THE HYDROLOGIC SUSTAINABILITY OF SECOND-GENERATION BIOFUEL CROPPING SYSTEMS

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ABSTRACT

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Maize, switchgrass, miscanthus, and hybrid poplar are four of the leading crops considered as potential sources of biomass for conventional and cellulosic renewable biofuels. Many studies have investigated the evapotranspiration and soil water dynamics of these crops, but less is known about how they will affect deep drainage. More work is also needed to understand how the relationship between crop yield and water use will vary with climate. This thesis describes two studies investigating the hydrologic sustainability of these crops. The first is an observational study that makes use of yield, runoff, soil water content, and drainage measurements to estimate evapotranspiration and water use efficiency. Drainage was measured using automated equilibrium tension lysimeters. This advanced form of drainage measurement has not yet been used under this range of crops. The second study uses the Systems Approach to Land Use Sustainability (SALUS) crop growth model to simulate the response of crop yield and evapotranspiration to 30 years of variable climate. Results of these studies suggest that a) drainage under cellulosic crops will be significantly different from maize and b) climate will have a greater impact on the amount of water going to evapotranspiration than crop type.

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INTRODUCTION

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 multi-year 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. In chapter 1, soil water content (SWC) probes and Automated Equilibrium Tension Lysimeters (AETL) were used 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.

Heavy reliance over the last decade on maize and other grain-based biofuels has highlighted several drawbacks of conventional biofuels including increased maize prices and environmental impacts associated with increased land brought into production to satisfy the additional demand. Increased production of cellulosic biofuels, including a switch to non-traditional crops such as switchgrass and miscanthus may alleviate some of the negative consequences of conventional biofuels production. Yields of these cellulosic biofuel crops is the most directly relevant to their feasibility, but consideration must also be given to how much

water is used in their production and how that relationship will likely change with varying climate. Crop models provide a way to investigate the complex dynamics of these systems. The objectives of this study were to: a) develop and optimize crop-soil-water simulations for maize, switchgrass, and miscanthus using data from a test-plot experiment conducted from 2012-2014 and the Systems Approach to Land Use Sustainability (SALUS) model, b) use the optimized model for 30-year simulations of continuous growth for the three crops, and c) analyze the simulated yield, portion of available growing season water going to ET, and water use efficiency under wet and dry conditions. The results of the study suggest that maize will have higher yields relative to switchgrass and miscanthus, but be more sensitive to dry conditions, and that climate may have more impact on the amount of available water going to ET than crop choice in biofuel cropping systems.

CHAPTER 1

Introduction

There is a critical need to increase sustainable practices for water, energy, and food resources (Smidt et al., 2016; Robertson et al., 2017). 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 et al., 2012; Haddeland et al., 2014). There are complex linkages between water, energy and food as the US 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). Using renewable biomass to produce biofuel can help mitigate climate change by reducing dependence on fossil fuels and ultimately decrease greenhouse gas (GHG) emissions (IPCC, 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 (Fargione et al., 2008; Chang et al., 2017). 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 et al. (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 and Verma, 2005), Germany (Petzold et al., 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 (Ryu et al., 2008; Hickman et al., 2010; Yimam et al., 2014; Garcia and Strock, 2016; Wagle et al., 2016).

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 et al., 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 non-drought conditions (Mann et al., 2013) and have produced yields as high as 30 T/ha (Heaton et al., 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 and 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 (Skinner and Adler, 2010; Eichelmann et al., 2016). 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 et al., 2002; Jarvis et al., 2007; Bonin et al., 2012; Zaibon et al., 2017). In a study by Zaibon et al. (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 et al. (2008) observed preferential flow paths due to root channels and macropores within soil column taken from a maize treatment. Also using CT, Cercioglu et al. (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 (e.g., Brye et al., 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 (Smith et al., 2013; Daigh et al., 2015; Ferchaud and Mary, 2016; and Ruan et al., 2016).

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 (Masarik et al., 2004; Farahani et al., 2007; Barkle et al., 2011; Farsad et al., 2012). 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,

Materials and Methods

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), approximately 24 km north of Madison, WI (Figure 1.1). 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 12th 2011 (herein referred to as the 2012 dormant season) through October 12th 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 and Kucharik, 2013; Herzberger et al., 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; Table S1) (Sanford et al., 2016). 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 et al. (1999).

Figure 1.1 – Site map: Site map of experimental micro-plots at Arlington Agricultural Research Station (AARS). The site is located in South-Central Wisconsin at the southern edge of Columbia County approximately 24 km north of University of Wisconsin-Madison. Micro-plots within the 400 block (lower-right) were used in the analyses while those in the 200 block (upper-left) were used as duplication. Surface slope in all 400 block plots chosen in this study dip approximately 3% to the southeast with minimal surface depressions.

Daily weather data were obtained from a NOAA climate station approximately 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 (Fig. 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.

SWC, Runoff, and Drainage Measurements

Shallow and deep volumetric soil water content (m^3m^{-3}) 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 the 2011, 2012, and 2013 growing seasons within maize, switchgrass, and miscanthus plots. Runoff was collected from 1m x 1m sub-plots 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 sub-plot 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 greater than 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 (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 roots mass) and 156 g/m2 (11%), respectively (Sprunger et al., 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) (Figures S17 – 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 cm^2 with a height of 15 cm (28.1 L capacity). Lysimeter samples were collected weekly during dry periods and bi-weekly 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 (Q_0), 25% of annual flow had occurred (Q_{25}), and 50% of annual flow had occurred (Q_{50}).

Intra-plot duplicates were installed for all crops except miscanthus, and an inter-plot duplicate was installed in an adjacent experimental block for maize and switchgrass (Figures S3 and S15). For the drainage and yield analyses, calculations were completed for each plot, and duplicate maize and switchgrass plots were averaged to obtain a single value by crop along with associated standard error values (Tables S14 and S4). Due to crop failure in the primary block 400 maize plot directly overlying the AETL in 2014, only measurements under the 200 block sub-plot were used that year.

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/mm).

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 (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 midpoint depth 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 1.5d).

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 1.5c).

Results

Crop Yield

Total maize yields (grain plus stover) were consistently higher than the other crops, with 2.0 T/ha/yr more than the next highest yielding crop, miscanthus; switchgrass and hybrid poplar had much lower yields (Figure 1.2 and 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 across its 6-year growth cycle, produced the lowest yield of 6.1 T/ha/yr, which is 30% of the average total maize yield. Poplar yields may increase in the second growing cycle. See 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 – 1048 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.

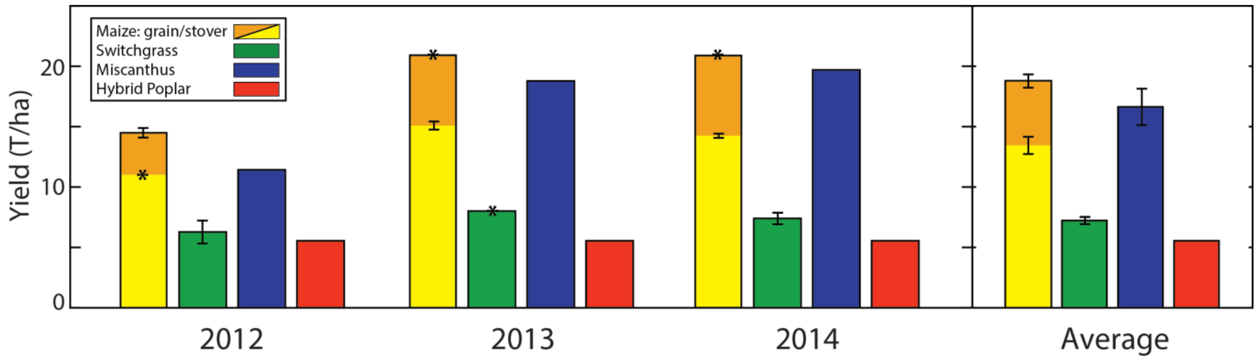

Figure 1.2 – Annual yield: Annual yield (T/ha) for maize grain (bottom segment) and stover (top segment), switchgrass, and miscanthus. Hybrid poplar was grown in a 6-year rotation planted in 2008 and harvested in 2013. Annualized average yield for hybrid poplar is shown in the annual average portion. Near-zero standard error values are indicated with (*).

<u>Soil Moisture</u>

Variations in SWC dynamics between the crops within the primary experiment block were most prominent during the 2012 drought (Figure 1.3, 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 approximately 60 days earlier than maize as can clearly be seen during the 2012 drought in both the shallow and deep zones (Figure 1.3, details in 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 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.

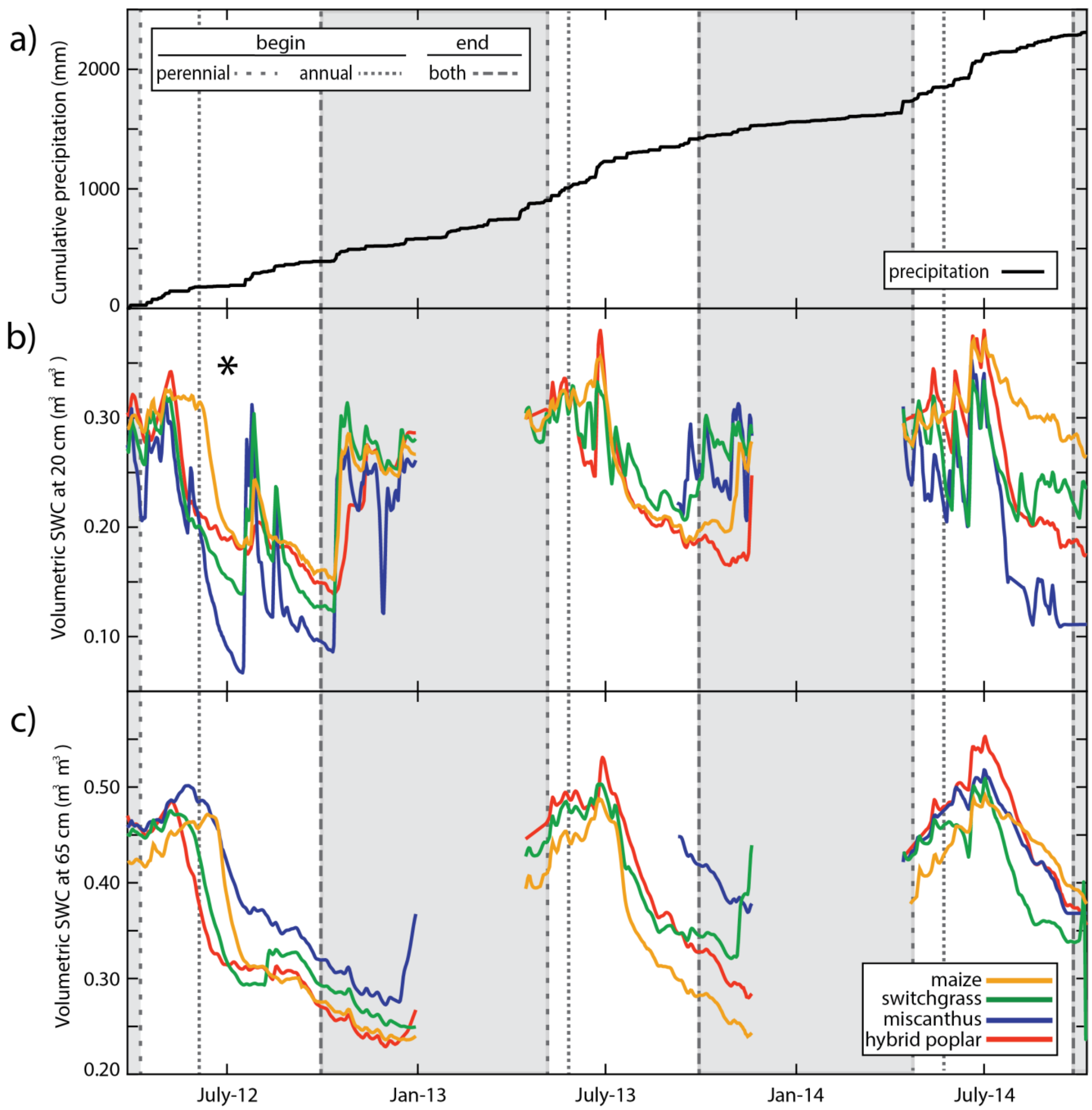

Figure 1.3 – Soil water content: a) Daily cumulative precipitation (mm) and soil water content (m^3m^{-3}) for **b)** shallow (20 cm) and **c)** deep (65 cm) zones. Values shown are for the analysis test plots within the 400 agricultural block. Grey regions represent the dormant season defined as the period from crop senescence to the subsequent year's transpiration. Gaps in lines during the dormant season represent frozen or otherwise unusable/unavailable SWC data. Nearly all miscanthus data in the 2013 growing season were not available due to equipment failure. The 2012 growing season drought is also indicated (*).

Drainage

The crops exhibited differences in subsurface drainage that were generally consistent across the three study years (Figure 1.4a and 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 1.4c and 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 (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 Q_0, Q_{25}, and Q_{50} 51, 58, and 12 days earlier than maize, respectively.

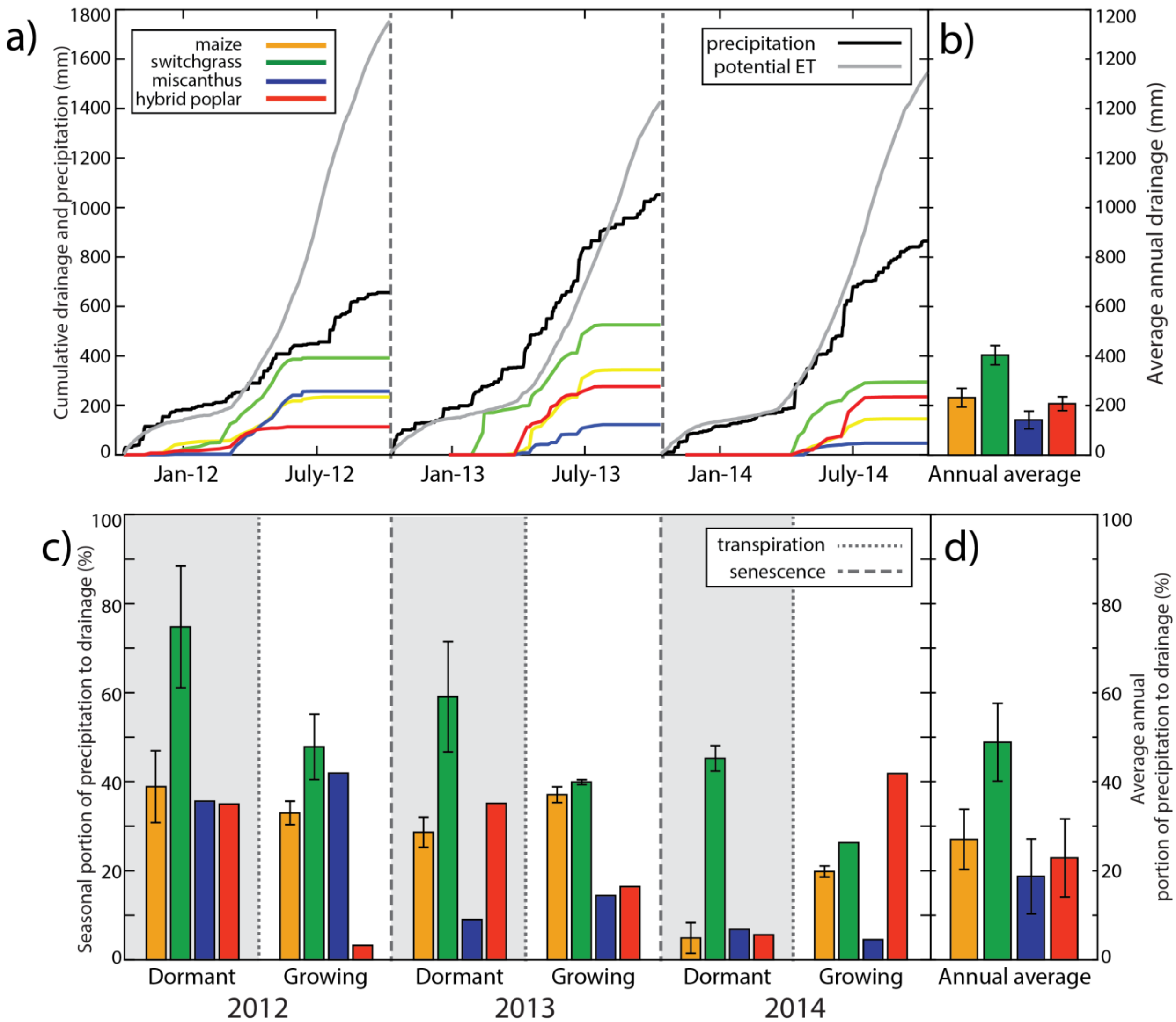

Figure 1.4 – Cumulative drainage: a) Cumulative drainage, precipitation, and potential ET (mm) in water years starting on October 12th, 2011, **b)** average annual drainage (mm), **c)** seasonal portion of precipitation to drainage (%) for each season, and **d)** average annual portion of precipitation to drainage (%).

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 1.5f and 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 (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 1.5g and Table S8b) was highest for total maize (57 T/ha/mm) with miscanthus near that of corn grain alone, and switchgrass and hybrid poplar having much lower WUE. This low WUE 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.

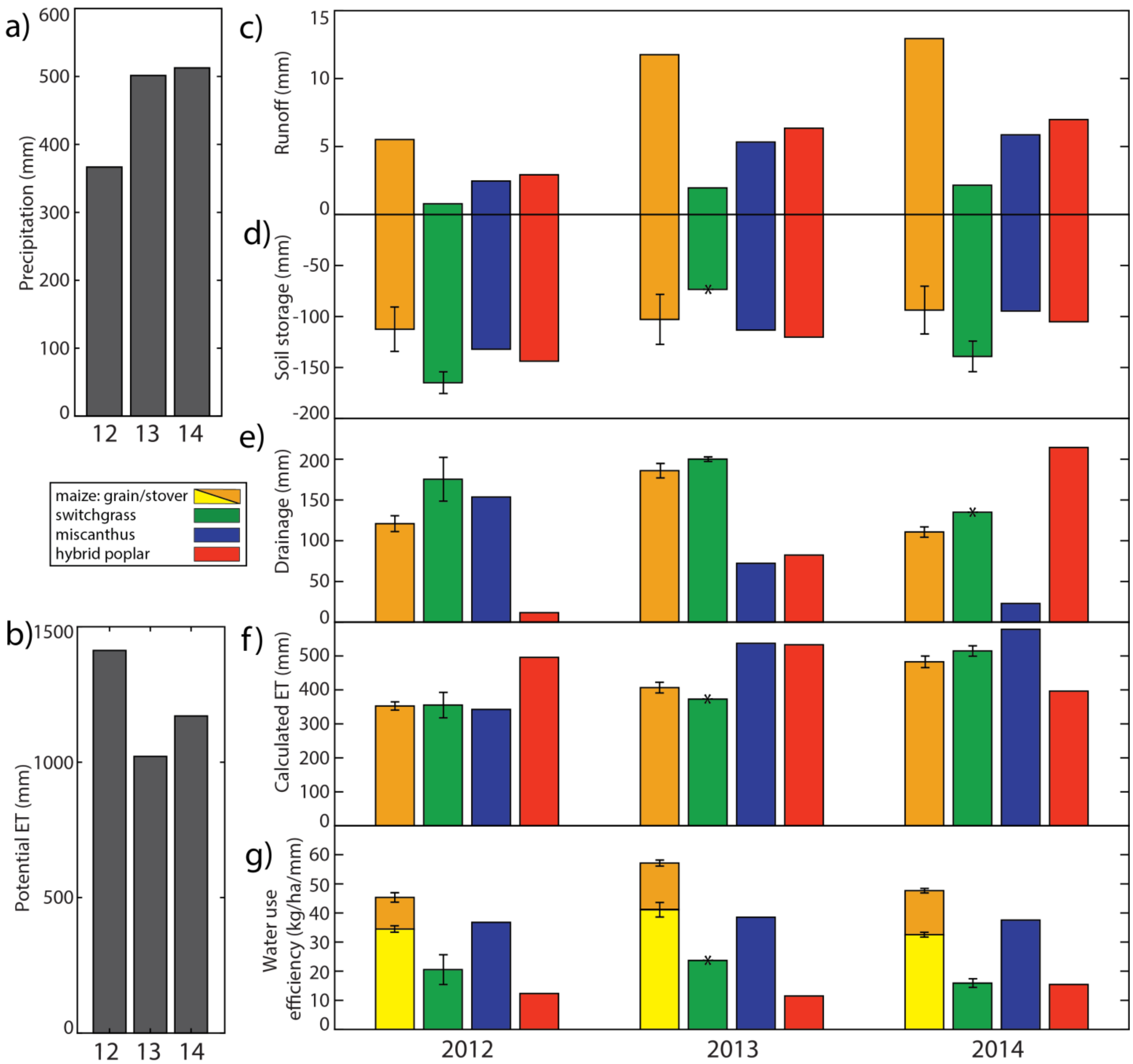

Figure 1.5 – Residual water balance: a) Growing season precipitation (mm), **b)** potential ET (mm), **c)** runoff (mm), **d),** change in soil storage (mm), **e)** drainage, **f)** calculated ET (mm), and **g)** water use efficiency (kg/ha/mm) for maize grain (lower portion) and stover (upper portion), switchgrass, miscanthus and hybrid poplar. Hybrid poplar was grown in a 6-year rotation and harvested in 2013 with the 6-year average shown.

Conclusion

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 and 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 (Heaton et al., 2008; Dohleman and Long, 2009). 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/yr were consistent with the results by others studying hybrid poplar (Cannell et al., 1988; Labrecque and Teodorescu, 2005; Somerville et al., 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 and 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 approximately 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. 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 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 et al. (2012) in showing a lower WUE for miscanthus than maize. The main difference is the high corn yields observed in this study relative to VanLoocke 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.

CHAPTER 2

Introduction

Population growth and climate change present significant challenges to future global water resources. By 2050, 760 million to 1.1 billion people will likely experience an increase in water scarcity due to climate change (Gosling and Arnell, 2016). While water demand due to climate change will vary widely by region, demand driven by population increases will likely have the greatest impact on the agriculture sector as irrigation water demand will grow to maintain high yields (Wang et al., 2016). In addition to food supply, water will also be needed to supply a growing biofuel sector. The United States Energy Independence and Security Act (EISA) and the associated Renewable Fuel Standard (RFS) aim to mitigate drivers of climate change and reduce greenhouse gas (GHG) emissions by replacing energy produced from fossil fuels with renewable biofuels derived from either conventional (e.g., maize) or cellulosic (e.g., switchgrass and miscanthus) crops (US Congress, 2007).

There is substantial motivation to develop cellulosic rather than conventional biofuel systems due to negative effects on the supply and price of food (Carter et al., 2016). A review of the effect of conventional biofuel policies on maize prices found that producing 1 billion gallons of ethanol from maize led to an increase in maize prices of 2-3% (Condon et al., 2015). With appropriate management, growing perennial (cellulosic) biofuel crops on marginal lands could both alleviate competition with food supplies and provide environmental benefits (Robertson et al., 2017). An analysis of the feasibility of growing biofuel crops in Nebraska found that 22% of the state's energy requirements could be met by growing these crops on marginal land (Gopalakrishnan et al., 2009). Chang et al. (2017) calculated "biomass to tank" metrics for maize and switchgrass in terms of GHG emissions and found that producing fuel blends with switchgrass had a greater GHG benefit than maize. However, crop expansion from 2008-2012 corresponded to a substantial loss in unmanaged grasslands (Lark et al., 2015).

Development of sustainable cellulosic biofuel systems will require policies that balance production achieved through increased land use with yield from increased water use (Bonsch et al, 2016). If land is converted to biofuel crop production, the type of land conversion will be important in terms of the resulting environmental benefits and economic costs (Zhong et al., 2016). Changes in surface ET on a large scale will likely translate to changes in groundwater storage. Production of miscanthus could reduce subsurface drainage at conversion rates as low as 25% (VanLoocke et al., 2010). Mathioudakis et al. (2017) also calculated the water footprint of energy production using combinations of various crop reside feedstocks, including maize byproducts, and conversion techniques. Their results suggested that producing energy using miscanthus would have a greater water footprint than using crop residues

Decisions regarding the location and management of biofuel crop production will need to consider the drivers of yield and water use for each crop, which can be expressed as a ratio as Water Use Efficiency (WUE) (kg/ha/mm). Many studies have concluded that yield is the primary determinant of WUE as it has more annual variability than ET (Abraha et al., 2015; Hamilton et al., 2015; Robertson et al., 2017). A crop simulation study by Basso and Ritchie (2012) also found that when yield is increased by better crop management, ET is largely unaffected, leading to increased WUE. In a study assessing ecosystem and intrinsic WUE of maize and switchgrass, Abraha et al. (2016) found little variation in WUE across years. While simulating various WUE metrics, VanLoocke et al. (2012) showed that miscanthus generally had the highest WUE while switchgrass had a similar WUE as maize. Additionally, miscanthus can have yields comparable to maize, its water use is less affected by drought than maize (Hamilton et al., 2015; Eichelmann et al., 2013).

Biofuel production will need to consider all economic, social, and environmental outcomes (Watkins et al., 2015; Gerssen-Gondelach et al., 2017). According to Smidt et al. (2016), the best future water use practices will be those that focus on farmer profit and consider water as an input to energy and food systems. To that end, biofuel policies could create incentives to grow crops that use less water as opposed to directly reducing groundwater pumping. Humpenoder et al. (2018) suggest that the negative impacts of biofuel production could be mitigated with policies that enhance environmental protection and increase agricultural efficiencies.

While many studies have used crop models to investigate the WUE of conventional and cellulosic biofuel crops, they are often limited to short-term analyses and/or carried out at large scales. More work comparing the long-term WUE of biofuels crops at the plot scale is needed. To better understand how sustainable conventional and cellulosic biofuel crops would be, here we apply a crop systems model to simulate crop response to 30 years of historical weather data. To optimize and validate models for maize, miscanthus, and switchgrass, we use a suite of in-situ field measurements: runoff, drainage, soil moisture, leaf area index (LAI), and end-of-season crop yield. We then drive this model using 30-years of historical weather data to examine the role of climate dynamics on the variability in crop yields and water use efficiency for these cropping systems. Insights gained from this field site are broadly applicable across temperate, rainfed agricultural regions like the US Glaciated Midwest and Corn Belt.

Materials and Methods

Study Site and Weather Data

Data for this study were collected from 2012 to 2014 at the University of Wisconsin Arlington Agricultural Research Station (UW-AARS), approximately 24 km north of Madison, Wisconsin (Figure 2.1; 43˚ 17’ N, 89˚ 22’ W). In addition to numerous other crops and rotations, test plots for maize, switchgrass, and miscanthus were planted by the Great Lakes Bioenergy Research Center (GLBRC) in 2008 using a randomized complete block design (Figure 2.1); all crops were well-established before this observational study started (Duran and Kucharik, 2013; Herzberger et al, 2014; Oates et al., 2016; Sanford et al., 2016). Each plot contained a main section used to measure yield (grain plus stover; T/ha) and a subsection installed along the plot edge to measure soil water storage and drainage fluxes. The soil at the field site is a Plano silt loam deposited over a course glacial till. Soil above the glacial till becomes finer with depth and the median profile texture is 8% sand, 65% silt, and 27% clay (Table S10).

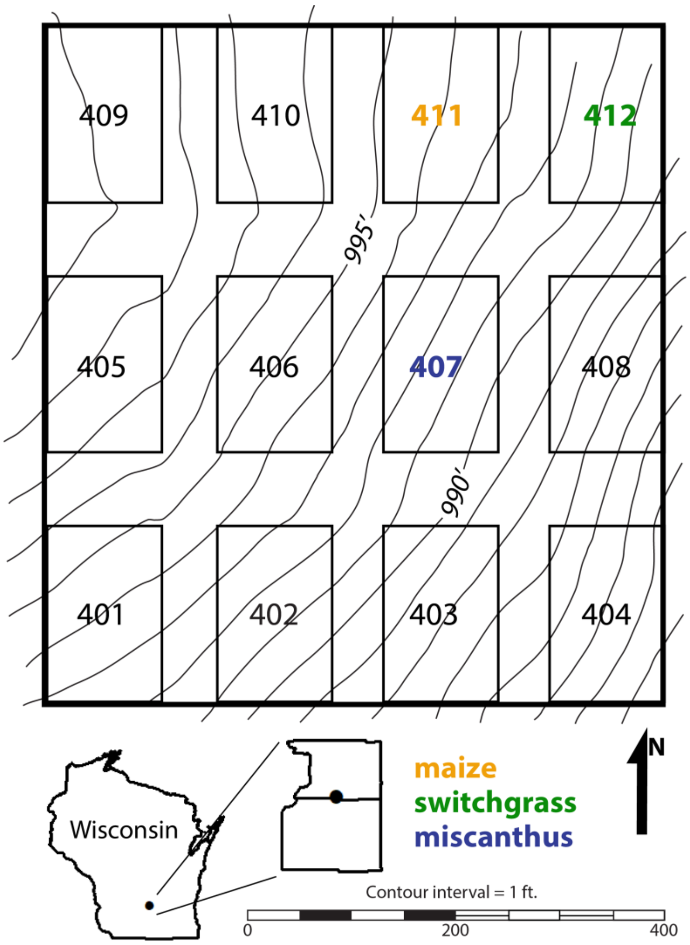

Figure 2.1 – Site map: Site map of maize, switchgrass, and miscanthus test plots at the University of Wisconsin Arlington Agricultural Research Station (UW-AARS)

Daily weather data for precipitation and temperature were synthesized from a combination of an onsite weather station operated by the UW-Extension Automated Weather Observation Network and a NOAA climate station approximately 6.5 km east of the site (Menne et al., 2012). Observations were first selected from the NOAA station, filling data gaps using available UW-Extension data. Remaining gaps with no available data from either source were filled with zero precipitation and linearly interpolated temperature values. NOAA data were selected before on-site data due to the more robust handling of frozen precipitation by the NOAA instrumentation.

Observational Data

For the 2012 – 2014 period, four types of observational data were collected: 1) shallow and deep soil moisture, 2) surface runoff, 3) deep drainage, and 4) crop yield. These data were then used both to optimize and validate the models, as described in the next section.

Volumetric soil water content measurements were taken at 20 and 65 cm depths using Time Domain Reflectometry (TDR) sensors (CS616-L, Campbell Scientific, Inc. Logan, UT; Noborio, 2001). Raw hourly data were first cleared of erroneous measurements, aggregated to daily values, calibrated to volumetric soil water content, then gap-filled using linear interpolation. Changes in soil storage was calculated relative to SWC starting at the beginning of the growing season for each crop.

Surface runoff and deep drainage measurements were collected within each plot. Surface runoff measurements were collected during the 2012 and 2013 growing seasons using a metal trough, PVC pipe, 1 L sample bottle, 19 L bucket, and 38 L trashcan. Accumulated runoff was recorded after all precipitation events greater than 2.5 mm. Deep drainage was measured using Automated Equilibrium Tension Lysimeters. Pressure in the lysimeter was continuously monitored and automatically increased or decreased to match the surrounding measured soil pressure to emulate undisturbed water flow (Brye et al., 2000; Farsad et al., 2012). Additional details on these experiments can be found in Parish et al. (2018) and Stenjem et al. (2018).

Crop yield data for maize were collected from a combine while data for switchgrass and miscanthus were collected using haybine and chopper. Harvest dates for 2012, 2013, and 2014 in the maize plot were October 22, 23, and November 8, respectively. Switchgrass and miscanthus were generally harvested later on November 7, October 23, and November 7 in 2012, 2013, and 2014 respectively.

Several quantities were derived from these four data types for comparison with the model and discussion. Growing season ET was calculated as the residual balance of precipitation, change in soil storage, surface runoff, and deep drainage (Figure S13). Water Use Efficiency was then calculated as that year's yield divided by the ET estimate. Growing Season Available Water (GSAW) was calculated as the sum of growing season precipitation plus the soil water storage in the top 100 cm on the first day of the growing season (Figure S13).

Crop Growth Modeling in SALUS

We conducted two simulation experiments: 1) a three-year (2012 – 2014) simulation of each crop (maize, miscanthus, and switchgrass) for optimization and validation, spun-up with historical weather and management information starting in 1985, and 2) a 30 year simulation using the validated models under fixed management, driven with weather data from 1985 – 2014. This two-part simulation structure allows us to develop confidence in a model that can be heavily influenced by prior management conditions, and then separately simulate how each cropping system might respond to dynamic climatic inputs.

Model Optimization and Validation

Crop growth simulations were developed for each experimental plot using the Systems Approach to Land Use Sustainability (SALUS) model. SALUS was designed to simulate continuous crop-soil-water conditions at a daily time-step within three main modules representing crop growth, soil nutrient cycling, and a soil water balance (Basso et al., 2006). The model has been used to analyze the ET and yield dynamics of biofuel cropping systems at both the plot and the regional scales (Hamilton et al., 2015; Liu and Basso, 2016) and shares many characteristics with other crop-soil-water models such as CropSyst (Stockel et al., 1994), STICS (Brisson et al., 1998), and ALMANAC (Kiniry et al., 2008). The crop growth and water balance modules of SALUS were derived from the CERES model, and were designed to calculate the effects of water stress on crop yields (Ritchie, 1985). The simulated water balance includes a time-to-ponding parameter and subsequent refinement of runoff and drainage processes during infiltration (Basso, 2000). ET in SALUS is based on routines described by Ritchie (1972) with a refined soil evaporation mechanism (Basso and Ritchie, 2012; Syswerda et al., 2012). Model performance using grain yield and SWC have been described by Basso et al. (2010), Giola et al. (2012), and Culman et al. (2013).

SALUS requires four types of input data; crop parameters, annual management practices, daily climate data, and soil characteristics. Crop growth can be represented using either a simple model based on a potential LAI curve and a thermal time to maturity calculation or a complex model based on known genetic characteristics (Basso et al., 2010). Due to the limited availability of the complex model parameters, only maize was simulated using the complex model while switchgrass and miscanthus used the simple model. The maximum potential LAI input was determined using direct LAI measurements taken during the 2011 and 2012 growing seasons. Crop management inputs, such as seeding rate, row spacing, fertilizer type and rate, and harvest date were set using agronomic summaries from 2008 to 2014. The daily climate data required by the model include daily precipitation (mm), minimum and maximum temperature (˚C), and solar radiation ($MJ/m^2/day$). These inputs were synthesized from data collected at the NOAA weather station described above (Figure S14).

The soil profile within the SALUS water balance module is fixed at 2, 7, 15, 26, 40, 57, 77, 100 cm and continues to the set total soil depth in intervals of 25 cm. Soil profile inputs were distributed using the same four layer intervals used in the measured soil analysis; 10, 25, 50, and 100 cm. The input intervals are automatically redistributed to fit the fixed intervals within the model. Soil characteristic inputs for each experimental plot were derived from daily volumetric soil water content data collected from 2012 to 2014 and soil texture, % organic carbon, and bulk density measurements taken in 2008 and 2009 (Table S10). The drained upper and lower limit water contents were determined using soil drying curves near saturation and near the wilting point, respectively. Saturated hydraulic conductivity was determined using algorithms developed by Ritchie et al. (1999) and Suleiman (2001). Percent saturation was estimated using bulk density where:

$$SAT = 0.92 * (1 - (BD/2.65)) \quad \text{Equation 1}$$

Bulk density was only measured to 25 cm so the value for the 25 cm measurement was used in the two deeper layers, along with the subsequent value of saturation (Table S11). Saturation measurements below 50 cm and lower than the estimated DUL for that layer were increased to 1% greater than DUL to accommodate. The maximum surface ponding depth was set at 1 cm.

The model was run for 30 years such that 1985-2011 was considered “spin-up”, while 2012 and 2013 were used for parameter estimation, and 2014 data were used for model validation. Parameters of interest within each experimental plot simulation were initially set using the data described above before an optimization routine, in a similar manner to Dzotsi et al. (2013). Estimated parameters included shallow (0-75 cm) and deep (75-200 cm) soil hospitality factor (SHF) and saturated hydraulic conductivity for each soil layer (Table S12). MATLAB’s non-linear optimization routine *fminsearch* (D’Errico, J., 2010) was used to optimize model parameters. For this optimization, observational datasets included yield, runoff, SWC, and drainage (Tables S12–S14). The objective function was:

$$\Phi = w_1 \times \text{rmse}(Y_{sim}, Y_{obs}) + w_2 \times \text{rmse}(R_{sim}, R_{obs}) + w_3 \times \text{rmse}(D_{sim}, D_{obs})$$

$$+w_4 \times \frac{1}{2}[\text{rmse}(S_{sim}, S_{obs})_{20} + \text{rmse}(S_{sim}, S_{obs})_{65}] \qquad \text{Equation 2}$$

Where w_1 through w_4 are weights on each of the terms of the objective function Φ, set as described below. The Y_{sim} and Y_{obs} terms are the annual yield values for each of the simulation and observations, respectively. Likewise, the R terms correspond to cumulative annual runoff, and D to cumulative annual drainage. The S terms are soil moisture values, with depths of 20 and 65 cm denoted. The rmse indicates the root-mean-squared error for each of the values.

The initial weights w were set by running the model once using initial parameter values. From this run the un-weighted values of each of objective function term (yield, runoff, drainage, and soil moisture) was calculated. The initial weights were set to the inverse of these values, thus the weighted values for each component of the objective function equaled 1, and the summed initial value of Φ=5. The weights were then held constant during the automated optimization procedure.

Shallow and deep soil moisture within the growing season, annual yield, and cumulative annual drainage for 2014 were then used to validate the model using the optimized parameters. Runoff was not used in validation as measurements were not collected in 2014. RMSE was calculated for shallow and deep soil moisture and percent difference from observed was calculated for annual yield and cumulative drainage.

<u>30-year Climate Experiment</u>

Following parameter optimization and model validation, long-term yield and ET were analyzed using climate simulations designed to grow maize, switchgrass, or miscanthus in continuous production for 30 years (1985-2014) at the UW-AARS site used in model validation; such continuous simulations are necessary to account for year to year carryforward of carbon, nutrients and water (Basso et al., 2015). Management practices during the observed study period (2012-2014) were used to design representative management inputs for each crop simulation.

To compare the effects of precipitation dynamics on crop yield and water use, GSAW (the sum of in-season precipitation and plant-available soil water at the start of the growing season) over the 30 year period was used to identify dry and wet years (Figure S17). Years where growing season precipitation was less than the 25th percentile (507.4 mm) were consider dry and those with more than the 75th percentile (706.6 mm) were considered wet (Figure S18). Frequency distributions were calculated for each output representing dry and wet years and compared across the crops.

Results

SALUS Model Optimization and Validation

Following optimization, SALUS estimates of yield, soil moisture content, drainage, and runoff were all within acceptable limits. Tables S12 – S14 summarize the simulation results for each of the three crop types for both optimization (2012 – 2013) and validation (2014) periods, respectively. Shallow SHF values for maize, switchgrass, and miscanthus were 0.80, 0.77, and 0.90, respectively. Optimized Ksat values for maize increased two orders of magnitude relative to initial values throughout the soil profile. Optimized values in for switchgrass increased much less throughout the profile with an exceptional increase of three orders of magnitude in the top layer. Optimized values for miscanthus increased one order of magnitude throughout the soil profile.

SALUS simulated yield was similar but somewhat higher than the observed yield (Figure 2.2). RMSE values considering optimization datasets for maize, switchgrass, and miscanthus yield were 9.7, 1.3, and 3.5 T/ha, respectively. While simulated maize yield was consistently higher than the observed, the discrepancy with switchgrass and miscanthus occurred primarily in the lower yielding drought year. Miscanthus also showed a notably lower simulated range in yield (2.96 T/ha) relative to the observed 9.11 T/ha (Table S15).

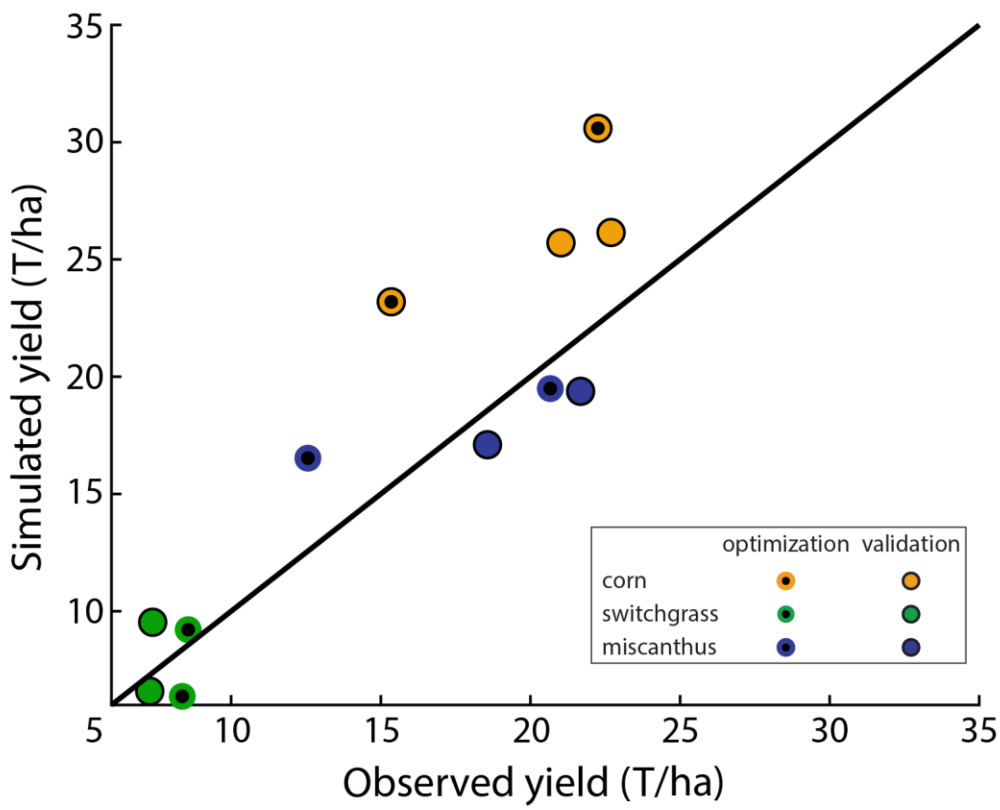

Figure 2.2 – Observed and simulated yield: Observed and SALUS simulated yield (T/ha) for 2011 to 2014. A one-to-one line is shown for reference. Points from the optimization period are shown with a black dot and points from the validation are shown with a black outline. 2011 results are also shown for reference.

Following optimization, SALUS also provided reasonable estimates of volumetric soil water content at 20 and 65 cm (Figure 2.3 and S15). Daily errors in SWC (calculated as RMSE) at 20 cm were small: 0.05, 0.04, and 0.05 for maize, switchgrass, and miscanthus, respectively; RMSE values at 65 cm were similar at 0.04, 0.03, and 0.03. Importantly, SALUS was able to capture key changes in soil moisture content following end-of-season or large in-season precipitation events.

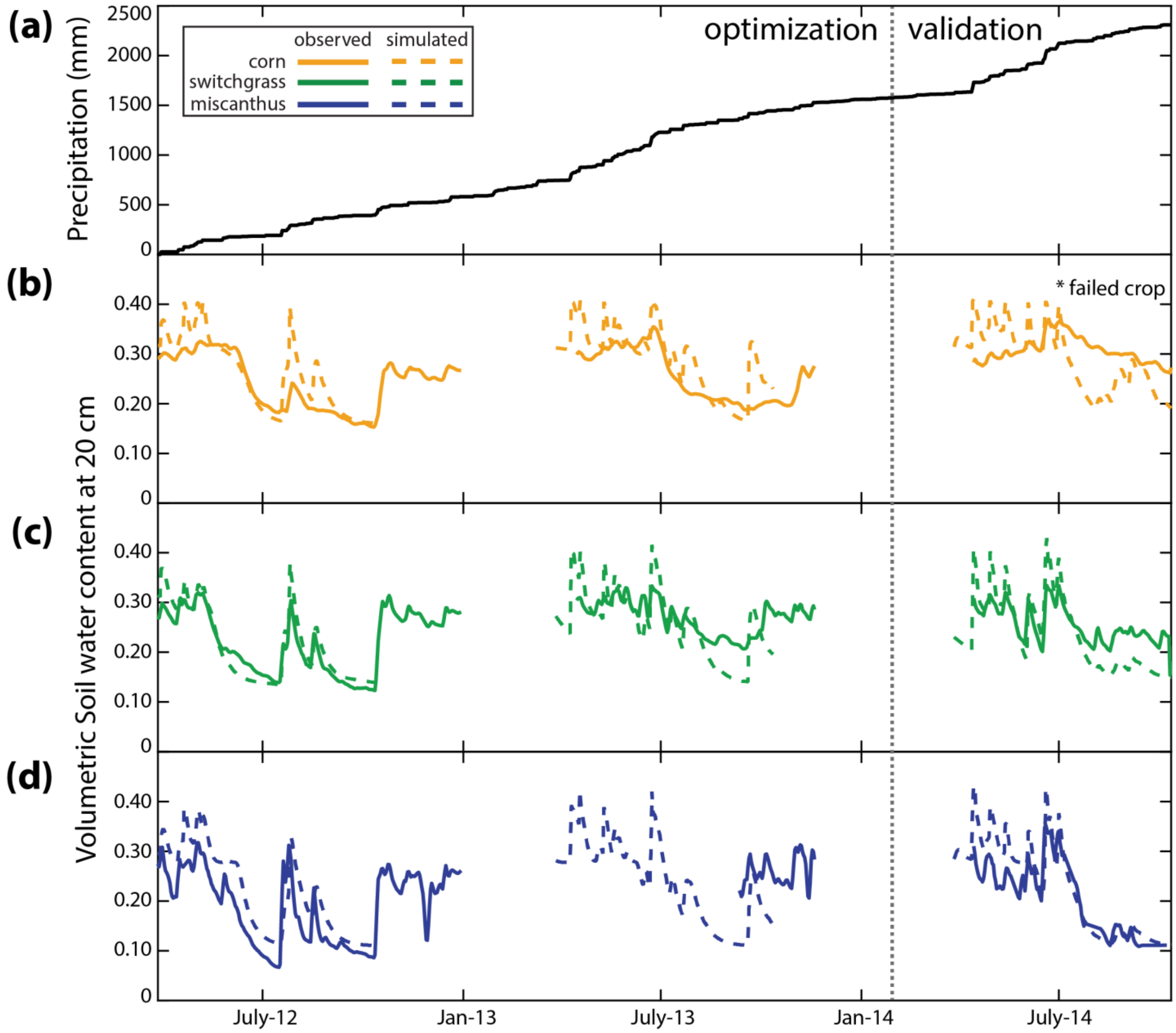

Figure 2.3 – Observed and simulated soil moisture: a) Cumulative daily precipitation (mm) data and observed (solid) and SALUS simulated (dashed) volumetric SWC at 20 cm for the 2012 to 2014 growing seasons in **b)** maize, **c)** switchgrass, and **d)** miscanthus plots. 2012 and 2013 were used in optimization and2014 was used as validation. Note that the maize crop used in the experiment failed in 2014. Data from a duplicate maize were used in simulation design and validation.

SALUS simulated drainage compared well to observed drainage for maize and miscanthus, but was lower for switchgrass (Figure S16). RMSE values following optimization for maize, switchgrass, and miscanthus were 82.1, 362.0, and 181.6 (mm), respectively. Simulated runoff compared well to observed runoff in all plots (Table S14). RMSE values following optimization for maize, switchgrass, and miscanthus were 11.8, 0.57, and 0.08, respectively.

30-year Climate Experiment

Following the successful site-scale optimization and validation of the SALUS models for each of the three crops, we can now apply these models to understand how the crops might respond to a much broader range of climate conditions. Here we conduct a continuous 30-year experiment using the historical weather data from 1985 – 2014, with management conditions similar to those during our field experiment (detailed above).

In the continuous 30-year simulation, the yield for maize was significantly higher than in the switchgrass and miscanthus plots (Figure 2.4). Yield was highest in the wet years with a maximum maize yield of 28.6 T/ha. Maximum yield for switchgrass and miscanthus was 9.5 and 14.3, respectively. The approximate ranges in simulated yield for maize (25–30 T/ha) and switchgrass (5–10 T/ha) were similar between the optimization and 30-year simulations. Miscanthus yields in the 30-year simulations (10–15 T/ha) were notably lower than in the validation simulation (15-20 T/ha). The difference in yield between wet and dry years was also greatest in maize. Average maize yield in wet years was 25.8 T/ha while dry years average was 23.5 T/ha. In contrast, average yield in wet and dry years in switchgrass and miscanthus varied by 1.3 T/ha and 0.1 T/ha, respectively. Miscanthus yields were generally higher than for switchgrass with median wet year yields of 12.9 and 12.3 T/ha. The relationship between total GSAW and yield in all 30 years can also be seen in Figure S19.

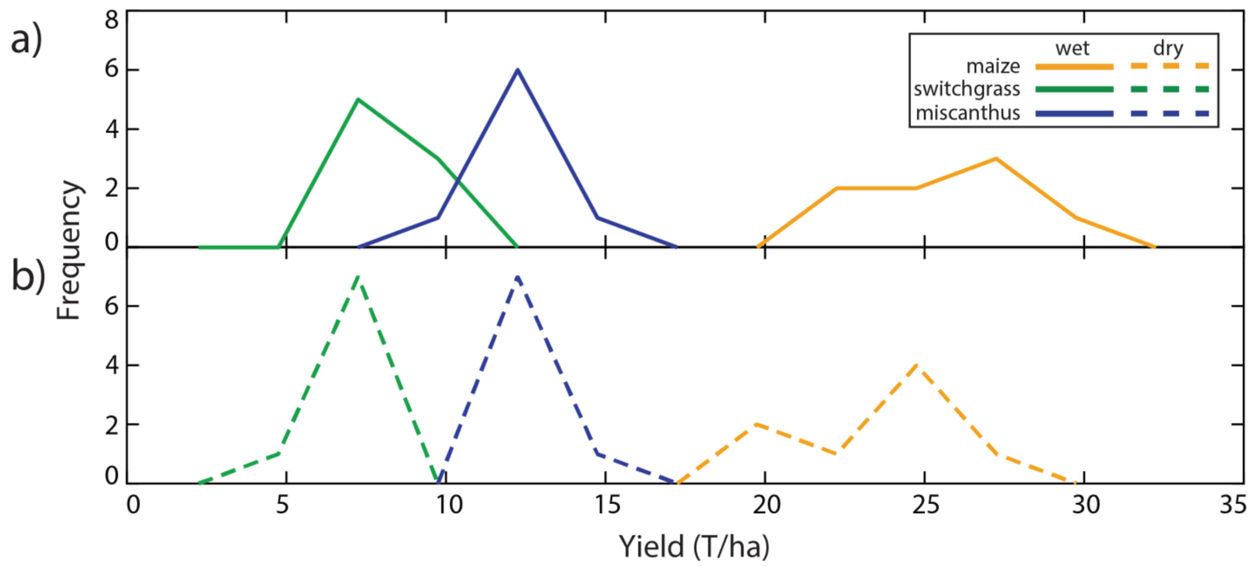

Figure 2.4 – Simulated yield: Frequency distribution of yield (T/ha) in **a)** wet (solid) and **b)** dry (dashed) years from 1985 – 2014. Wet and dry years are those with growing season precipitation above the 75th percentile and below the 25th percentile, respectively. Each group contains 8 years.

Growing season ET varied much less between the crops than yield and generally increased with increasing GSAW (Figure 2.5). Average growing season ET for maize, switchgrass, and miscanthus was 456.5, 494.5, and 468.8 mm, respectively. Despite having a lower average ET than switchgrass, miscanthus had higher rates of ET in years with higher GSAW. The portion of GSAW that went to ET (%) was significantly higher during dry years than during wet years for all crops (Figure 2.6). A greater portion of GSAW went to ET under switchgrass than maize and miscanthus in both wet and dry years. The average portion of GSAW that became ET under maize, switchgrass, and miscanthus was 53.8, 58.7, and 56.7% in wet years and 82.8, 87.5, and 81.3% in dry years.

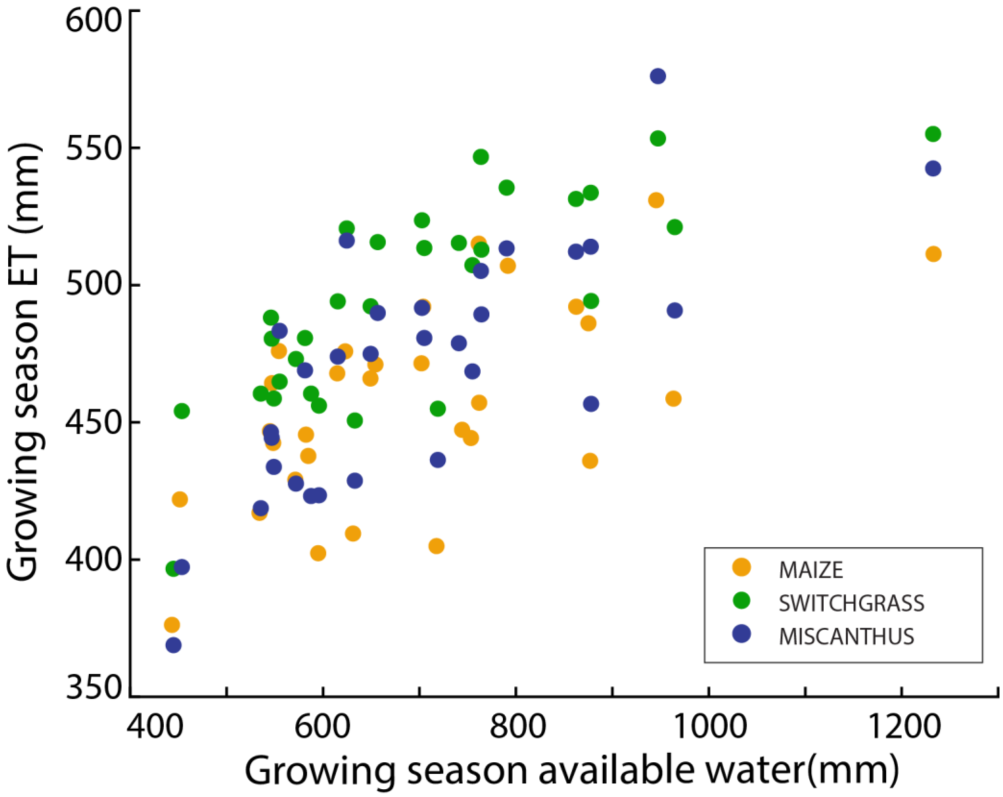

Figure 2.5 – Growing season available vs. ET: Growing Season Available Water (mm) vs. growing season ET for each year from 1985 to2014. Note that ET can be higher than growing season available precipitation due to soil moisture storage at the start of the growing season. The three years of miscanthus growing season ET between 600 and 800 mm GSAW and significantly lower than the trend are associated with a failed crop within the simulation in those years (see GSAW vs. yield; Figure S19)

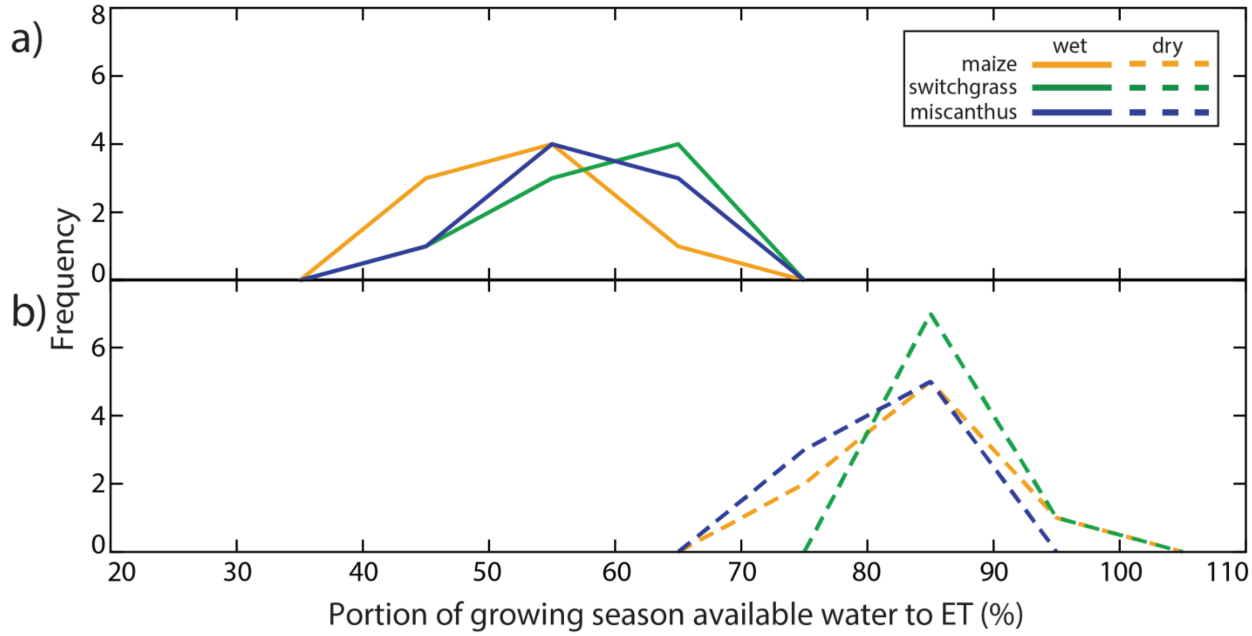

Figure 2.6 – Simulated ET: Frequency distribution of the ratio of precipitation to ET in **a)** wet (solid) and **b)** dry (dashed) years from 1985 to 2014.

WUE closely followed yield and was significantly higher for maize than switchgrass and miscanthus (Figure 2.7). The average WUE across all years was 55, 16, and 26 for maize, miscanthus, and switchgrass. Maize WUE ranged from a minimum of 47 to a maximum of 64 kg/ha/mm. Maize and switchgrass showed almost no different in WUE between wet and dry years while miscanthus had a consistently higher average WUE in dry years (29 kg/ha/mm) than in wet years (24 kg/ha/mm).

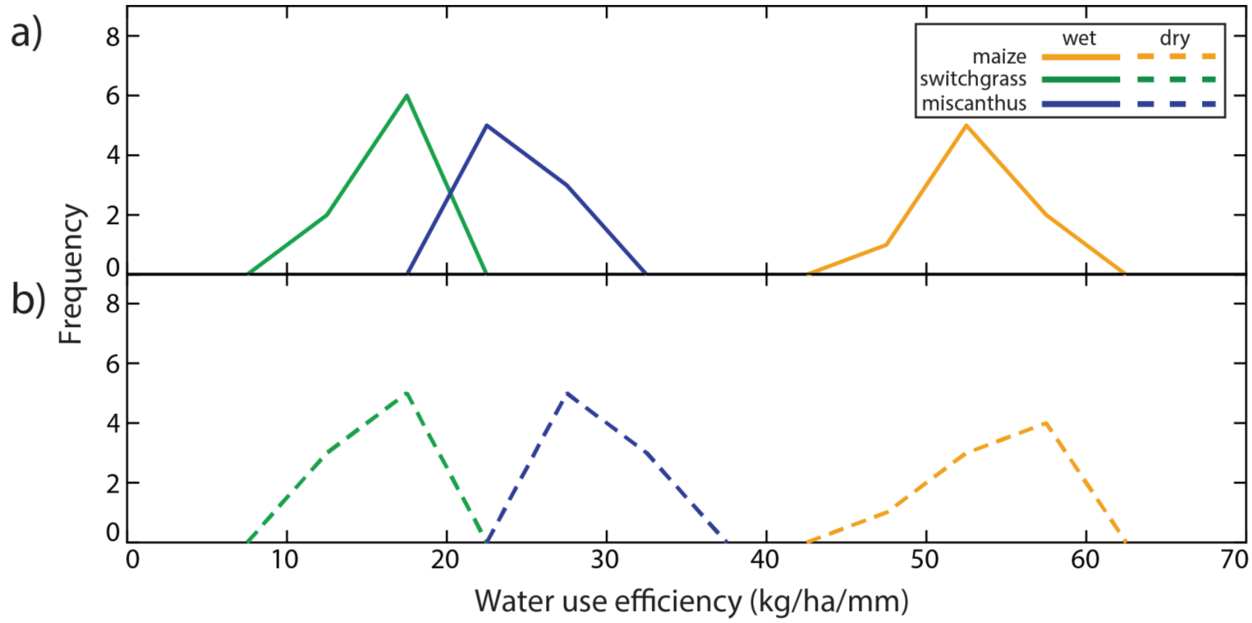

Figure 2.7 – Simulated water use efficiency: Frequency distribution of 1985-2014 Water Use Efficiency in **a)** wet (solid) and **b)** dry (dashed) years from 1985 – 2014.

Conclusion

There is a need to increase production of cellulosic over conventional biofuel crops to develop sustainable and economical sources renewable energy (Bonsch et al, 2016). This will require an understanding of not only the relationship between available water, crop water use, and crop production among the leading crops, but also how this relationship may be affected by a changing climate. The results of the 30-year climate simulation provide insights into how crop yield and the accompanying water use will respond in wet and dry conditions.

The two-year optimization consisted of a drought year followed by an average year. This likely contributed to the yield and soil-water dynamics as the optimized SHF profile with depth showed a unique response for each crop (Table S12). Notably, miscanthus SHF in the shallow (0-75 cm) layer optimized at 0.90 while maize and switchgrass in the same layer optimized to 0.80 and 0.77, respectively. This is consistent with published work describing miscanthus tendency to conserve a shallower roots mass relative to other crops (Mann et al., 2013). Greater root development deeper in the profile during the 2012 drought could have enabled increased water use in 2013, leading to higher yields than were observed. Furthermore, the simulated SWC at 20 cm in 2012 is a better fit with the observations in 2013. The simulated rate of soil-water depletion in 2013 is greater than the observed values, which may have also contributed to simulated yield greater than observed.

Maize consistently had the highest yields in the climate analysis with miscanthus and switchgrass following in descending order. However, simulated yield showed discrepancies that likely transferred to the climate analysis. Along with higher overall yields, maize also showed the greatest differences in both wet and dry year yields. This difference was also present in ET, leading to a relatively constant WUE values through time. This contradicts the suggestion that ET will have lower variability than yield and WUE will then be driven by yield (Basso and Ritchie, 2012). However, the higher yield and consistent ET in Basso and Ritchie was the result of improved management practices while management in this study remained constant. The results of the climate analysis also differ from those in VanLoocke et al. (2012) with lower WUE for miscanthus than maize. Both of these differences may be due to the approach of simulating miscanthus yield and its response to wet and dry conditions within the simulation. However, the WUE results agree with those of Abraha et al. (2016) in showing a generally constant WUE across years for the various crops.

The highest yields were seen in maize, a conventional crop, but they were also the most sensitive to changes in precipitation with a decrease of 2.3 T/ha in dry years. Of the two cellulosic crops, miscanthus had slightly higher yields and was more consistent between wet and dry years with average yields of 12.6 and 12.5, respectively. Again, this may be due to the simulation not capturing enough sensitivity to increased precipitation in miscanthus and providing unrealistically low yields.

In addition to sufficient yields, sustainable biofuel crop production will require consideration of the resulting changes to the water balance (Mathioudakis et al., 2017). The portion of GSAW that went to ET showed a distinct difference between wet and dry conditions. While the relative portion of GSAW to ET between the crops was similar in wet and dry conditions, approximately 30% more GSAW went to ET in dry years than in wet years for all crops. This suggests that changes to the water balance within conventional and cellulosic biofuel cropping systems will be driven more by variability in climate than a change in crop production. Lower variability in growing season ET than in yield led to a WUE with yield as the major determinant. This finding agrees with much of the published literature on the relationship between precipitation and WUE (Basso and Ritchie, 2012; Abraha et al., 2015; Hamilton et al., 2015; Robertson et al., 2017). An exception to this was miscanthus which showed a slightly higher WUE in dry years than wet.

Water demand for developing biofuel cropping systems represents one of the many challenges to future water supplies. The goal set by the RFS to produce 136 billion L of renewable biofuel includes annually by 2022 includes 60 billion liters to come specifically from cellulosic crops. Consideration of the amount of biomass produced, the land type being used to grow it, and the amount of water used is needed in order to develop sustainable cropping systems. Climate change will likely have an important effect on the relationship between these parameters as global precipitation patterns change. Crop models have proven useful tool in investigating the relationship between precipitation, yield, and water use. SALUS model simulations were developed and optimized using observed data within experimental plots for maize, switchgrass, and miscanthus. 30-year climate simulation was then used to analyze yield, portion of growing season available water to ET, and water use efficiency across wet and dry years. The results presented here suggest that maize will have the highest yields of the leading crops, but also could have decreased yields in response to dry conditions. Furthermore, the variability in portion of available water going to ET was generally low across the crops. However, a much greater portion of available water did go to ET in dry years relative to wet years in all crops suggesting that climate may be greater driver of changes to the water balance that crop type.

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