada-Lizarazu et al. (2012). The 2011 growing season also had the highest vapor pressure deficit among the three seasons in this study (Table 1), and a higher vapor pressure deficit tends to result in lower WUE (Sinclair et al., 1984).

The WUE values of biomass sorghum differed significantly among years where the largest value was observed in 2013 and smallest values in 2011. In 2011, a partial crop failure due to the severe drought impacted the yield of biomass sorghum whereas in 2013, the area received above average rainfall resulting in greater biomass yield (Table 1). Greater water availability in 2013 may also have favored above-ground biomass production over root growth; higher temperatures in 2011 and 2012 may have resulted in higher respiration, which could have reduced biomass production; and a lower vapor pressure deficit in 2013 may also have contributed to the increased WUE (Table 1). In southern Italy, Garofalo and Rinaldi (2013) observed a reduction in the difference between WUE values for biomass sorghum across years from 75% to ~30% by normalizing the WUE values by vapor pressure deficit. Similarly, in our study differences in vapor pressure deficit across growing seasons explained some of the year-to-year differences in WUE, but a sizable portion of the variability appears to be due to other

factors. The greater WUE for biomass sorghum in 2013 than in 2011 or 2012 was mainly due to the dramatic increase in above-ground biomass rather than a reduction of evapotranspiration or transpiration. Increased WUE due to increase in biomass as opposed to reduction in water use has also been observed by previous researchers (e.g. Koshi et al., 1982; Hendrickson et al., 2013; Hao et al., 2014).

The WUE_{ET} values in this study for switchgrass ($8-21 \text{ kg ha}^{-1} \text{ mm}^{-1}$) were higher than the results of Koshi et al. (1982), who reported values between $3-8 \text{ kg ha}^{-1} \text{ mm}^{-1}$ for different harvest and water regimes. In that study under dryland conditions in Big Spring, Texas, the average biomass was $< 3 \text{ Mg ha}^{-1}$. Our estimated WUE_{ET} were also higher than the $9.7 \pm 0.4 \text{ kg ha}^{-1} \text{ mm}^{-1}$ observed in Illinois, where the switchgrass used more water but had lower yield (Hickman et al., 2010). Our switchgrass WUE_{ET} values are higher than those of Koshi et al. (1982) and Hickman et al. (2010) mainly as a result of the relatively high switchgrass biomass yields in the 2012 and 2013 growing seasons. VanLoocke et al. (2012), using the Agro-IBIS model, simulated annual (not growing season) WUE_{ET} values for switchgrass in the Midwest US ranging from ~ 5 to $15 \text{ kg ha}^{-1} \text{ mm}^{-1}$. That range of values is quite similar to the one we observed, considering that dormant season ET represents $\sim 15\%$ of the annual ET for switchgrass at our study site (Yimam et al., 2014).

Values of WUE_T for switchgrass ($12-28 \text{ kg ha}^{-1} \text{ mm}^{-1}$) in this field study were comparable with $15-18 \text{ kg ha}^{-1} \text{ mm}^{-1}$ measured in a seedling experiment by Xu et al. (2006), but well below the values of $30-50 \text{ kg ha}^{-1} \text{ mm}^{-1}$ estimated by Kiniry et al. (2008) using the ALMANAC model. To our knowledge, there are no prior reported WUE_T values for switchgrass based on field measurements of mature switchgrass stands.

Our WUE_{ET} values for biomass sorghum ($9-49 \text{ kg ha}^{-1} \text{ mm}^{-1}$) were similar to or lower than the values reported by Hao et al. (2014) in Texas ($30-47 \text{ kg ha}^{-1} \text{ mm}^{-1}$); by Narayanan et al. (2013) in Kansas ($34-76 \text{ kg ha}^{-1} \text{ mm}^{-1}$); and by Garofalo and Rinaldi (2013) in southern Italy ($40-85 \text{ kg ha}^{-1} \text{ mm}^{-1}$). In all of those studies, irrigation was applied to the sorghum whereas our experiment was rainfed. We are not aware of any prior reports on WUE_T for biomass sorghum. Xin et al. (2009) measured WUE_T values of $47-71 \text{ kg ha}^{-1} \text{ mm}^{-1}$ across 25 lines of grain sorghum in a pot experiment, and our results ($22-83 \text{ kg ha}^{-1} \text{ mm}^{-1}$) encompass that range.

4. CONCLUSION

Improved understanding of non-productive and productive components of the ET from these candidate bioenergy crops can inform their deployment in the US Southern Great Plains. For both crops, canopy rainfall interception was the largest component of non-productive loss accounting for >25% of growing season rainfall. Soil evaporation was a more important component of ET for biomass sorghum than for switchgrass because of early season canopy cover in switchgrass. Biomass sorghum had greater non-productive losses than switchgrass; however, biomass sorghum also had greater seasonal WUE values, due to its high above-ground biomass production in the year with greatest water availability. Biomass sorghum shows potential to outperform switchgrass in terms of water use efficiency in the Southern Great Plains, but decision makers must consider other factors such as ecosystem services and socio-economic benefits if they intend to develop sustainable biofuel feedstock supply systems for the region.

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621

Table 1 Above-ground dry biomass, growing season rainfall, plant available water (PAW) at greening/ planting, and average daytime vapor pressure deficit during 2011, 2012, and 2013 growing seasons by switchgrass (SWG) and biomass sorghum (BMS). Values inside the bracket represent one standard error.

Year	Crop	Above-ground dry biomass Mg ha ⁻¹	Growing season rainfall mm	PAW at planting/ greening	Vapor pressure deficit kPa
2011	SWG	4.3 (1.1)	407	236 (46)	2.01
	BMS	4.4 (2.1)	350	212 (23)	2.12
2012	SWG	13.2 (2.5)	408	235 (51)	1.78
	BMS	12.9 (1.0)	218	307 (7)	1.93
2013	SWG	14.5 (0.4)a†	658	233 (54)	1.35
	BMS	32.5 (3.7)b	603	241 (43)	1.43

† Different lower case letters represent significant differences between cropping systems within a year at $\alpha = 0.1$.

636

637 Table 2 Growing season evapotranspiration (ET), canopy rainfall interception (I), soil
 638 evaporation (E_s), transpiration (T), and transpiration to ET ratio (T:ET) for switchgrass (SWG)
 639 and biomass sorghum (BMS). Values inside the bracket represent one standard error.

Year	Crop	ET	I	E_s	T	T : ET
		mm				fraction
2011	SWG	521 (9)a†	126 (7)a	28 (2)a	366 (11)a	0.70a
	BMS	446 (18)b	116 (10)b	148 (14)b	181 (22)b	0.41b
2012	SWG	616 (25)a	103 (9)	41 (5)a	472 (24)a	0.77a
	BMS	503 (22)b	99 (4)	54 (3)b	351 (26)b	0.70b
2013	SWG	786 (38)	171 (5)a	71 (1)a	544 (37)	0.69a
	BMS	683 (72)	160 (5)b	106 (3)b	417 (68)	0.61b

640 † Different lower case letters represent significant differences between cropping systems within a
 641 year at $\alpha = 0.1$.

Fig. 1. Study period monthly anomalies of air temperature (T_{air}) and precipitation from the long term (50-yr.) average at Stillwater, OK

Fig. 2. Percent green cover and total canopy cover (both green leaf and senescence) by switchgrass (SWG) and biomass sorghum (BMS) during 2011, 2012, and 2013 growing seasons.

Fig. 3. Time series of cumulative soil evaporation (E_s), interception (I), and transpiration (T) by switchgrass (upper panels) and biomass sorghum (lower panels) during the 2011, 2012, and 2013 growing seasons.

Fig. 4. Water use efficiency values based on ET (WUE_{ET}) and based on transpiration (WUE_T) in kg ha⁻¹ mm⁻¹ for the three growing seasons by switchgrass (SWG) and biomass sorghum (BMS). Letters above bars shows significant difference between species within a year at $p \leq 0.10$