INTRODUCTION

There is a critical need to increase sustainable practices for water, energy, and food resources (Robertson et al., 2017; Smidt et al., 2016). In light of world population projected to grow beyond 9 billion by 2050 (United Nations, 2013), an integrated approach is needed to find balance between current and projected challenges to global water resources (Gleeson, Wada, Bierkens, & Beek, 2012; Haddeland et al., 2014). There are complex linkages between water, energy, and food as the United States follows a path set by the US Energy Independence and Security Act of 2007 and its Renewable Fuel Standard to produce 136 billion liters of biofuel from renewable biomass annually by 2022 (US Congress, 2007).

Cellulosic biofuel crops alter evapotranspiration and drainage fluxes: Direct quantification using automated equilibrium tension lysimeters

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Abstract
An increasing number of crops are being considered as potential sources of biomass for both conventional (e.g., maize/corn) and cellulosic (e.g., switchgrass, miscanthus, and hybrid poplar) biofuels. Studies investigating the hydrologic characteristics of these crops are often conducted at either the field scale with a focus on evapotranspiration (ET) or at the plot scale where experiments generally rely on soil water storage dynamics and residual water balances. While this has led to many important insights into crop–soil water interactions under these crops, there does not appear to be any multiyear direct comparisons of the drainage fluxes under this range of biofuel crops. Furthermore, important advancements in drainage flux measurement technologies have yet to be applied to quantify hydrologic fluxes below a range of biofuel crops. Here, we use soil water content (SWC) probes and automated equilibrium tension lysimeters (AETL) to characterize detailed differences in soil water storage and drainage fluxes under conventional and cellulosic biofuel crops. The results of this study suggest that there are significant differences between subsurface water fluxes under some conventional and cellulosic biofuel crops, such as 75% greater average annual drainage and more rapid drainage accumulation under switchgrass relative to maize.

KEYWORDS
automated equilibrium tension lysimeters, cellulosic biofuel, drainage, drought, evapotranspiration, hydrology, macropore flow, residual water balance, soil water content, water use efficiency
Using renewable biomass to produce biofuel can help mitigate climate change by reducing dependence on fossil fuels and ultimately decrease greenhouse gas (GHG) emissions (Intergovernmental Panel on Climate Change, 2015). However, US market prices for maize rose nearly 40% in 2007, partly due to demand for biofuel conversion (Lazer, 2008). To reduce price pressures on crops critical to global food supplies, the renewable fuel standards specify that 60 of the mandated 136 billion liters are to come from cellulosic crops. Producing biofuel from cellulosic biomass will likely reduce production-related GHG emissions relative to conventional crops (Chang et al., 2017; Fargione et al., 2008). Meeting biofuel goals will require an increase in cellulosic crop production, but this will have hydrologic impacts that are not well understood.

Numerous studies demonstrate that the annual ET of biofuel cropping systems in rainfed production varies little in response to precipitation. Studies conducted in the Midwestern US by Abraha et al. (2015) and Hamilton, Hussain, Bhardwaj, Basso, and Robertson (2015) found similar water use by both annual and perennial cropping systems across dry and wet years. However, studies conducted across a wide range of climate and soil conditions including the US Great Plains (Burba & Verma, 2005), Germany (Petzold, Schwärzel, & Feger, 2011), and China (Sun et al., 2011; Zhou et al., 2014) show that water use within the growing season is determined in large part by water availability and antecedent conditions, especially during periods of water stress. Furthermore, a close relationship between longer growing seasons and greater water use has been observed—which is significant because perennial grasses emerge and begin transpiring much earlier than maize (Garcia & Strock, 2016; Hickman, Vanloocke, Dohleman, & Bernacchi, 2010; Ryu, Baldocchi, Ma, & Hehn, 2008; Wagle, Kakani, & Huhnke, 2016; Yimam, Ochsner, Kakani, & Warren, 2014).

In contrast to the small interannual variability in ET (449–639 mm; Abraha et al., 2015; Hamilton et al., 2015), annual yield across the biofuel crops shows distinct differences during dry conditions. In the Midwestern US, switchgrass can maintain yields from 5 to 11 T/ha (Schmer, Vogel, Mitchell, & Perrin, 2008) across a wide range of climate conditions, including drought, since it can utilize more water from greater depths than other crops (Almaraz et al., 2009). In contrast, miscanthus yields respond much more to increases in precipitation than switchgrass in nondrought conditions (Mann, Barney, Kyser, & DiTomaso, 2013) and have produced yields as high as 30 T/ha (Heaton, Dohleman, & Long, 2008), exceeding that of maize and hybrid poplar (Sanford et al., 2017). Hybrid poplar, unlike perennial grasses, is grown in cycles over multiple growing seasons and commonly produces less annual biomass than maize, switchgrass, and miscanthus (Sanford et al., 2017).

Alterations in soil water storage and drainage in response to precipitation variability likely differ across conventional and cellulosic crops. A study by Wu & Liu (2012) suggests that converting annual cropland to switchgrass production in the Midwestern US would increase the amount of soil moisture. Miscanthus, however, conserves greater root mass at shallower depths than switchgrass, which has a tendency to develop downward (Mann et al., 2013). Evidence also suggests that soil water conditions under perennial crops will respond to high-intensity precipitation differently than annual systems like maize. While comparing the effects of cropping systems on soil water availability and use, Garcia and Strock (2016) observed more soil water replenishment after heavy rainfall under a perennial prairie relative to maize/soybean rotations.

Of the cellulosic crops, switchgrass has demonstrated the strongest capability to alter soil water dynamics. In response to drought conditions, it can draw shallow soil water content (SWC) down below the soil texture-determined wilting point (Eichelmann, Wagner-Riddle, Warland, Deen, & Voroney, 2016; Skinner & Adler, 2010). In addition, infiltration within switchgrass systems can be double that of maize due to the development of large-scale structural pores, known as macropores (Bharati, Lee, Isenhart, & Schultz, 2002; Jarvis, 2007; Bonin, Lal, Schmitz, & Wullschleger, 2012; Zaibon et al., 2017). In a study by Zaibon, Anderson, Kitchen, and Haruna (2016), soil macroporosity under switchgrass doubled relative to a maize/soybean rotation, leading to a 73% increase in saturated hydraulic conductivity. The increase in macroporosity in that study was attributed to greater root development during establishment. Macroporosity due to root growth has also been observed in maize and miscanthus cropping systems. Using computed tomography (CT), Luo, Lin, and Halleck (2008) observed preferential flow paths due to root channels and macropores within soil column taken from a maize treatment. Also using CT, Cercioglu, Anderson, Udawatta, and Haruna (2018) found greater macroporosity under miscanthus relative to various cover crop and switchgrass treatments.

Differences in shallow and deep soil water dynamics across annual and perennial systems will likely affect the magnitude and timing of drainage. Despite this, studies directly comparing drainage under these crops are much less abundant than those investigating yield or SWC. Studies that compared cumulative annual drainage under maize and perennial grasses similar to switchgrass and miscanthus found lower drainage under the grasses relative to maize (Brye, Norman, Bundy, & Gower, 2000; Daigh et al., 2014). Different drainage dynamics have also been observed between maize and perennial systems; Daigh et al. (2014) observed not only a reduction in peak drainage volume under prairie relative to maize, but also a delay in the initiation of dormant season drainage. This
suppressive effect of the prairie system on drainage was largest during relatively dry periods.

There is a clear need to better understand how conventional and cellulosic biofuel crops affect hydrology. Many hydrologic studies have involved the crops discussed here, but have often focused only on crop yield or ET for multiple crops. Drainage under these crops has been investigated; however, this has generally been in the context of nutrients (Daigh et al., 2015; Ferchaud and Mary 2016; Ruan, Bhardwaj, Hamilton, & Robertson, 2016; Smith et al., 2013).

Automated equilibrium tension lysimeters (AETL) are a tool that can measure fluxes below the root zone. They operate automatically, while emulating the surrounding soil water tension, and capturing highly variable flow volumes (Barkle et al., 2011; Farahani, Howell, Shuttleworth, & Bausch, 2007; Farsad, Herbert, Hashemi, & Sadeghpour, 2012; Masarik, Norman, Brye, & Baker, 2004). Such accurate measurements of variable drainage fluxes are needed to determine how biofuel crops alter infiltration and hydraulic conductivity, and how this translates to changes in drainage dynamics. This study uses state-of-the-art subsurface instrumentation to analyze and better understand hydrologic fluxes under common conventional and cellulosic biofuel crops under dry and wet conditions.

2 | MATERIALS AND METHODS

2.1 | Site description and climate data

Experimental plots for maize, switchgrass, miscanthus, and hybrid poplar were established in 2008 by the Great Lakes Biofuel Research Center (GLBRC) at the University of Wisconsin (UW) Arlington Agricultural Research Station (UW-AARS; 43°17’N, 89°22’W), ~24 km north of Madison, WI (Figure 1). All plots were planted following a randomized complete block design resulting in replicate plots randomly placed within adjacent experimental blocks. Yield, soil water storage, and drainage flux measurements were collected under a subset of plots including each of the four biofuel crops over a three-year period from October 12, 2011, (herein referred to as the 2012 dormant season) through October 12, 2014 (end of the 2014 growing season). All plots were tilled and sweep in fall 2007 and disk tillage in spring 2008 followed by no-till thereafter. By the year preceding this study, maize had been planted and harvested for four years, and the perennial crops were all fully established (Duran & Kucharik, 2013; Herzberger, Duncan, & Jackson, 2014; Oates et al., 2016; Sanford et al., 2016). Hybrid poplar was harvested following the 2013 growing season, making 2014 a re-establishment year for that crop. Each plot included a smaller “main
plot” within which total yield (grain plus stover; T/ha) was measured, to mitigate edge effects. For each crop, soil water storage and fluxes were measured within similarly managed strips along the edge of the main plot to prevent installation disturbances from impacting the main plot, while yield was measured within the main plot. The soils within all plots are a highly productive Plano silt loam (>1 m depth) over glacial till with similar root zone soil texture (median = 8% sand, 65% silt, and 27% clay; Sanford et al., 2016; Supporting information Table S1). The root zone wilting point (lower limit of plant water uptake), 0.18, and field capacity (drainage upper limit), 0.34, were estimated using a pedotransfer function developed by Ritchie, Gerakis, & Suleiman (1999).

Daily weather data were obtained from a NOAA climate station ~6.5 km east of the study site (Menne et al., 2012), which is in a temperate humid climate with 855 mm of average annual precipitation, and average daily temperatures over the study period from 30°C in July 2012 to −28°C in January of 2014. The NOAA station data compared closely to precipitation as rain measured on site through the UW-Extension Automated Weather Observation Network (Supporting information Figure S1). The primary source of climate data was the NOAA station; most gaps in that dataset were filled from a UW-extension station on the site. Remaining gaps with no data available (0.7% of the 30-year dataset) were filled with no precipitation and linear interpolation for temperature.

2.2 SWC, runoff, and drainage measurements

Shallow and deep volumetric soil water content (m³/m³) measurements were collected using Time Domain Reflectometry (TDR) sensors (CS616-L, Campbell Scientific, Inc. Logan, UT) at 20 and 65 cm below the surface (Noborio, 2001). TDR sensors were controlled by data loggers that also recorded measurements between data downloads. The raw data were first evaluated to exclude any clearly erroneous measurements and then aggregated to a daily average and calibrated to estimate volumetric water content. Measurements were excluded primarily due to freezing effects on data from the TDR sensor during the winter. Other excluded periods were generally shorter than seven days due to brief instrument malfunctions, except under miscanthus during the 2013 growing season where 83% of data was not available. Gaps were then filled using linear interpolation before a five-day moving average was applied to the dataset.

Surface runoff measurements were collected during 2011, 2012, and 2013 growing seasons within maize, switchgrass, and miscanthus plots. Runoff was collected from 1 m × 1 m subplots installed in the edge strips adjacent to the main plots, using steel plates (3 mm thick) driven into the ground and extending 15 cm above the ground. Runoff from each subplot drained to a metal collection trough and then through a buried PVC pipe (25.4 mm diameter) into a sample collector, which consisted of a 1 L sample bottle within a 19 L overflow bucket that was placed inside a 37.8 L metal trashcan. A Plexiglas shield prevented rain from entering the collection trough. Runoff volume was measured for all rainfall events >2.5 mm. Three sub-plot replicates were installed within each cropping system.

Drainage below the crops was monitored using AETLs installed laterally through trenches dug in a similarly managed strip adjacent to each main plot. Each installation included a pan lysimeter with a steel mesh top in direct contact with the above soil and an adjustable vacuum pump. The lysimeters were positioned such that the top surface was at the base of the B soil horizon for each individual plot (Supporting information Table S3); this was assumed to be the base of the root zone, however, some crops may have roots that extend beyond this depth. Root mass measurements conducted in November of 2013 to a depth of 100 cm show that the average root mass in the 50–100 cm layer under switchgrass and miscanthus was 241 g/m² (5% total root mass) and 156 g/m² (11%), respectively (Sprunger, Oates, Jackson, & Robertson, 2017). Heat dissipation tensiometers were included in the bulk soil near each lysimeter and directly above the porous plate to monitor soil water tension in both the surrounding environment and lysimeter interior. A control program run by dataloggers increases or decreases pressure within the lysimeter to maintain equilibrium with the surrounding soil, preserving undisturbed flow paths and avoiding artificial convergent or divergent flow due to the presence of the lysimeter (Brye et al., 2000; Farsad et al., 2012; Supporting information Figures S5–S10). Lysimeter suction within the switchgrass and hybrid poplar plots did occasionally exceed that of the surrounding soil, which may have caused convergent flow. However, since this only occurred in the late growing season and early dormant season when there was little to no drainage observed, it is unlikely to have cause a significant overestimation of drainage. The collection area of each lysimeter was 1.8 x 10⁻³ cm² with a height of 15 cm (28.1 L capacity). Lysimeter samples were collected weekly during dry periods and biweekly during wet periods. The capacity of the lysimeters was not exceeded at any time during the experiment. Cumulative annual drainage was calculated as the sum of drainage sampled by water year beginning in mid-October. Temporal drainage characteristics of each crop were analyzed using the day of water year at which drainage began (Q₁₀), 25% of annual flow had occurred (Q₂₅), and 50% of annual flow had occurred (Q₅₀).

Intraplot duplicates were installed for all crops except miscanthus, and an interplot duplicate was installed in an adjacent experimental block for maize and switchgrass (Supporting information Figures S2 and S3). For the drainage and yield analyses, calculations were completed...
2.3 Calculating ET and water use efficiency (WUE)

An estimate of growing season ET within the test plots was calculated using the residual water balance of precipitation, runoff, change in SWC storage, and measured lysimeter drainage. This estimate of ET was considered the total of transpiration from plants and evaporation from soil and plant surfaces and was thus different for each year. By using directly measured drainage via the AETL, our results are robust to large precipitation events that can lead to rapid drainage. Potential ET (PET) was extracted from the North American Land Data Assimilation System (NLDAS; Mitchell et al., 2004) and used to calculate ET/PET for each crop. We divided measured yield (T/ha) by these estimates of growing season ET, along with a conversion factor of \(10^3\), to calculate the amount of convertible biomass per unit of water used, herein referred to as Water Use Efficiency (WUE; kg ha\(^{-1}\) mm\(^{-1}\)).

Growing season ET and WUE calculations spanned the period immediately after the initiation of crop transpiration through crop senescence, but before crop harvest (~October 12th). Onset of crop transpiration and senescence were determined visually from shallow soil moisture drying in excess of what would be expected from drainage alone. Precipitation was also considered such that season cutoffs were not placed immediately after significant rain events. Crop transpiration began an average of 48 days earlier in the perennial systems (April 10th, May 16th and 7th in 2012, 2013, and 2014, respectively) than within maize (June 20th in 2012 and 2013 and 15th in 2014) while crop senescence was reached by October 8th, 12th, and 12th in all plots in 2012, 2013, and 2014, respectively (Supporting information Figure S4). The longer perennial growing season length was used in all residual water balance calculations, including maize, to obtain comparable values across all crops.

Growing season SWC storage was calculated as the change in estimated soil profile water contents from the beginning to end of the growing season. Total water content storage in the profile was calculated as the weighted average of SWC change in each of the two TDR sensors. The shallow sensor, placed at 20 cm, was assumed to represent SWC from the surface to the midpoint between the two sensors, at 44.5 cm. The deep TDR probe at 65 cm then represented SWC from the middepth of the sensors to 100 cm or the top of the lysimeter pan in each plot, whichever was shallower. SWC change below 100 cm was assumed to be minimal for those plots with lysimeters deeper than 100 cm. To estimate change in soil storage for 2013 miscanthus, we averaged the changes from the 2012 and 2014 growing seasons (Figure 5d).

Runoff from the hybrid poplar plot was approximated as the average of available volume data within the other crops since runoff was not collected in these plots. Runoff during the 2014 growing season was not collected from any plots, so it was approximated as the 2013 value scaled by the ratio of 2014 to 2013 growing season precipitation (an increase of 9%). These approximations likely have only marginal effects on the residual water balance estimates since the measured runoff volumes were an order of magnitude smaller than the other key flux components (see Figure 5c).

3 RESULTS

3.1 Crop yield

Total maize yields (grain plus stover) were consistently higher than the other crops, with 2.0 T ha\(^{-1}\) yr\(^{-1}\) more than the next highest yielding crop, miscanthus; switchgrass and hybrid poplar had much lower yields (Figure 2 and Supporting information Table S5); yields are high at the Arlington Agricultural Research Station due to highly productive soils and abundant precipitation (Sanford et al., 2017). Switchgrass yields exceeded maize stover alone by an average of 35%, and miscanthus yields exceeded those of grain and stover by 24% and 210%, respectively. Hybrid poplar, harvested just once during the study period and averaged

![Figure 2](https://www.example.com/figure2.png)

**Figure 2** Annual yield (T/ha) for maize grain (bottom segment) and stover (top segment), switchgrass, and miscanthus. Hybrid poplar was grown in a 6-year rotation planted in 2008 and harvested in 2013. Annualized average yield for hybrid poplar is shown in the annual average portion. Near-zero standard error values are indicated with (*)
across its 6-year growth cycle, produced the lowest yield of 6.1 T ha\(^{-1}\) year\(^{-1}\), which is 30% of the average total maize yield. Poplar yields may increase in the second growing cycle. See Supporting information Figure S2 for block duplicate yields.

Yield sensitivity to seasonal precipitation varied across crops. This three-year study included years that were dryer than (2012–660 mm total precipitation), wetter than (2013–1,048 mm), and approximately normal (2014–864 mm) relative to the 30-year annual average (855 mm). Miscanthus yields responded most strongly to precipitation, followed by maize and then switchgrass. In response to a 60% increase in growing season precipitation from 2012 to 2013, yields for miscanthus, maize, and switchgrass increased by 64%, 44%, and 28% respectively.

### 3.2 Soil moisture

Variations in SWC dynamics between the crops within the primary experiment block were most prominent during the 2012 drought (Figure 3; Supporting information Figure S3 shows a comparison across duplicate blocks). All crops extracted soil water to below the soil texture-determined wilting point of 0.18 with miscanthus, switchgrass, hybrid poplar, and maize reaching 0.05, 0.12, 0.13, and 0.15, respectively. Notably, all three cellulosic crops began transpiring ~60 days earlier than maize as can clearly be seen during the 2012 drought in both the shallow and deep zones (Figure 3, details in Supporting information Figure S4).

After the mid-growing season precipitation event in the midst of the 2012 drought, the increase in and subsequent drainage of shallow soil water storage was unique to each crop; SWC in the miscanthus plot responded the most, followed closely by switchgrass. These responses were significantly larger than under maize in both the shallow and deep layers. While shallow soil water content under hybrid poplar had a small response to the same precipitation event, there was little to no response in the deep zone. Less soil water content decline occurred under maize and hybrid poplar.
poplar during the 2014 growing season, relative to the preceding two years, because the 2014 maize crop over the lysimeter failed and the hybrid poplar had just been harvested at the end of the 2013 growing season.

3.3 | Drainage

The crops exhibited differences in subsurface drainage that were generally consistent across the three study years (Figure 4a; Supporting information Table S6a). Drainage was generally lowest under miscanthus and highest under switchgrass. In 2012, 2013, and 2014, respectively, annual drainage under switchgrass exceeded that of maize by 67%, 52%, and 147%. Miscanthus and hybrid poplar, in contrast, had 38% and 10.5% less average annual drainage than maize, respectively. As expected, more drainage occurred during the dormant season than the growing season as a proportion of seasonal precipitation. However, the change in drainage across seasons was different among crops. From the dormant to the growing season in 2013, the portion of precipitation to drainage under switchgrass and hybrid poplar decreased by 32% and 53% respectively while maize and miscanthus increased by 29% and 30% (Figure 4c; Supporting information Table S6d).

Analysis of the drainage onset and accumulation following the growing season also indicates distinct differences among the crops. Temporal drainage patterns below miscanthus and hybrid poplar were more similar to maize than switchgrass (Supporting information Table S7). Most notably, in the 2013 dormant season, drainage began in switchgrass lysimeters an average of 51 days prior to maize, while drainage onset was delayed relative to maize by 3 days beneath both miscanthus and hybrid poplar plots. During the 2012 drought, both switchgrass and miscanthus accumulated drainage at the same rate as maize while switchgrass accumulated much more rapidly in the following year, reaching Q₀, Q₂₅, and Q₅₀ 51, 58, and 12 days earlier than maize, respectively.

3.4 | Evapotranspiration and water use efficiency (WUE)

Calculated ET was sensitive to drought conditions for maize, switchgrass, and miscanthus, but hybrid poplar showed little response (Figure 5f; Supporting information Table S8a). During the 2012 drought in particular, there was little difference in calculated ET between maize, switchgrass, and miscanthus (352, 355, and 342 mm, respectively) while ET in hybrid poplar exceeded maize by 41% (495 mm). Average growing season ET/PET ranged from 0.35 for maize and switchgrass to 0.42 for miscanthus (Supporting information Table S9). Miscanthus responded the most to increased precipitation from 2012 to 2013, increasing yield by 64%, ET by 57%, and slightly increasing WUE. The average WUE (Figure 5g; Supporting information Table S8b) was highest for total maize (57 T ha⁻¹ mm⁻¹) with miscanthus near that of corn grain alone, and switchgrass and hybrid poplar having much lower WUE. This low WUE

**FIGURE 4** (a) Cumulative drainage, precipitation, and potential ET (mm) in water years starting on October 12th, 2011, (b) average annual drainage (mm), (c) seasonal portion of precipitation to drainage (%) for each season, and (d) average annual portion of precipitation to drainage (%)
may be due to low yields related to early plot establishment and could increase in later years after the study due to the increase in yields.

### 4 | DISCUSSION

The response of yield to dry and wet conditions was unique for each analyzed biofuel crop. Switchgrass yields were typical of those reported in the literature at 6–8 T/ha (Schmer et al., 2008; Propheter & Staggenborg, 2010) with less response to dry conditions than maize as seen by Almaraz et al., (2009). Miscanthus also achieved yields similar to those in other studies, and consistently exceeded maize (corn) grain yields alone (Dohleman & Long, 2009; Heaton et al., 2008). Similar to the results of Mann et al. (2013), Miscanthus yields were substantially enhanced by more precipitation while switchgrass maintained consistent yields throughout drought conditions. Low hybrid poplar yields of 6.1 T ha\(^{-1}\) yr\(^{-1}\) were consistent with the results by others studying hybrid poplar (Cannell, Sheppard, & Milne, 1988; Labrecque & Teodorescu, 2005; Somerville, Youngs, Taylor, Davis, & Long, 2010).

The cellulosic biofuel crops (switchgrass, miscanthus, and hybrid poplar) exploited initial and early growing season soil water under dry conditions allowing for a greater
growing season ET. This was similar to the responses seen under prairie land cover (Burba & Verma, 2005), hybrid poplar (Petzold et al., 2011), and switchgrass (Yimam et al., 2014). Each cellulosic crop was well established prior to the 2012 drought with the resulting root structures allowing transpiration to begin ~60 days earlier than maize. This different between maize and the cellulosic crops suggest that evaporation was water limited thus transpiration was the primary mechanism for soil moisture declines. Both switchgrass and miscanthus also showed more rapid soil water replenishment after heavy rain relative to maize and hybrid poplar similar to observations by Garcia and Strock (2016).

This is the first published work to use directly measured subsurface drainage fluxes to estimate growing season ET and WUE for cellulosic crops; most studies have relied on calculations of differential soil moisture. This is significant given the propensity for switchgrass in particular to show rapid soil moisture increases and drainage fluxes after precipitation and snow melt events. Supporting information Figure S12 shows the similar rapid fluxes seen in duplicate switchgrass plots and lysimeters. These observed phenomena provide evidence of better-established macropore pathways within perennial grasses. Thus, calculating ET based on differential soil water content alone is likely to miss rapid water fluxes through these pathways, and thus underestimate soil water content due to the water stored within those pathways. More frequent lysimeter sampling would allow for a finer temporal resolution to the ET estimation as well. While the crops likely grew roots below the depth of the lysimeters, this is a very small fraction of the total root mass and, aside from the most water-limited conditions, will provide little of the total water needed by the crop. The results are shown here differ slightly from Hamilton et al. (2015) with regard to greater growing season ET under miscanthus relative to maize as well as 40% greater average annual ET for hybrid poplar than maize. Hamilton et al. (2015) also observed greater yields for miscanthus than maize leading to a greater WUE. The estimation of WUE in this analysis differs from a regional study by VanLoocke, Twine, Zeri, & Bernacchi, (2012) in showing a lower WUE for miscanthus than maize. The main difference is the high corn yields observed in this study relative to VanLooke et al. (2012), who quantify WUE and yields using a regional model. The high corn yields in this study are likely due to idealized soil and climate conditions at the AARS. This could lead to significant variations in yield and WUE—especially since simulation results would be highly dependent upon the particular management scheme chosen for the model.

We are not aware of other published articles that have shown greater drainage under a cellulosic crop (switchgrass) than under a conventional crop (maize). The episodic nature of drainage under switchgrass during the spring suggests macropores created by root development. Considering the tendency for switchgrass to develop deeper root systems (Mann et al., 2013), especially in response to droughts (Eichelmann et al., 2016), the significantly greater drainage in the 2013 dormant season was likely due to deep root structures grown in response to the 2012 growing season drought. The other two cellulosic crops (miscanthus and hybrid poplar) did reduce drainage considerably relative to maize, which is consistent with other literature (Brye et al., 2000; Daigh et al., 2014).

Meeting sustainable energy goals will likely require increased production of cellulosic biofuel crops, thus it is important to understand the yields of such crops along with the hydrologic implications of their production. Average yield was the highest for total maize, with miscanthus, switchgrass, and hybrid poplar following in decreasing order. Switchgrass yields were much less affected by differing levels of precipitation relative to maize, miscanthus, and hybrid poplar. Because miscanthus produces yields near those of maize but could reduce deep drainage (and by extension groundwater recharge), it may be an appropriate crop to grow in areas with abundant water. Furthermore, consistent yields even in drought conditions along with the potential to increase groundwater recharge suggest that switchgrass may be well suited to grow in areas where water limitations limit the growth of traditional crops.

The results presented here describe previously undemonstrated hydrologic behavior under conventional and cellulosic crops, which affects crop ET and resultant WUE estimates. During the 2012 drought year, soil water uptake dynamics varied considerably across the crops relative to wetter years. All three cellulosic crops had more variable shallow SWC relative to maize. While drainage under miscanthus and hybrid poplar was generally lower than under maize, switchgrass nearly doubled the three-year cumulative drainage and greatly increased the portion of annual precipitation going toward drainage. This significantly affected ET estimates relative to those estimated using soil moisture storage changes alone. Considering these results, more studies incorporating AETLs or similar technologies are needed to characterize the detailed and highly variable drainage characteristics under perennial cropping systems as biofuel crops.

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Additional supporting information may be found online in the Supporting Information section at the end of the article.

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