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Water use and biomass yield of bioenergy crops in the North Carolina Piedmont

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Abstract

Crops grown for bioenergy purposes are a potential alternative to traditional row crops and pasture–hay systems in the North Carolina (NC) Piedmont, but there is limited information available about their biomass yields and water requirements in this region. The goal of this study was to evaluate biomass yield and water-use efficiency of switchgrass (*Panicum virgatum* L.), giant miscanthus (*Miscanthus* × *giganteus* Greef et Deu.), biomass sorghum (*Sorghum bicolor* spp.), silage corn (*Zea mays* L.) and tall fescue (*Lolium arundinacea* Schreb.). The perennial systems were established in 2012 while annuals were planted each spring. Crop water use was evaluated for the 2016 and 2017 growing seasons using a water balance approach. Giant miscanthus had the highest 2-yr average biomass yield (29.1 ± 0.8 Mg ha^{-1}) followed by corn (23.6 ± 0.6 Mg ha^{-1}) and biomass sorghum (22.0 ± 1.8 Mg ha^{-1}). Switchgrass and tall fescue had the lowest biomass yields, 14.2 ± 1.9 and 12.5 ± 1.2 Mg ha^{-1}, respectively. Fescue had the highest season-long water use in both years of the study. Perennial grasses giant miscanthus and switchgrass had similar seasonal water use, but giant miscanthus had higher water-use efficiency due to greater biomass yields. The annual crops corn and sorghum used less water than the perennial systems because of their shorter growing season, and, consequently, had higher water-use efficiencies. This information can aid growers when making management decisions about converting land into bioenergy crops.

1 | INTRODUCTION

Government initiatives to reduce the use of fossil fuels have led to an interest to convert traditional regional cropping systems to potential lignocellulosic bioenergy systems. In North Carolina (NC), research and development of second generation bioenergy crops has been promoted by the NC Department of Agriculture and Consumer Services through the NC Bioenergy Initiative. The NC Piedmont is a temperate humid region in the southeastern United States comprised of diverse agricultural systems including grain and forage crop production. Also in this region, marginal land, or land currently not used for row crop production, covers an appreciable fraction of the landscape. These sites are characterized by moderately eroded soils, susceptibility to episodic drought during the growing season, and lack of irrigation infrastructure, which imposes limitations to the use of first-generation bioenergy crops such as corn (*Zea mays* L.). Due to these restrictions, the NC Piedmont has been considered a candidate location

Abbreviations: DOY, day of year; ET, evapotranspiration; NC, North Carolina; WUE, water-use efficiency.

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for the establishment of perennial rhizomatous grasses such as giant miscanthus (*Miscanthus* × *giganteus* Greef et Deu.) and switchgrass (*Panicum virgatum* L.) as second-generation bioenergy crops for ethanol production.

Miscanthus and switchgrass have shown potential to be productive with little input of water and nutrients, which makes them a promising low-maintenance alternative for growers (Lewandowski et al., 2003; Roozeboom et al., 2018; Varvel et al., 2008). Heaton, Voigt, and Long (2008) reported that biomass yields of miscanthus were 33–48 Mg ha^{-1} following 3 yr of establishment in Illinois. In a review of U.S. lowland and upland switchgrass yields from 17 states, Wullschleger et al. (2010) reported that, across all cultivars, commonly observed yields were 10–14 Mg ha^{-1}. For the NC Mountains, yields of 18.4 and 20.9 Mg ha^{-1} were observed for miscanthus and switchgrass, respectively, following 3 yr of establishment (Palmer et al., 2014). In the NC Piedmont, Wang et al. (2017a) observed significantly higher yields for miscanthus than switchgrass from the second through the fourth year of management. Miscanthus also outperformed switchgrass in the NC Coastal Plain during 4 yr of consistent management (Wang et al., 2017b). Although it typically requires approximately 3 yr for perennial bioenergy grasses to achieve maximum yields (Alexopoulou et al., 2015; Heaton et al., 2008; Palmer et al., 2014), miscanthus and switchgrass have been observed to maintain yields for up to 14 yr following establishment (Alexopoulou et al., 2015).

Recent reports of biomass sorghum (*Sorghum bicolor* spp.) indicate that it has potential to produce similar yields to perennial grasses in the Midwest region of the United States. Yimam et al. (2015) reported that yields for biomass sorghum were similar to or higher than switchgrass for a 3-yr study in Oklahoma. Biomass sorghum yields of 10.1–26.1 Mg ha^{-1} were reported by Wang et al. (2017a) for the NC Piedmont, whereas (Heitman et al., 2017) reported yields of 15.7 ± 5.1 Mg ha^{-1} in the NC Coastal Plain, which suggests that biomass sorghum grown in NC could produce high biomass yields as seen in other areas of the United States. Sorghum yields between 14.6 and 23.5 Mg ha^{-1} were observed by Hao et al. (2014) for an irrigated system in Texas. The same authors also noticed that yields decreased to 12.1–18.2 Mg ha^{-1} for dryland sorghum, indicating that sorghum can be influenced by water availability. Yimam et al. (2015) reported that the yields of rainfed biomass sorghum were strongly influenced by seasonal water supply when comparing growing seasons with drought to growing seasons with adequate rainfall.

In the Piedmont region of NC, most field sites are unirrigated and may be susceptible to the occurrence of short-duration drought events during the season. These conditions should be taken into consideration when evaluating the suitability of perennial and annual bioenergy grasses. In Illinois, biomass yield of giant miscanthus was reported to be more strongly influenced by water than that of switchgrass (Heaton et al., 2004). Contrary to that study, giant miscanthus yields reported by Dohleman et al. (2012) did not decrease during two growing seasons that experienced below average rainfall in a similar geographical location. In a study conducted by Wilson et al. (2014) in Iowa, yields of corn and sorghum were more influenced by drought than switchgrass, suggesting that annual crops may be more susceptible to drought stress than established perennial cropping systems. At present, little is known about bioenergy crop biomass yields and their water use in the NC Piedmont region. The goal of this study was to evaluate the performance of bioenergy crops in the NC Piedmont to determine their productivity and water use. Specifically, we evaluated the biomass yields of three alternative bioenergy crops (switchgrass, miscanthus, and sorghum) and two traditional crops (corn and fescue, *Lolium arundinacea* Schreb.) and their season-long water use by means of a water balance approach. Based on these measurements, we also estimated their cropping system water-use efficiencies.

Core Ideas

- Miscanthus had the highest biomass yields, followed by corn and sorghum.
- Annual crops used less water than perennials due to a shorter growing season.
- High water-use efficiency (WUE) of annual crops was due to high biomass yields and low cumulative evapotranspiration.
- Miscanthus WUE was comparable to that of corn and sorghum.

2 | MATERIALS AND METHODS

2.1 | Site description and establishment

The study was conducted in a preexisting bioenergy field experiment located at the Piedmont Research Station in Salisbury, NC (35°41′ N, 80°37′ W) that was initiated in 2012 (Wang et al., 2017a). Mean annual air temperature ranges from 15 to 20 °C at this site. The soil type was a Mecklenburg clay loam (fine, kaolinitic, thermic, Ultic Hapludalf). Slope at the site ranged from 2 to 8%. The site was previously managed for fescue hay production with consistent management practices for more than 5 yr prior to establishment of the experiment. Five crops were included, consisting of three perennials (giant miscanthus ‘Freedom’, switchgrass ‘Colony’, and fescue [cultivar unknown]), and two annuals (corn ‘Pioneer 31G71’ [HX1/LL/RR2, CRM119, Pioneer] and sorghum ‘Blade ES5200’ [photoperiod-sensitive dedicated bioenergy sorghum hybrid, Ceres, Inc.]). Corn was managed for silage harvest. The crops were arranged in a randomized complete block design with four replications. Each plot was 9 by 12 m. Details for the establishment of switchgrass and miscanthus can be found in Wang et al. (2017a). Corn and sorghum were planted each spring using no-till practices. Corn and sorghum were planted on 0.8-m row spacing at populations of 74,000 seeds ha^{-1} and 247,000 seeds ha^{-1}, respectively. Prior to the 2016 growing season the continuous corn treatment was a corn–wheat (*Triticum aestivum* L.)–soybean [*Glycine max* (L.) Merr.] rotation. Planting and harvest dates as well as fertilizer rates used for each crop are listed in Table 1. Fertilizer rates and other management practices were performed following guidelines from the NC State Extension Service.

Miscanthus and switchgrass were harvested after senescence. A 2.3 by 12 m swath was harvested from the center of each plot with a mechanical forage plot harvester (Wintersteiger Inc.). Sorghum and corn were harvested by hand cutting two 1.5 m long rows from two locations within the center four rows of each plot and weighing the biomass. Fescue hay was cut using a tractor-driven hay mower, twice in 2016 and three times in 2017; then total biomass was collected by hand and weighed. For each harvesting operation, subsamples of approximately 500–600 g wet mass were taken from each plot and were dried at 65 ˚C until consistent moisture content was reached to determine dry biomass yield.

2.2 | Crop evapotranspiration and water-use efficiency

Crop evapotranspiration (ET_c) was calculated using a biweekly water balance during the 2016 and 2017 growing seasons to quantify the rate of water use of the crops. The water balance of a field can be calculated as:

$$ET_c = P - \Delta S - R - D \tag{1}$$

where P is precipitation, ΔS is change in soil profile water storage, R is runoff, and D is drainage (all in units of mm). Precipitation was measured using an on-site tipping bucket rain gauge maintained by the North Carolina State Climate Office. Biweekly measurements of volumetric soil water content (θ) were used to estimate ΔS. Two capacitance probes (model PR2/6, Dynamax Inc.) were used to measure θ at depths of 0.1, 0.2, 0.3, 0.4, 0.6, and 1 m via an access tube located in the center of each experimental unit. Each θ measurement consisted of an average of three readings within each access tube, at each depth. Probes were calibrated at the field site in 2017. Briefly, the calibration procedure consisted of installing additional access tubes adjacent to the research plots and regressing θ measurements to gravimetric determinations (corrected for soil bulk density) from augured samples around the access

TABLE 1 Crop establishment, fertilizer rates, and harvest dates at the experimental site in Salisbury, NC. All fertilizer was broadcasted unless otherwise stated

Crop	Planting date	Fertilizer rates	Harvest date
		kg ha^{-1}	
Switchgrass	June 2012	112 N[a]	Dec. each year
Miscanthus	June 2012	112 N[a]	Dec. each year
Fescue	Pre-2012	34 N, 30 P, and 56 K[b]	2–3 times per year
		112 N side-dressed	
		30 N and 34 P[b]	
Corn	6 Apr. 2016	30 N and 34 P[b]	8 Sept. 2016
	8 May 2017	34 N, 30 P, and 56 K[c]	11 Aug. 2017
		112 N side-dressed	
Sorghum	3 June 2016	112 N side-dressed[b]	8 Sept. 2016
	14 June 2017	34 N, 30 P, and 56 K[c]	7 Sept. 2017
		76 N[c]	

[a]Only at establishment in 2012.
[b]Only 2016 season.
[c]Only 2017 season.

tubes. Measurements of θ at all depths were corrected using the calibration equations for both the 2016 and 2017 datasets. Runoff was not directly measured in this study. Instead, criteria were established based on storm intensity to calculate ET_c from the water budget only when the rainfall intensity did not exceed 1.24 cm h^{-1}. This value was selected because it is below the lowest measured surface saturated hydraulic conductivity of the soil at the study location (Wang et al., 2017a). Weeks with rainfall intensities above this threshold were assumed to result in some surface runoff that would lead to an overestimate of the actual ET_c given the slope of the landscape and soil type. These measurement periods were therefore excluded. This approach is similar to that used by Wilson et al. (2001). In combination with the biweekly θ data, tensiometers were installed at depths of 0.3, 0.6, and 0.9 m for soil water potential measurements in each experimental unit. These were used together with estimated unsaturated hydraulic conductivity (calculated using the van Genuchten-Maulem model fitted to measured soil properties) to estimate drainage flux in each plot. Our calculations showed that drainage flux was negligible (<1% of ET_c) for all measurement intervals and thus D was not included in the estimates of ET_c.

Daily reference crop evapotranspiration (ET_0) was calculated using the FAO-56 Penman-Monteith equation (Allen et al., 1998). Parameters used to calculate ET_0 were measured by a weather station located onsite (Model ET107, Campbell Scientific Inc.). Crop coefficients (K_c) were developed for each cropping system using field measured values of ET_c and ET_0 for the 2016 and 2017 growing seasons. Because the water balance approach results in non-continuous ET_c, K_c values were averaged using the available data for each growing season. Cumulative ET_c for the cropping systems were calculated using ET_0 and their respective K_c.

Water-use efficiency (WUE), in units of kg mm^{-1} ha^{-1}, was estimated for each crop as the ratio of dry biomass yield to cumulative ET_c across the growing season. For the perennial systems, the growing season was considered April–October each year, similar to that used in Dohleman et al. (2012). Although fescue can grow year-round in this region, it may experience some summer slump; nevertheless, this observed growing season allows for comparison of the perennials while they were all actively growing. The growing season for the annual systems was the day of planting until the day of harvest (Table 1).

2.3 | Statistical analysis

Data from both growing seasons were collected from the same experimental unit, and therefore year was treated as a repeated measure. Crop species and year were considered to be fixed effects whereas replications were considered random effects. Biomass yields were analyzed using the Glimmix procedure in SAS ver. 9.3 (SAS institute) to determine main effects and interactions between crop and years. Means for crop yields were compared by Tukey's Honestly Significant Difference test (HSD). Significance was determined at the 5% probability level. The crop × year interaction was not significant ($p < .05$) so crop yields were averaged for the two growing seasons. Rates of ET_c, K_c values, and water use efficiencies were not compared statistically because of the imbalanced observations between the annual and perennial crops due to the difference in growing season length.

3 | RESULTS AND DISCUSSION

3.1 | Weather conditions

Annual and monthly totals of precipitation and ET_0 for 2016 and 2017 are presented in Table 2. Little variation in total annual ET_0 was observed between the years, whereas total annual precipitation varied considerably between 2016 and 2017, with 2016 being drier than 2017. Both years were above the 30-yr normal precipitation average of 839 mm yr^{-1} for the site. In the 2016 growing season (April–October), ET_0 exceeded precipitation by 274 mm, whereas in 2017 there was a surplus of 25 mm. In both years, the months of July and August had the highest precipitation deficit (difference between precipitation and ET_0). On average, ET_0 exceeded precipitation by 74 mm in July–August 2016, whereas in 2017 it was by 67 mm.

3.2 | Crop water use

Average daily ET_c rates estimated throughout the 2016 and 2017 growing seasons using a biweekly soil water balance approach are presented in Figure 1. In both years, all crops showed peak ET_c rates during days of year (DOY) 180–210, which corresponds to the month of July when ET_0 exceeded precipitation, but also when crops were at their peak growth rate. Apart from an early ET_c peak in 2017 on DOY 130 for the perennial cropping systems (Figures 1a, 1b, and 1c), in general ET_c rates were small at the early and late season. Because in 2017 precipitation totals in April and May were considerably higher than in 2016 (Table 1), the observed early peak is likely explained by a greater contribution of direct soil evaporation to ET_c. The decrease toward the end of the growing season is due to the senescence of the crops.

The annual crops had higher daily maximum ET_c rates than the perennial ones in both years (Figure 1). Daily ET_c rates of corn ranged from 2.1–9.5 and 3.0–11.0 mm d^{-1} during the 2016 and 2017 growing seasons, respectively (Figure 1d). Corn ET_c rates were similar to the rates observed in Texas

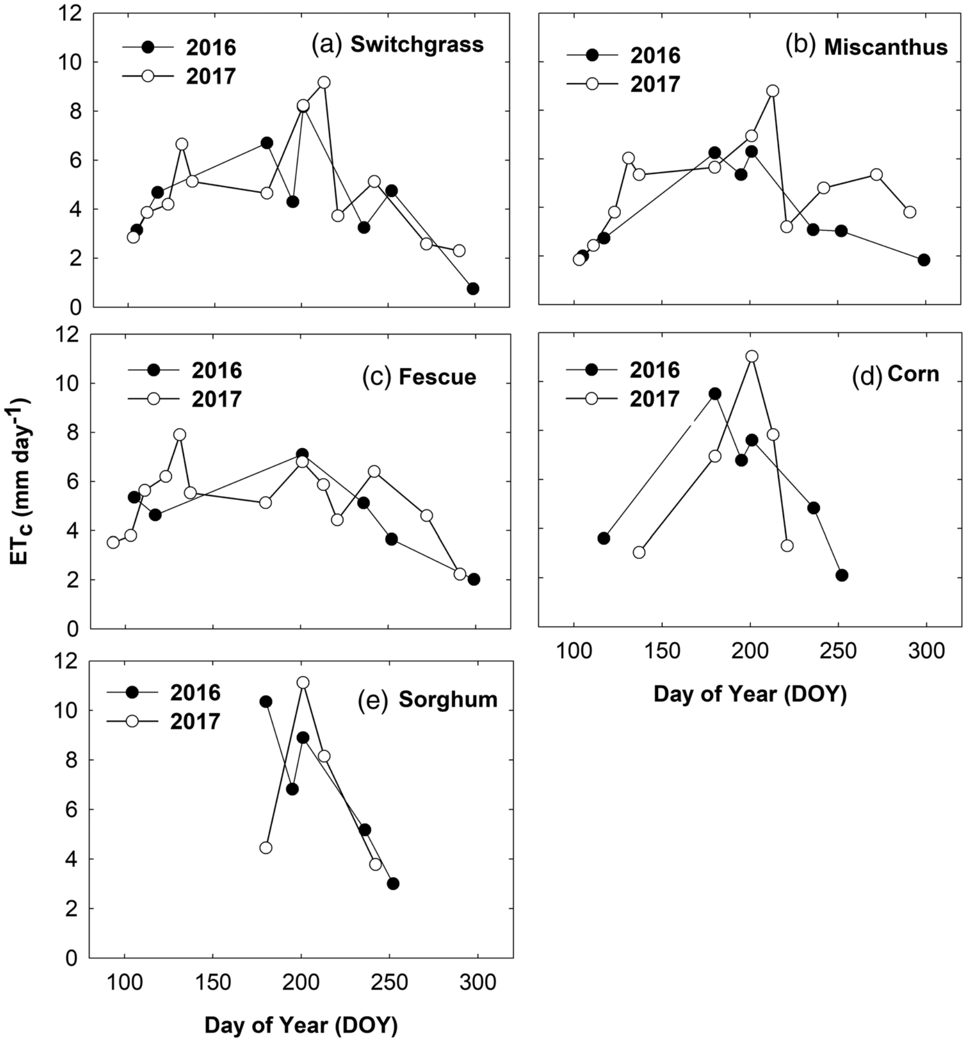

FIGURE 1 Average daily crop evapotranspiration (ET_c) in 2016 and 2017 growing seasons for (a) switchgrass, (b) miscanthus, (c) fescue, (d) corn, and (e) sorghum in Salisbury, NC

(Howell et al., 1998; Piccinni et al., 2009). Daily ET_c rates of sorghum ranged from 3.0 to 10.3 mm d^{-1} in 2016 and 3.8–11.1 mm d^{-1} in 2017 (Figure 1e). The maximum rate of ET_c observed in our study for sorghum was higher than the maximum weekly average rate of 6.7 mm d^{-1} reported in Oklahoma (Wagle et al., 2016). These differences are likely explained by environmental conditions and the methodology used to measure ET_c. In the Oklahoma study ET_c was measured using an eddy covariance system. Growing season ET_c rates of miscanthus ranged from 1.8–6.3 mm d^{-1} in 2016 and 1.9–8.8 mm d^{-1} in 2017 (Figure 1b). Rates of ET_c observed at our study site were within the range reported for a study in Italy (Triana et al., 2015). Switchgrass had a similar range of daily ET_c rates to miscanthus. Switchgrass ET_c rates were 0.8–8.2 and 2.3–9.2 for the 2016 and 2017 growing seasons, respectively (Figure 1a). The maximum rate of ET_c for switchgrass of 9.2 mm d^{-1} is higher than reported by Skinner and Adler (2010), Abraha et al. (2015), Eichelmann et al. (2016), and Wagle et al. (2016), which may also be explained by differences in environmental conditions and in measurement approach. Daily ET_c rates of fescue were 2.0–7.1 and 2.2–7.9 mm d^{-1} for the 2016 and 2017 growing seasons, respectively (Figure 1c). During a 2-yr study, Pinnix and Miller (2019) reported ET_c rates that ranged from 1 to 8 mm d^{-1} for tall fescue turf in North Carolina. The maximum rate of ET_c of fescue found in our study was higher than ET_c rates of tall fescue turf reported by Carrow (1995). That might be explained by the fact that fescue grown for hay has a larger canopy than that of fescue turf, which should result in greater transpiration rates.

Soil moisture profile data during a drying cycle from DOY 180 to 213 in 2017 are shown in Figure 2. These measurements correspond to the month of July, when a precipitation deficit of 64 mm was observed (Table 2). Profile data show that for all crops, the greatest water uptake occurred at a depth of 0.6 m. The annual crops used the greatest amount

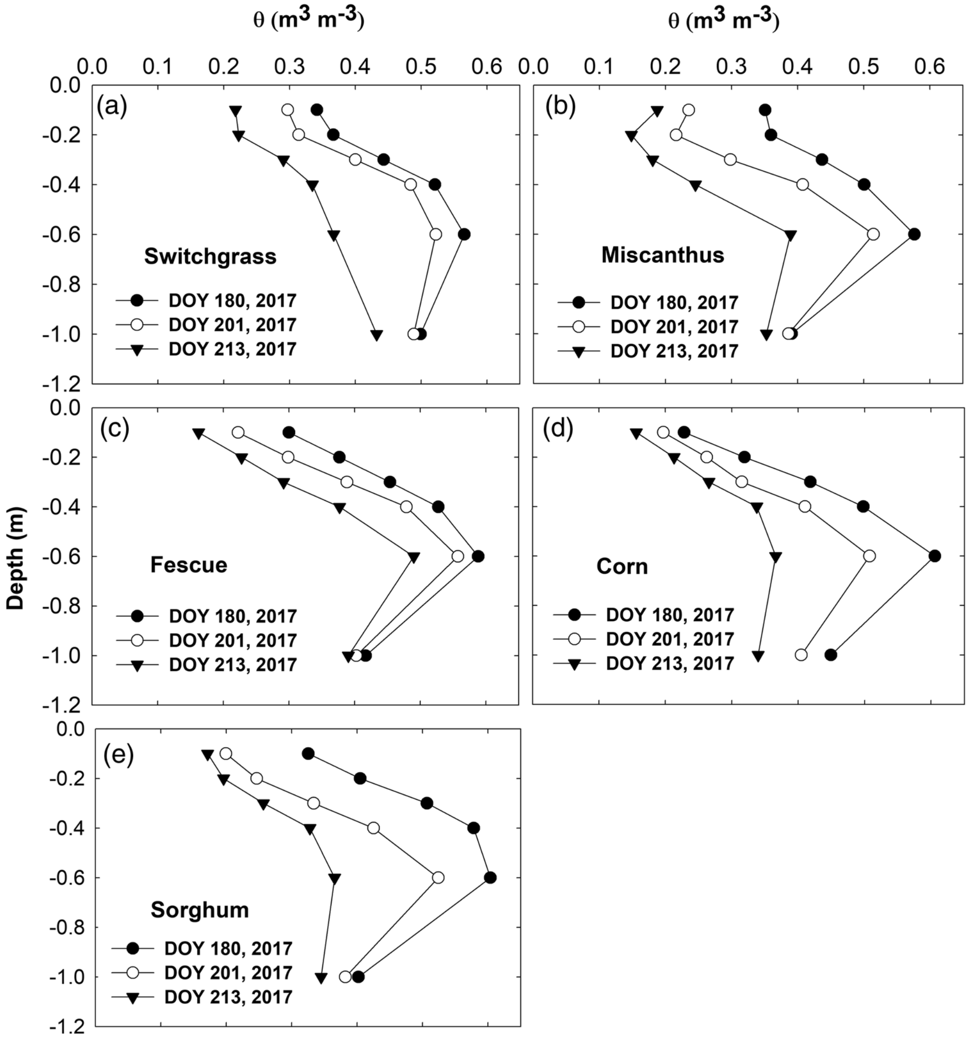

FIGURE 2 Soil profiles of volumetric water content (θ) for days of year (DOY) 180, 201, and 213 in the 2017 growing season for (a) switchgrass, (b) miscanthus, (c) fescue, (d) corn, and (e) sorghum in Salisbury, NC

of stored water in a depth increment of 0.3 m centered on the measurement depth of 0.6 m. For this layer, from DOY 180 to 213 corn and sorghum extracted 72 and 71 mm of water, respectively, whereas fescue extracted only 29 mm. Integrated over the whole soil profile, from DOY 180 to 213 sorghum used the greatest amount of water (187 mm), whereas fescue the least (105 mm). Annual crops use water at higher rates than perennial crops during midseason likely due to rapid biomass accumulation. That suggests that annuals may be more susceptible than perennials to adverse effects of soil water deficits during periods of insufficient rainfall because of the greater rate of soil water depletion needed to sustain high rates of water use. Joo et al. (2017) measured latent heat fluxes from perennial and annual crops using eddy covariance systems as part of a long term study, and found that during an exceptionally dry year, miscanthus was able to sustain higher evapotranspiration rates than switchgrass, prairie, and corn–soybean rotation agroecosystems. These authors argued that this response is likely due to the more extensive root system of miscanthus, which enabled greater uptake of soil moisture from deeper soil layers.

Average crop coefficients (K_c) were calculated based on ET_c and ET_0 and are shown in Table 3. Due to the nature of the soil water balance approach to estimate ET_c and the rainfall patterns found in our study, not all measurements could be used to estimate ET_c for the crops and, consequently, build their characteristic K_c curve. Given these constraints, we performed a statistical analysis to test for differences in K_c values before and after canopy closure. Because we found no significant differences, values were averaged to compute the K_c for each crop, which consequently represents a single season-long K_c value. This was a similar approach to that used by Beale et al. (1999) where a single crop coefficient was used to describe the seasonal water dynamics of giant miscanthus. The K_c values reported in Table 3 are an average of the 2016 and 2017 growing seasons.

Crop coefficients from our study were generally similar to those we found in the literature. The K_c value of 1.27 for

TABLE 2 Annual and monthly totals of reference evapotranspiration (ET_0) and precipitation in 2016 and 2017 at Salisbury, NC

Month	2016		2017	
	ET_0	Precipitation	ET_0	Precipitation
	mm			
Jan.	36	63	40	135
Feb.	51	87	67	16
Mar.	97	30	92	74
Apr.	124	44	115	174
May	133	148	138	191
June	125	85	158	184
July	180	96	179	115
Aug.	145	81	134	65
Sept.	115	76	112	130
Oct.	80	98	85	87
Nov.	49	16	37	30
Dec.	34	66	30	56
Total	1,169	890	1,187	1,257

TABLE 3 Average biomass yield, crop coefficient (K_c), estimated cumulative crop evapotranspiration (ET_c), and crop water-use efficiency (WUE) during 2016 and 2017 in Salisbury, NC

Crop	Biomass yields	K_c	Cumulative ET_c	WUE
	Mg ha^{-1}		mm yr^{-1}	kg mm^{-1} ha^{-1}
Switchgrass	14.2 ± 1.9[a] C[b]	0.93	847 ± 13	16.7 ± 2.0
Miscanthus	29.1 ± 0.8 A	0.97	883 ± 14	33.0 ± 1.5
Fescue	12.5 ± 1.2 C	1.13	1,029 ± 16	12.1 ± 1.4
Corn (silage)	23.6 ± 0.6 B	1.12	596 ± 103	36.8 ± 6.2
Sorghum	22.0 ± 1.8 B	1.27	691 ± 29	36.0 ± 1.2

[a]Plus or minus (±) the standard error of the mean.
[b]Letters indicate significant differences at the .05 probability level.

sorghum was similar to values reported in a Mediterranean environment using lysimeters (Garofalo et al., 2011). The K_c value for sorghum was higher than that found for an irrigated study in Spain (López-Urrea et al., 2016). In that study, K_c values calculated from lysimeter data were averaged among the growing seasons. Daily observation of ET_c during the growing season could have resulted in lower average K_c values than the biweekly observation approach used in our study. The corn K_c value of 1.12 was within the range of values suggested by Allen et al. (1998) and Piccinni et al. (2009). Sufficient precipitation in our study could have resulted in K_c values similar to irrigated corn systems. In a rain-fed study that experienced below average rainfall in the Virginia coastal plain, midseason corn K_c values of 0.65–0.91 were reported (Roygard et al., 2002), which are considerably lower than the season long K_c value we calculated. Values of K_c for rainfed systems are typically lower than for irrigated systems due to the restrictions imposed by soil water deficits on crop water use. Fescue had a season long K_c value of 1.13. The K_c value for fescue we found was within the range of values reported for a tall fescue turf study (Carrow, 1995). Miscanthus and switchgrass had season long K_c values of 0.97 and 0.93, respectively. Miscanthus K_c values for our site are within range of the values reported from studies conducted in Europe (Beale et al., 1999; Triana et al., 2015). We are currently unaware of any published reports of switchgrass K_c values.

Season-long (April–October) cumulative ET_c for the crops in 2016 and 2017 are shown in Figure 3, and their average is presented in Table 3. These curves were calculated using the K_c values presented in Table 3. Fescue had the highest cumulative ET_c of all perennial crops. The cumulative ET_c for switchgrass was higher than what was reported in Oklahoma and Illinois (Hickman et al., 2010; Yimam et al., 2015). This is likely explained by the longer growing season observed in our study. Cumulative ET_c for miscanthus was comparable to observations reported by studies in Italy and Illinois (Hickman et al., 2010; Triana et al., 2015). Both annual crops, corn and sorghum, had less cumulative ET_c than the perennial systems because of their shorter growing seasons. This occurrence was also noted in Illinois where Hickman et al. (2010) stated that the large disparity in water use between corn and perennial species (switchgrass and miscanthus) was attributed to the length of the growing season. The cumulative ET_c for biomass sorghum was comparable to the range observed in Oklahoma and Italy (Garofalo et al., 2011; Yimam et al., 2015). Cumulative ET_c of corn was less than that observed for corn harvested for grain in Texas (Howell et al., 1998). The lower value of cumulative ET_c, in our study was likely a result of the shorter growing season of corn silage. Cumulative ET_c for corn was higher than reported by Roygard et al. (2002), which might be explained by greater precipitation received at our field site. Lastly, since we used a single season-averaged K_c to characterize each crop, daily ET_c during early and late season growth are likely to be overestimated, whereas midseason daily ET_c is likely to be underestimated.

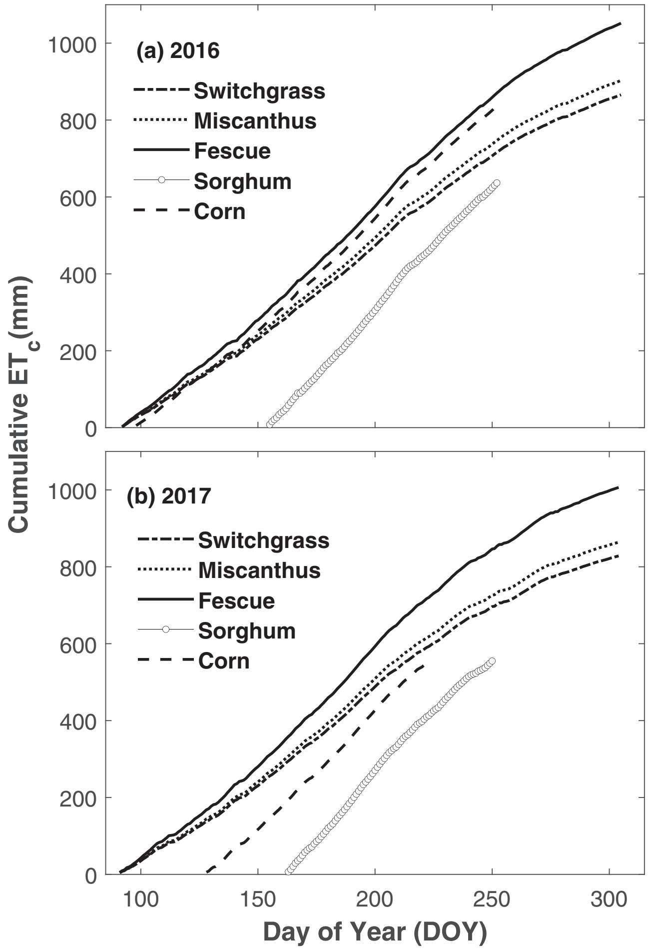

FIGURE 3 Cumulative crop evapotranspiration (ET_c) during the (a) 2016 and (b) 2017 growing seasons for switchgrass, miscanthus, fescue, sorghum, and corn at Salisbury, NC

3.3 | Biomass yields and water use efficiency

Biomass yields are presented in Table 3. Because the crop species × year interaction was not significant ($p < .05$), the 2-yr average biomass yield was reported. Miscanthus yielded significantly more biomass than the other crops. Switchgrass had similar yields to fescue, but significantly less than the annual crops. Silage corn and sorghum had similar yields.

Data from our study suggest that miscanthus yields did not reach their plateau by 4 yr after establishment in the NC Piedmont region. Wang et al. (2017a) reported yields of 16.5–21.2 Mg ha^{-1} at the same experimental site in which we conducted our study. This differs from the reports of Heaton et al. (2008), Palmer et al. (2014), and Alexopoulou et al. (2015) where maximum yields of miscanthus were achieved within 3 yr following establishment. Miscanthus biomass yields at the Piedmont region were also greater than those reported in the mountains of NC where it was suggested that water availability was the limiting factor to plant productivity (Palmer et al., 2014). Miscanthus biomass yields were similar to those observed in Italy by Angelini et al. (2009) but lower than those by Heaton et al. (2008), where peak yields reached 33–48 Mg ha^{-1}.

Switchgrass yields were similar to what has been previously reported in the NC Piedmont region (Wang et al., 2017a) and to other areas of the United States (Wullschleger et al., 2010). Yields in the Piedmont region were lower than what was reported in the NC Mountains (Palmer et al., 2014), which may be explained by the use of a different variety in our study.

Biomass yields for sorghum were within the range previously reported at this site and other locations in the United States (Hao et al., 2014; Wang et al., 2017a; Wortmann et al., 2010; Yimam et al., 2015). Corn biomass yields in our study are within the range reported by Karlen et al. (1994) for the southern United States. Because biomass sorghum yields similarly to corn silage over multiple growing seasons with comparable annual fertilizer inputs, our data indicate biomass sorghum could be a viable option when considering the potential of this crop for regional production.

Water-use efficiency data are shown in Table 3. In general, the annual crops had higher WUE than the perennial crops. Miscanthus had WUE that was similar to that of sorghum and corn, whereas switchgrass and fescue had considerably lower WUE than the other cropping systems.

In our study the annual crops maintained a high WUE over both growing seasons because of sufficient rainfall, which was not a limiting factor to plant productivity. Biomass sorghum was within the range of WUEs reported by Yimam et al. (2015) and Hao et al. (2014). The WUE of corn silage for our site was higher than Hickman et al. (2010), who reported total corn biomass (corn silage) WUE of 29.7 ± 1.1 kg ha^{-1} mm^{-1}.

Water-use efficiency of miscanthus was higher than switchgrass and fescue because of its significantly higher yields. Miscanthus WUE at our site was higher than what was reported in Illinois because of the higher yields observed during our study (Hickman et al., 2010). Switchgrass yields were significantly lower than miscanthus, but because they had similar amounts of cumulative ET_c, WUE for switchgrass was low. Switchgrass was found to have lower WUE in comparison to miscanthus in a study also conducted in Illinois (Hickman et al., 2010). Switchgrass WUE for our site was comparable to the 8–21 kg ha^{-1} mm^{-1} observed in Oklahoma (Yimam et al., 2015). As a result of low yields and high cumulative ET_c, fescue had the lowest WUE of the perennial crops. That may be explained by the fact that C3 species, such as fescue, typically have lower WUE at the leaf level than C4 species, such as the perennial and annual bioenergy grasses (Hsiao & Acevedo, 1974).

3.4 | Summary and conclusions

Perennial and annual bioenergy crops were evaluated during 2 yr in the Piedmont region in NC. Perennial crops use more water than annuals on a seasonal basis due to their longer growing season and have similar or lower dry matter yields. Annual crops have higher daily rates of water use than perennials due to their greater growth rate. Miscanthus had the highest biomass yields of all crops with comparable WUE to that of corn grown for silage and sorghum. Fescue had lowest yields and highest water use of all. These results suggest that for the NC Piedmont region, land conversion from fescue hay production to bioenergy crops with taller, higher yielding grasses such as switchgrass and miscanthus would allow for greater biomass return on the amount of available water during a growing season. An additional benefit of such conversion is the lower fertilizer input required as miscanthus was only fertilized at establishment whereas fescue was fertilized annually. Our data also suggest that corn and bioenergy sorghum are also viable options; however, they may be more susceptible to the negative effects of soil water deficits due to their greater water use rates, and they have similar or higher fertilizer needs than fescue.

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

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