TWO-WAY INTERACTIONS BETWEEN

BIOENERGY CROPPNG SYSTEMS AND WATER

RESOURCES

By

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Abstract: Understanding the two-way interactions between bioenergy cropping systems and water resources is imperative for the successful deployment of these crops in the US Southern Great Plains (SGP); however, such information is limited in the region. This study was conducted (i) to quantify and compare water budget components under switchgrass, biomass sorghum, and mixed perennial grasses in Oklahoma; (ii) to partition evapotranspiration (ET) components and determine the water use efficiency (WUE) of these cropping systems; and (iii) to model watershed scale hydrological impacts of switchgrass biomass production on grasslands versus marginal croplands. Soil water content was measured regularly from 2011 to 2013 at two locations, and ET was estimated using the soil water balance approach. The ET was partitioned by measuring canopy interception and estimating soil evaporation. Transpiration was calculated as the difference. WUE was estimated as the ratio of above-ground biomass produced to ET and transpiration. The Soil and Water Assessment Tool (SWAT) was used for the watershed-scale study. The result showed that soil water depletion occurred mainly above 2 m under all crops considered. The total growing season soil water depletion varied from 4 to 287 mm depending on the initial soil water content and growing season rainfall. Crop year ET also varied from 493 to 846 mm and was greater for perennial grasses than biomass sorghum except during a wet year when the two systems had similar ET. Transpiration was the largest component of growing season ET for all cropping systems. The non-productive loss portion of ET was greater for biomass sorghum than switchgrass, but biomass sorghum had higher WUE than switchgrass, which compensated for its higher non-productive losses. SWAT simulated average switchgrass yield of 12 Mg ha^{-1} on grasslands and marginal croplands along with an increase in ET and reduction in streamflow relative to the baseline scenario. The hydrologic cost per ton of biomass production is predicted to be approximately five times greater for grasslands than marginal croplands. In the SGP, rainfed bioenergy production system based on biomass sorghum may consume less water per unit land area than systems based on perennial grasses, but the non-productive losses and other ecosystem services need to be considered. From a hydrologic perspective, it may be preferable to convert marginal croplands to switchgrass production rather than converting existing grasslands.

TABLE OF CONTENTS

Chapter   Page

LIST OF TABLES

Chapter II

Chapter III

Chapter IV

LIST OF FIGURES

Chapter II

Chapter III

CHAPTER I

INTRODUCTION

Background

Modern society is highly dependent on energy. Our major energy sources at the moment, such as petroleum, natural gas, and coal, are non-renewable, and they are being depleted day by day. In addition, these energy sources are also major sources of environmental pollution. As a result of increasing concerns about environmental pollution and energy security, societies have begun looking for renewable energy sources which are environmentally safe. Bioenergy, renewable energy obtained from biological sources, is one such candidate.

The global production of biofuel (i.e. liquid bioenergy fuel) has grown from 132 million gallons per day in 2000 to 797 million gallons per day in 2011. The US share of world ethanol production also increased from 34% at the start of the new millennium to 51% in 2011. This amount of ethanol is the equivalent of 9.6% of the gasoline consumed in 2011 in the US (US Energy Information Administration, 2014). The US has a goal of producing more than 36 billion gallons of biofuels annually by 2022 (Sissine, 2007). US biofuel production was 13.3 billion gallons in 2013 (Renewable Fuel Association, 2013) primarily as ethanol from corn grain. However, corn-based ethanol is capped at 15 billion

gallons by 2015, and future increases in biofuel production are expected to come mostly from cellulosic feedstock (Johnson et al., 2007). The USDA estimates that of the 36 billion gallons of biofuel projected to be produced in 2022, about 13.4 billion gallons are expected to come from dedicated energy crops, which include perennial grasses, energy cane, and biomass sorghum (USDA, 2010).

The US Southern Great Plains (SGP) has potential for biofuel feedstock production due to the region's long growing season and availability of land (USDA, 2010). In Oklahoma, a variety of cellulosic bioenergy crops have been studied for their potential as dedicated biofuel feedstocks. These crops include switchgrass (*Panicum virgatum* L.), mixed perennial grasses (switchgrass and other perennial grass species in various ratios), and biomass sorghum (*Sorghum bicolar* L. Moench). Foster (2013) evaluated the effect of nitrogen and cropping system on biomass yield and quality of these bioenergy crops for the state of Oklahoma. In addition, he investigated the spatial variability of biomass yield, soil carbon, and nitrogen in a switchgrass field. Similarly, by measuring net ecosystem exchange of CO_2 and H_2O using eddy covariance systems, Wagle (2013) quantified and examined the seasonal variation in net ecosystem exchange, evapotranspiration, and ecosystem water use efficiency over switchgrass and biomass sorghum. This dissertation is a continuation of these research efforts to investigate the potential of bioenergy feedstock production in Oklahoma by focusing on the interactions of these crops with water resources.

Although it is widely recognized that water plays a crucial role in the biofuel industry, much uncertainty remains at the nexus between bioenergy cropping systems and water resources. Availability of water is one of the major factors that determine the

sustainability of dedicated biofuel feedstock in the SGP, and large scale production of bioenergy crops in this region may have significant impacts on water resources (Dale et al., 2011; Berndes, 2002). Therefore, it is important to understand the interaction between bioenergy cropping systems and water resources, since the two systems are inseparable.

Biofuel production requires a substantial amount of water during both feedstock production and industrial processing. The predominant portion of this water is used for feedstock production, and the amount is dependent on the type of feedstock used, and on geographic and climatic variables. For example, Dominguez-Faus et al. (2009) found that the land and water required to produce 1 L of ethanol from grain sorghum was higher than that for sugar cane, sugar beet, switchgrass, or corn grain. Similarly, to produce from irrigated grain sorghum enough ethanol for driving one mile would require 90 gallons of water for sorghum grown in Nebraska and 115 gallons for sorghum grown in Texas. This variability complicates quantification and comparison of water utilization by different bioenergy crops over different regions and time scales. Hence, it is important to determine water utilization of bioenergy crops for each region separately for improved decisions and technical optimizations (Jørgensen and Schelde, 2001). This can be achieved by detailed analysis of the overall soil water budget and water use efficiency under bioenergy cropping systems. However, such analyses are limited in the SGP.

Different bioenergy cropping systems will have varying impacts on water and land resources, and their overall impacts on these resources depends on local conditions, including previous land use (Berndes, 2013). Land use conversions to bioenergy crop production may impact the water quality and quantity as a result of differences in water utilization among crops. For instance, McIsaac et al. (2010) showed an increase in ET of

3

104 mm yr^{-1} by miscanthus compared with maize-soybean, which could reduce the annual drainage water flow by 32% in Central Illinois. They also reported significantly high inorganic nitrogen leaching under maize-soybean as compared to switchgrass and miscanthus. Similarly, using a mechanistic multilayer canopy-root-soil model, Le et al. (2010) estimated an increased in total seasonal ET by approximately 36% when converting maize to switchgrass.

In water-limited regions, like the SGP, large scale production of bioenergy cropping systems will require selection of crops that produce high yields and use water efficiently. It is also important to identify areas where that might be most suitable to grow these crops. To reduce competition with food crops, many have suggested planting bioenergy crops on marginal lands (e.g. Graham, 1994; Tilman et al., 2006), which are currently under crop cultivation or grasslands. However, the absence of well-defined and widely used definition of marginal lands creates difficulty to identify these locations on a map, and hinders a regional scale perspective on the bioenergy-water nexus.

Objectives

The overall objective of this research is to evaluate the two-way interaction between selected candidate bioenergy crops and water resources in the SGP. The specific objectives of this dissertation are:

- Objective 1. To quantify and compare soil water dynamics and evapotranspiration under switchgrass, biomass sorghum, and mixed perennial grasses managed for biofuel production;

- Objective 2. To partition ET by switchgrass and biomass sorghum to transpiration, interception, and soil evaporation, and quantify and compare the WUE of the two cropping systems; and

- Objective 3. To estimate the switchgrass biomass production potential of grasslands and marginal croplands in north central Oklahoma, and evaluate the hydrological impacts of converting grasslands and marginal croplands to switchgrass production.

Dissertation organizations

This dissertation is organized in four chapters. Chapter one provides a general introduction and introduces the dissertation objectives. Chapter two addresses objective 1 and is organized as a manuscript titled "Soil water dynamics and evapotranspiration under annual and perennial bioenergy crops" which has been published in SSSAJ. The third chapter addresses objective 2 and is formatted as a manuscript titled "Evapotranspiration partitioning and water use efficiency of switchgrass and biomass sorghum managed for biofuel". The fourth chapter addresses objective 3 and is formatted as a manuscript titled "Grasslands versus marginal croplands for switchgrass production: modeling biomass and hydrological impacts" which is under review for possible publication in Biomass and Bioenergy. References are included at the end of each chapter.

REFERENCES

Berndes, G. 2002. Bioenergy and Water – the implications of large-scale bioenergy production for water use and supply. Global Environ Change 12:253-271.

Berndes, G. 2013. Bioenergy and water: challenges and opportunity. P. 49-61. In J.F. Dallemand and P.W. Gerbens-Leenes (ed.) Bioenergy and water. Luxembourg: Publications Office of the European Union.

Dale, V.H., K.L. Kline, L.L. Wright, R.D. Perlack, M. Downing, and R.L. Graham. 2011. Interactions among bioenergy feedstock choices, landscape dynamics, and land use. Ecol Appl 21:1039-1054.

Dominguez-Faus, R., S.E. Powers, J.G. Burken, and P.J. Alvarez. 2009. The water footprint of biofuels: A drink or drive issue? Envrion. Sci. Technol. 43:3005-3010

Foster, A.J. 2013. Remote sensing application in biomass crop production systems in Oklahoma. Doctoral dissertation, Oklahoma State University

Graham RL. 1994. An analysis of the potential land base for energy crops in the conterminous United States. Biomass Bioenergy 6:175-89.

Johnson, J.M., M.D. Coleman, R. Gesch, A. Jaradat, R. Mitchell, D. Reicosky, and W.W. Wilhelm. 2007. Biomass-bioenergy crops in the United States: A changing paradigm. Am J Plant Sci-Biotech, 1:1-28.

Jørgensen, U., and K. Schelde, 2001. Energy crop water and nutrient use

efficiency. Prepared for the International Energy Agency Bioenergy Task 17

Short Rotation Crops. Danish Institute of Agricultural Sciences. Tjele, Denmark.

Le, P.V., P. Kumar, and D.T. Drewry. 2011. Implications for the hydrological cycle

under climate change due to the expansion of bioenergy crops in the Midwestern

United States. Proc. Natl. Acad. Sci. U.S.A. 108:15085-15090

McIsaac, G.F., M.B. David, C.A. Mitchell. 2010. Miscanthus and switchgrass production

in central Illinois: impacts on the hydrology and inorganic nitrogen leaching. J.

Environ. Qual. 39:1790-1799

Renewable Fuel Association (RFA). 2013. http://www.ethanolrfa.org/pages/statistics

(accessed 7/24/2014).

Sissine, F. 2007. Energy independence and security act of 2007. RL34294. Congressional

Res. Serv, Washington, DC.

Tilman, D., J. Hill, and C. Lehman. 2006. Carbon-negative biofuels from low-input high-

diversity grassland biomass. Science 314:1598-1600

USDA, A. U. 2010. Regional roadmap to meeting the biofuel goals of the renewable

fuels standard by 2022

http://www.usda.gov/documents/USDA_Biofuels_Report_6232010.pdf (accessed

on 1/31/2014)

US Energy information Administration:

> http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm?tid=79&pid=79&aid=1
> (accessed 7/24/2014).

Wagle, P. 2013. Net ecosystem exchange of carbon dioxide and water vapor fluxes in
> switchgrass and high biomass sorghum. Doctoral dissertation, Oklahoma State
> University

CHAPTER II

SOIL WATER DYNAMICS AND EVAPOTRANSPIRATION UNDER ANNUAL AND PERENNIAL BIOENERGY CROPS

A paper published in the Soil Science Society of American Journal

ABSTRACT

Understanding soil water dynamics and evapotranspiration (ET) is imperative to predict the interactions between bioenergy cropping systems and water resources; yet measurements of these variables under bioenergy crops in the US Southern Great Plains (SGP) are limited. The objectives of this study were to quantify and compare soil water dynamics and ET under switchgrass (*Panicum virgatum* L.), biomass sorghum (*Sorghum bicolor* L. Moench), and mixed perennial grasses managed for biofuel production. Soil water content was measured from 2011 through 2013 at Stillwater, Oklahoma, and from 2012 through 2013 at Chickasha, Oklahoma, and ET was estimated using the soil water balance approach. For these crops, soil water depletion occurred mainly above the 2.0 m depth, suggesting negligible root water uptake below 2.0 m. Growing season soil water

depletion ranged from 4 to 287 mm and was greater ($\alpha = 0.10$) for sorghum than switchgrass in two out of five site years, while mixed grasses exhibited greatest soil water depletion in one out of three years. Growing season soil water depletion was positively related to initial soil water content. Crop year ET ranged from 493 to 846 mm and was greater for switchgrass than sorghum in two out of three site years. At Stillwater, average crop year ET measured over two years was 676 mm for switchgrass, 630 mm for sorghum, and 717 mm for mixed grasses. In the SGP, rainfed bioenergy production systems based on biomass sorghum may consume less water per unit land area than systems based on perennial grasses.

Abbreviations: ET, evapotranspiration; PSE, precipitation storage efficiency; SGP, Southern Great Plains

INTRODUCTION

Concerns regarding the sustainability of first generation biofuels (produced mainly from food crops) have driven research efforts to develop second generation biofuels produced from ligno-cellulosic feedstocks (Sims et al., 2010). In the US Southern Great Plains (SGP), crops being evaluated for their potential as second generation bioenergy crops include switchgrass and biomass sorghum. Many factors contributed to the selection of switchgrass as a model bioenergy crop for the region, including: high biomass production, low management requirements, adaptability to poor soils, and drought resistance (McLaughlin and Kszos, 2005). Biomass sorghum, an annual crop, is also receiving attention as a candidate bioenergy feedstock for its high biomass (Rooney et al., 2007). Mixed-species systems have also shown potential for feedstock production. Tilman et al. (2006) showed that, on marginal land, a low-input high-diversity grassland had greater bioenergy yields and was more carbon negative than a monoculture grassland. One of the major factors that must be considered when evaluating these candidate feedstocks in the SGP is the availability and use of water.

Sustainable bioenergy crop production requires a clear understanding of the dependency of these crops on the available water, as well as the potential impacts of the bioenergy crops on the hydrology and climate of the region. For example, a recent modeling study (Georgescu et al., 2011) predicted a significant local to regional cooling as a result of increased ET from the conversion of agricultural areas to perennial bioenergy crops in the central United States. Design of large scale bioenergy cropping systems in the SGP should consider possible detrimental effects on water resources, since water is already a limiting factor in the region. Drought is a recurrent feature in the SGP

(Basara et al., 2013), hence, water availability may be a major constraint on feedstock yields. In situ measurements of water balance components are needed to better understand the relationship between bioenergy crops and water availability.

The change in soil water storage (ΔS) in the root zone is a core component of the water balance, and soil water content is a major factor that limits plant growth in the SGP. Understanding differences in the ability of various biomass crops to utilize soil water may be helpful in selecting feedstocks for the region, but thus far few data are available. Monti and Zatta (2009) monitored the soil water content for the top 1.2 m of the soil profile under selected perennial and annual bioenergy crops in northern Italy for one growing season. They found that swichgrass and fiber sorghum had similar soil water content to 1 m and below that the soil water content was higher under sorghum. Soil water content monitored to 0.9 m depth in Illinois by McIsaac et al. (2010) showed that switchgrass depleted the soil water earlier in the growing season, while later in the season the depletion was greater under a maize (*Zea mays* L.) - soybean [*Glycine max* (L.) Merr.] cropping system. A mesocosm study in California (Mann et al., 2013) showed that, in the first 32 weeks after planting, switchgrass roots grew continuously into regions with available soil water while the surface soil layers became increasingly dry, suggesting a drought avoidance strategy. The switchgrass roots reached a depth of > 2 m in that time. None of these studies has identified the maximum depth of soil water uptake under switchgrass nor the soil water dynamics under switchgrass in the climate of the SGP. In addition, detailed soil water dynamics studies under mixed grasses and rainfed biomass sorghum in the SGP are lacking.

Evapotranspiraton is a dominant component of the annual water balance, so the hydrological effects of bioenergy feedstock production may be determined primarily through effects on ET. For instance, applying a hydrological model to a watershed in Iowa, Schilling et al. (2008) showed that compared to annual crops, perennial grasses would increase ET, which would reduce deep drainage and surface runoff. Similar effects were predicted for the entire upper Mississippi river basin by Wu and Liu (2012). Using eddy covariance system, Skinner and Adler (2010) obtained a four year average annual ET of 474 mm yr^{-1}, ranging from 515 to 446 mm yr^{-1}, during the establishment and early production years of switchgrass in the northeastern US. The growing season (May to September) ET values ranged from 331 to 350 mm. Wagle and Kakani (2014) observed an ET of 450 mm from May 2011 to mid-November for switchgrass one year after establishment in Oklahoma. For photoperiod-sensitive biomass sorghum, Hao et al. (2014) reported a growing season ET ranging from 230 to 260 mm under rainfed conditions at Bushland, TX. However, none of these studies allows a direct comparison of ET under switchgrass and biomass sorghum, and none provides estimates of ET from mixed grass feedstocks.

Another important component to consider for bioenergy crop production is fertilizer input. Utilizing winter legumes as a N source might reduce the need for inorganic N (Hargrove, 1986), but in water limited environments like the SGP, winter legumes may use water that could otherwise be available during the early growing season of the main crop. In prior research in the SGP, using legumes as a N source was not effective, primarily because legumes used water necessary for the main crop (Rao and Northup, 2011). Prior research on incorporating legumes was performed primarily under

annual cropping systems. Since the characteristics of annual and perennial cropping systems are different, the impact of winter legumes on the available soil water may also be different.

In this field study we evaluated the soil water balance under switchgrass, biomass sorghum, and mixed perennial grasses under two N regimes in Oklahoma. The specific objectives of this study were to quantify and compare 1) the depth and degree of soil water depletion and 2) the growing season and annual ET totals for these candidate feedstocks. The study was conducted from April 2011 to December 2013, during which time the sites experienced diverse climatic conditions, from severe drought in the 2011 growing season to above average precipitation in the 2013 growing season.

MATERIALS AND METHODS

Study area and experimental design

A plot scale study was conducted at Oklahoma State University, Efaw Research Farm (36.13^o N, 97.10^o W) near Stillwater, OK. The soil is a deep and well-drained Easpur loam (fine-loamy, mixed, superactive, thermic Fluventic Haplustoll). The area has an average (1961 – 2010) annual precipitation of 880 mm, and the average daily minimum and maximum temperatures are 8.6^oC and 21.9^oC, respectively (Oklahoma Climatological Survey, 2014). A split plot experimental design with three replications was established in May 2010. Three no-tilled cropping systems, 'Alamo' switchgrass, 'ES5200' biomass sorghum, and mixed perennial grasses were the main plots, and two N managements, 84 kg N ha^{-1} and 0 N + winter legumes were the subplots. The mixed grass

plots were seeded with 50% switchgrass, 25% 'Kaw' big bluestem (*Andropogon gerardi*
Vitman), and 25% 'Cheyenne' indiangrass [*Sorghastrum nutans* (L.) Nash]. The plots
were on flat land and were 9 m by 9 m. Every year, greening of the perennial grasses took
place between March 17 and April 16, while biomass sorghum was planted between
April 20 and May 12. Harvest of all cropping systems took place on the same date and
occurred between November 16 and December 4. In the winter legume split plots, hairy
vetch (*Vicia villosa* Roth) was planted on 23 February 2011, crimson clover (*Trifolium
incarnatum* L.) was planted on 27 February 2012, and hairy vetch was planted on 4
March 2013. For the 2011 growing season, urea ammonium nitrate (UAN) solution was
band applied to the 84 kg N ha^{-1} split plots on 23 May for the annual and perennial
cropping systems. In 2012, fertilizer was applied on 19 April for perennials and on 4 May
for the biomass sorghum. In 2013, fertilizer was applied on 30 April for the perennials
and 7 June for biomass sorghum. Sevin (Carbaryl [1-naphthyl N-methylcarbamate])
insecticide (Bayer Environmental Science, Research Triangle park, NC, USA) was used
in 2012 and 2013 growing seasons to control grasshoppers (Insecta, Orthoptera,
Caelifera) because we observed grasshopper damage in the 2011 growing season.

A field scale study was established in 2010 at the Oklahoma State University
South Central Research Station near Chickasha, OK (35.04^{o}N, 97.91^{o}W). The
predominant soil series at the site is Dale silt loam. The Dale silt loam (fine-silty, mixed,
superactive, thermic Pachic Haplustolls) is characterized by deep, well-drained soil
formed from materials weathered from loamy alluvium. The area has an average annual
precipitation of 850 mm, and the average daily minimum and maximum temperatures are
9.4^{o}C and 23.5^{o}C, respectively (Oklahoma Climatological Survey, 2014). The study

fields were established in the spring of 2010, and had an area of 8 ha for 'Alamo' switchgrass and 16 ha for 'ES5200' biomass sorghum. Greening of switchgrass occurred in the last week of March in 2012 and middle of April in 2013. Biomass sorghum was planted on 15 May 2012 and 14 May 2013. Harvest of both crops took place in mid-November. The area was fertilized within a few days after planting or greening at a rate of 84 kg N ha^{-1} for switchgrass and 112 kg N ha^{-1} for biomass sorghum.

Measurement and estimation of water budget components

A neutron moisture meter (CPN 503 HydroProbe, InstroTek Inc., Raleigh, NC) was used to measure soil water content. At Stillwater, measurements were made to a depth of 2 m in 0.2-m intervals starting from 0.1 m below the land surface. At the Chickasha site, measurements were taken to a depth of 2.6 m at the same intervals. Readings were taken every 2 weeks during the growing season and every 4 weeks during the dormant season from April 2011 to December 2013 at Stillwater and March 2012 to December 2013 at Chickasha.

At each measurement depth, soil texture was determined by the hydrometer method (Gavlak et al., 2003; Gee et al., 1986), bulk density by the core method (Grossman and Reinsch, 2002), and soil water content at -1500 kPa using a pressure plate extractor (Dane and Hopmans, 2002) (Table 2.1). For the Stillwater location, soil water retention was determined in the laboratory using Tempe cells (Soilmoisture Equipment Corp., Santa Barbra, CA) for pressures less than 100 kPa and a pressure plate extractor (Soilmoisture Equipment Corp., Santa Barbra, CA) for pressures between 100 and 1500 kPa. In addition, saturated hydraulic conductivities were measured in the laboratory using

a permeameter (Eijkelkamp-Agrisearch Equipment, Giesbeek, the Netherlands). The soil water retention data and saturated hydraulic conductivity data were used to parameterize the van Genuchten-Mualem unsaturated hydraulic conductivity function (van Genuchten, 1980) for the 1.8 to 2.0-m soil layer at Stillwater.

Rainfall data were obtained from Oklahoma Mesonet (McPherson et al., 2007) and National Oceanic and Atmospheric Administration (NOAA) stations within 500 m of both study sites. Runoff was assumed negligible due to the flat nature of both landscapes, and field visits during rainfall events provided no evidence of runoff in the study areas. Deep percolation was estimated for the Stillwater location using the Darcian method (Nimmo et al., 2005), assuming a negligible matric potential gradient at the deepest measurement depth. Percolation rates were thus numerically equivalent to the unsaturated hydraulic conductivity values associated with the soil water content data from the deepest measurement depths. Estimated unsaturated conductivity was always < 0.025 cm d^{-1} based on model estimates and observed water contents throughout the study. We found deep percolation totals of < 19 mm for each cropping system for the whole study period. These totals are smaller than the uncertainty associated with the Darcian method; thus, we did not consider deep percolation in our water balance equation for either location. Evapotranspiration was determined as the difference between precipitation and change in soil profile water storage in the root zone. Reference evapotranspiration (ET$_o$) was estimated with the FAO Penman-Monteith equation (Allen et al., 1998). Plant available water for selected layers for each measuring date was calculated as the sum across those layers of the differences between measured water contents and water contents at -1500

17

kPa. Precipitation storage efficiency (PSE) in the dormant season was calculated as the percentage of dormant season precipitation that was stored in the 2-m soil profile.

Neutron probe installation and measurement of soil water storage

Neutron probe access tubes were installed in each subplot at Stillwater. At Chickasha, four tubes per cropping system were installed in each field on east-west running transects with 30-m intervals between the tubes. Electrical metallic tubing having a nominal diameter of 1.5 inch (3.81 cm) was used as access tubing for the neutron probe. Before installation, the bottom of each tube was sealed with a welded metal cap to prevent seepage of water into the tubes. The holes for the access tubes were created using a hydraulic soil probe (#15-SCS Model GSRPS, Giddings Machine Company Inc., Windsor, CO, USA). During coring, care was taken to create holes which closely matched the outside diameter of the access tube. To create the holes, a 1-5/8 inch (4.13 cm) outer diameter Giddings sample tube was used first with a quick relief bit to create the hole and then with a reverse taper bit to clean the hole. The access tube was then pushed down the hole to the desired depth (> 2 m at Stillwater and >2.6 m at Chickasha). Extra tubing at the surface was removed leaving approximately 7 cm above the soil surface. This extra extension above the surface was small enough to not interfere with the operation of farm machines in the field, and at the same time it was large enough to hold the depth control stand (Evett et al., 2003) for the neutron probe. The top of the access tube was covered with a cap when not in use to prevent the entrance of water and other materials into the tube. Additional access tubes were installed near the boundary of the plots for calibrating the neutron probe.

Calibration of the neutron probe required a range of water content values that covered the expected range of water content under field conditions (Hignett and Evett, 2002). At the Stillwater location, calibration was completed during the summer of 2011. Since the summer of 2011 was exceptionally dry, obtaining dry conditions for calibration was easy. In order to get the wet end calibration, the area around the calibration tubes was flooded for about a month to create the wettest possible condition at the bottom of the tubes. At the Chickasha site, calibration of the dry end was made in the summer of 2012, while the wet end calibration was completed in the spring of 2013.

Calibration of the neutron probe was accomplished by comparing the neutron probe readings in the calibration tubes with the volumetric soil water content determined by subsequent soil sampling around the tubes. Two neutron probe readings were made per depth; then immediately adjacent to the calibration tubes, four intact soil samples were collected from each depth using the hydraulic soil probe. Each soil sample was cut in the field to 0.2 m in length. The soil cores were weighed and dried in the laboratory for the determination of gravimetric soil water content and bulk density. From these two parameters, volumetric soil water content was calculated. Finally, a calibration curve was developed for each depth. The slope and intercept of calibration curves from different depths were subjected to multi-comparison analysis using "aoctool" and "multcompare" functions in the Matlab Statistical Toolbox (ver. R2013b, The MathWorks, Inc.). Curves which were not significantly different were merged together. In addition, since the response of neutron probe readings at the 0.1 m depth might be affected by the air above the soil, a separate calibration curve was used for the surface layer (0 to 20 cm).

Using the calibration equations, volumetric soil water content was calculated for every reading. From the volumetric water content and its corresponding depth, the soil water storage was calculated. These bi-weekly soil water content measurements were used to calculate the soil water depletion during the growing seasons and soil water recharge during the dormant season.

Statistical analysis

At the Stillwater location, to test the effect of cropping systems and N management on the soil water dynamics and evapotranspiration, the GLIMMIX procedure in SAS 9.3 (SAS Institute, 2011) was used for each growing season and crop year. The growing seasons are from greening or planting to harvest; whereas, the crop year was from greening (planting) to greening (planting) of the next growing season. The crop years were not exactly 365 days, since the start dates were different from year to year. Crop years were numbered by the calendar year in which they began. Class values were block, cropping system, and N management. The model statement was parameter = cropping system | N management; using block (cropping system) in the random statement. The SAS GLM procedure was employed for the analysis of data from the Chickasha site treating the access tubes as replicates in a completely randomized design.

RESULTS

Table 2.2 shows the long term (50-yr.) average and study period 6 month precipitation totals at the two experiment sites. At Stillwater, April through September 2011 was the driest 6 month period since 1961, while the following 6 month period

(October 2011 through March 2012) was wetter than average. In 2012, the April through

September precipitation total was the third lowest since 1961, with only 1984 and 2011

being drier. Despite the low precipitation in the 2012 growing season, the preceding

wetter than average dormant season provided enough initial soil water to support

markedly better crop growth in 2012 than 2011. The 6 month period from October 2012

through March 2013 was the eighth driest since 1961. This dormant season drought was

followed by a wetter than average growing season in 2013. Thus, at the Stillwater site,

the study period consisted of a growing season drought in 2011, growing season drought

preceded by a wet dormant season in 2012, and dormant season drought followed by a

wet growing season in 2013. At the Chickasha site, precipitation was near the long term

average for the 2012 growing season and above the long term average for the 2013

growing season.

Soil water dynamics

At both sites two neutron probe calibration equations were developed: one for the

surface (0 to 0.2 m) and another for the subsurface (0.2 to 2.0 m at Stillwater, and 0.2 to

2.6 m at Chickasha) soil profile (Table 2.3). The slope and intercepts in these equations

were comparable to those reported in other studies (Evett et al., 2007). The observed time

series of soil water content distributions with respect to depth for the three cropping

systems during the entire study period at the Stillwater location are shown in Fig. 2.1.

For the 2011 growing season, the profile average soil water contents at greening

of the perennial grasses were 0.26 m^3 m^{-3} under switchgrass, 0.22 m^3 m^{-3} under biomass

sorghum, and 0.29 m^3 m^{-3} under mixed grasses. These differences (at $\alpha = 0.1$

significance level) in soil water content among the cropping systems might have been a carry-over effect from the 2010 growing season. Being an annual crop, biomass sorghum produced more biomass in 2010 than the perennial grasses, which were in their first year of establishment (data not shown). Mixed grasses were not well established in 2010, which allowed the soil under them to have higher soil water content than switchgrass at the beginning of 2011. In the 2011 growing season, biomass sorghum growth was poor, presumably due to lower initial soil water content and the presence of drought. Early senescence was observed in all three cropping systems in the 2011 growing season. The early senescence, combined with rainfall late in the growing season resulted in the recharge of the surface layers beginning in Oct. 2011 (Fig.2.1).

In the 2012 growing season, a profile average soil water content of 0.28 m^3 m^{-3} was observed under biomass sorghum at greening of the perennial crops, while soil water contents were 0.26 m^3 m^{-3} under mixed grasses and 0.24 m^3 m^{-3} under switchgrass. Only 2 mm of rain fell in July 2012, a month which began a string of seven consecutive months with below average precipitation. As a result, dry conditions developed throughout the root zone and persisted for approximately nine months until April 2013. The three cropping systems had similar soil water content profiles at harvesting in November 2012, each having an average soil water content of 0.15 m^3 m^{-3}, almost equal to the profile average soil water content at permanent wilting point (0.14 m^3 m^{-3}).

April 2013 began four consecutive months of above average precipitation at Stillwater during which recharge of the soil profile occurred under all three cropping systems (Fig. 2.1). However, the soil water recharge was deeper and more prolonged under biomass sorghum than under switchgrass or mixed grass. This difference was

likely due to the later start to the growing season for the annual biomass sorghum compared to the perennial grasses. Higher soil water contents under biomass sorghum persisted from July 2013 through the end of the study.

The depth profiles of soil water content for selected measurement dates in 2012 and 2013 at Chickasha are shown in Fig. 2.2. For switchgrass minimum soil water contents for each depth occurred in September, and changes in soil water content over time at depths > 2.0 m were below the root mean square error (RMSE) values of our neutron probe calibration. For biomass sorghum minimum soil water contents occurred in September at depths ≤ 0.5 m and in October or November for deeper depths. Again, changes in soil water content over time at depths > 2 m were smaller than the uncertainty of our measurements. These results suggest that biomass sorghum had greater root water uptake in September and October than switchgrass, and that root water uptake for both crops was negligible for depths > 2 m.

In order to study the plant water uptake by these crops, the plant available water (PAW) was computed by dividing the 2.0 m soil profile into three depth intervals: 0 to 0.8 m, 0.8 to 1.4 m, and 1.4 to 2.0 m (Fig. 2.3). With the exception of the beginning of the 2011 growing season, the PAW under biomass sorghum at Stillwater was equal to or greater than that under switchgrass and mixed grass. The difference was particularly obvious at depths > 0.8 m. At the Stillwater location, for the three cropping systems, PAW reached a minimum near zero to a depth of 1.4 m in August 2011 and again in August 2012, reflecting the severity of the drought conditions. Below 1.4 m the minimum PAW was 50 mm for these same time periods. This may indicate a lower root density at deeper depths.

For both sites, from the initial and harvest date soil water content values and dormant season rainfall, the total soil water depletion during the growing season and PSE of the dormant season were determined as shown in Table 2.4 for the Stillwater location and Table 2.5 for the Chickasha site. At the Stillwater location for the 2011 growing season at $\alpha = 0.1$ significance level, cropping system and cropping system x N management interaction had significant effects on soil water depletion (Table 2.4). Greater depletion was observed under mixed grass, followed by switchgrass, and finally biomass sorghum. Comparison of the effect of nitrogen within each cropping system showed a significant difference only for switchgrass where the 0 N + winter legume treatment had a higher depletion than 84 kg ha^{-1} of N treated plots. In the 2012 growing season, only cropping system showed a significant effect on soil water depletion, where higher water depletion was observed under biomass sorghum compared to the perennial grasses. In the 2013 growing season, soil water depletion was not different between the three cropping systems. At the Chickasha location in the 2012 growing season (Table 2.5), there was no significant difference in soil water depletion between switchgrass and biomass sorghum; whereas, in 2013 the biomass sorghum had greater depletion than switchgrass. These results reflect the relationship between soil water depletion and initial soil water storage, particularly at average and less than average growing season rainfall amounts. At the Stillwater location, highest initial soil water storage and greatest soil water depletion were observed under mixed grass in 2011, while in 2012, biomass sorghum had the highest initial soil water storage and the greatest soil water depletion.

The lengths of the dormant season for biomass sorghum were about a month longer than the dormant seasons of the perennial grasses for all site years. At the

24

Stillwater location in the 2011/12 dormant season, the average PSE were 0.57 for mixed grass, 0.47 for switchgrass, and 0.42 for biomass sorghum (Table 2.4). The PSE of the mixed grass was significantly greater than that of biomass sorghum. However, the PSE of the switchgrass was not significantly different compared with mixed grass or biomass sorghum. In the 2012/13 dormant season, N management and the interaction of cropping system x N management had significant effects on PSE. The PSE of the 84 kg N ha^{-1} treatment was greater than that of the 0 N + winter legume treatment across cropping systems. Within cropping systems, the PSE was higher under 84 kg N ha^{-1} than 0 N + winter legume treatment only in the case of switchgrass. The 2012/13 dormant season PSE at the Chickasha site was 0.26 by switchgrass and 0.31 by biomass sorghum (Table 2.5).

Evapotranspiration

The average daily ET rates between neutron probe readings at the Stillwater location for the entire study period are shown in Fig. 2.4. At this temporal resolution, maximum ET rates for all three cropping systems reached 7 – 8 mm d^{-1}. There was a general tendency for the perennial grasses to have higher ET rates than the biomass sorghum in April – June and for the biomass sorghum to have higher ET in July – September, although within season variation in ET rates was large. When PAW values were relatively high during the growing season, ET rates were close to ETo, e.g. June 2013. However, for much of the study, growing season ET rates were far below ETo, indicating plant water stress, particularly in the 2011 and 2012.

Total growing season ET and crop year ET are shown in Table 2.6 for Stillwater and Table 2.5 for Chickasha site. At the Stillwater location in 2011, growing season ET followed a similar statistical pattern to that of soil water depletion, with both cropping system and the cropping system x N management interaction having significant effects. Highest growing season ET was observed under mixed grass, followed by switchgrass, while biomass sorghum had the smallest ET. Among N treatments, growing season ET was different for only switchgrass, where it was lower for the 84 kg N ha^{-1} treatment than for the 0 N + winter legume treatment. In 2012, although higher soil water depletion was observed under biomass sorghum, its growing season ET was smaller than that of the perennial grasses. This was because the ET of the perennial grasses peaked in April when there was 157 mm of rainfall and the sorghum canopy had not yet developed, while the ET of the sorghum peaked in July when there was only 2 mm of rainfall. Thus, the sorghum was forced to rely more heavily upon the stored soil water. In the 2013 growing season, ET rates under all cropping systems and N management treatments were not significantly different.

Crop year ET totals at Stillwater ranged from 493 to 781 mm and were affected by both cropping system and the cropping system x N management interaction in 2011, but not in 2012. In the 2011 crop year, among N treatments, ET was different for only switchgrass, where it was lower for the 84 kg N ha^{-1} treatment than for the 0 N + winter legume treatment. Across the two complete crop years in this study, crop year ET averaged 676 mm for switchgrass, 630 for biomass sorghum, and 717 mm for the mixed grasses. The total rainfall for the 2011 crop year was 625 mm and for the 2012 crop year it was 671 mm. At the Stillwater location the ratio of crop year ET to crop year rainfall

was ≥ 1.00 for all treatments and years, except for biomass sorghum in 2011, where the ratios was 0.79 for 0 N + winter legume and 0.85 for 84 kg N ha^{-1}. The fact that these ratios were generally > 1 indicates that the soil water storage was, on the whole, decreasing from the start to the end of the study.

At the Chickasha site, growing season ET showed a similar pattern as the Stillwater site, with higher ET observed under switchgrass compared with biomass sorghum in 2012, and no significant differences in 2013 (Table 2.5). In the 2012 crop year (from March 28, 2012 to April 16, 2013) there was 836 mm of rainfall. The ratio of crop year ET to rainfall was 1.01 for switchgrass and 0.93 for biomass sorghum. Crop year ET was also significantly higher under switchgrass than under biomass sorghum in 2012.

Growing season ET under the perennial grasses was higher than under biomass sorghum, except in the 2013 growing season, when growing season ET at both sites was not statistically different across cropping systems. Crop year ET was significantly higher under perennial grasses than under biomass sorghum in two out of three site years. In the 2011 crop year at Stillwater, crop year ET under biomass sorghum was, on average, 26% less than under mixed grass and 22% less than under switchgrass. At the Stillwater location in the 2012 crop year, the ET totals during the dormant season were about 15 % of crop year ET under perennial grasses and about 33% under biomass sorghum. In 2012 at the Chickasha site, crop year ET by biomass sorghum was about 8% less than ET by switchgrass. At the Chickasha site for the same year, dormant season ET was 26% and 44% of the crop year total for switchgrass and biomass sorghum, respectively. The

differences in ET between these crops occurred mainly because the perennial grasses started transpiring before the planting of biomass sorghum.

DISCUSSION

The relatively deep soil water content measurements at Chickasha indicated that root water uptake under switchgrass and biomass sorghum occurred to a maximum depth of about 2.0 m, although these crops have been reported to have root systems that can exceed this depth (Mann et al., 2013; Weaver, 1954). For miscanthus (*Miscanthus* x *giganteus* J. M. Greef & Deuter ex Hodk. & Renvoize), another potential second generation bioenergy crop, maximum rooting depth can also exceed 2 m (Mann et al., 2013; Neukirchen et al., 1999). Despite evidence for maximum rooting depths ≥ 2 m, previous studies of soil water content under switchgrass (McIsaac et al., 2010; Monti and Zatta, 2009) and biomass sorghum (Hao et al., 2014) were restricted to depths ≤ 1.2 m. For accurate understanding of water and carbon fluxes and nutrient cycling under these crops, future experiments should include measurements spanning the full depth of the active root zone. Our result agreed well with the default maximum root depth for switchgrass of 2.2 m used in the SWAT and ALMANAC models (Kiniry et al., 2005).

Analysis of soil water content data at Stillwater indicates that carry-over effects from the prior year had a role in determining the initial soil water storage of the growing season, which was an important source of water for these crops, particularly during drier growing seasons. This implies that higher soil water storage left from the prior growing period would, in part, reduce the risk of complete crop failure due to drought. Previous

28

observations also show the importance of soil water left from the prior growing period in determining the growth condition of the next crop (Angus et al., 2001; Enloe et al., 2004). Soil water content under perennial grasses tended to be lower than that under biomass sorghum, particularly at deeper depths. These results agreed well with previous observations by Monti and Zatta (2009), who obtained similar soil water content values under switchgrass and sorghum to 1.0 m but higher soil water contents under sorghum between 1.0 to 1.2 m.

Soil water depletion and recharge patterns by switchgrass and mixed grass were similar in most of the study period, except early in the growing season of 2011 and late in the growing season of 2013 (Fig. 2.3). Growing season soil water depletion and ET by mixed grass was higher than switchgrass one in three years at Stillwater. Mixed grass had numerically higher soil water depletion and ET compared with switchgrass in the other growing seasons, too. This might be due to the difference in timing to maturity by these perennial grasses as reported by Henning (1993), where big bluestem and indiangrass green up and mature later than switchgrass.

The total crop year ET by switchgrass and mixed grasses were comparable to the ranges of annual ET values observed by Burba and Verma (2005) in north-central Oklahoma. They found an annual ET ranging from 640 to 810 mm for the tallgrass prairie. Smaller annual ET values (446 - 515 mm) were observed by Skinner and Adler (2010) for switchgrass in the northeastern USA. Burba and Verma (2005) found that 75 % of the annual ET occurred during the growing season for tallgrass prairie. In our study, 74 to 86 % of annual ET occurred during the growing seasons of perennial grasses. Wagle and Kakani (2014) reported a growing season (May to mid-November 2011) ET

of 450 mm by switchgrass at Chickasha one year after establishment using the eddy covariance method. For the same field at Chickasha, we observed a growing season ET of 629 mm in 2012 and 696 mm in 2013 (Table 2.6). The difference between our values and the observed value by Wagle and Kakani (2014) could be due to the difference in measurements techniques, weather conditions, and maturity level of switchgrass. The data from our experiments are not adequate to describe effects of stand age on soil water dynamics and ET in the perennial grasses. Further studies would be necessary to quantify those effects. In this study, the average daily ET between neutron probe readings by perennial grasses ranged from < 1 mm d^{-1} (just before harvest) to 7-8 mm d^{-1} (during active growing periods). These peak ET rates are somewhat higher than those previously reported. Wagle and Kakani (2014) reported daily ET ranged from 0.5 to 4.8 mm d^{-1} by excluding ET spikes during rainfall days and the following day after rainfall events of 5 mm or above. Burba and Verma (2005) also observed peak daily ET rates from 3.5 to 5 mm d^{-1} by tallgrass prairie.

Hao et al. (2014) reported total growing season ET values of 230 to 260 mm for biomass sorghum under non-irrigated conditions, and 489 to 517 mm at full irrigation. In our study, the growing season ET values of non-irrigated biomass sorghum (408 to 690 mm) were higher than their non-irrigated cases. This is likely because the total rainfall in our study area was greater than in the study area of Hao et al. (2014). Nonetheless, in 2013, the ET values for biomass sorghum at Stillwater and Chickasha were even higher than those at full irrigation reported by Hao et al. (2014). This might be, in part, because Hao et al. (2014) used only the top 1.2 m soil profile water content measurements to estimate ET, while we considered measurements to the 2.0-m depth.

The growing season and crop year ET values increased with increased availability of water for all cropping systems. Similarly, Hao et al. (2014) found increased seasonal ET by sorghum in Texas as water availability increased through irrigation, and Wagle and Kakani (2014) found within season increases in ET by switchgrass following significant rainfall. However, the perennial grasses and biomass sorghum demonstrated different sensitivities to the widely varying moisture conditions in this study. We observed more stable water utilization by the perennial grasses across seasons, while biomass sorghum showed a greater variability in ET from 408 mm in 2011 to 690 mm in 2013. The high ET by biomass sorghum in 2013 was accompanied with high biomass production (data not shown), which suggest the possibility of including supplemental irrigation systems as suggested by Hao et al. (2014). However, the costs and benefits of such irrigation would need to be examined with long term crop growth simulations, hydrologic modeling, and economic studies.

Finally, we observed significant differences in ET values between annual and perennial cropping systems. Three out of five site-growing seasons and two out of three site-crop years, the ET was higher under perennial grasses than biomass sorghum. This is consistent with prior model-based predictions of greater ET by perennial grasses than by annual crops used for bioenergy (e.g. Schilling et al., 2008). In addition to crop water use, many other factors (e.g. yield, feedstock quality, production costs, and other environmental impacts) should be considered when evaluating bioenergy cropping systems, but the results of these experiments add important new information to the knowledge base. One interesting result from our study was that perennial grasses and biomass sorghum had similar ET only when precipitation was above average (i.e. 2013).

31

In the season with above average precipitation, biomass sorghum had a relatively high ET rate that compensated for its shorter growing period, yielding ET totals similar to those of the perennial grasses. If ET totals for perennial grasses and biomass sorghum are similar in years with above average precipitation, and ET totals are lower for biomass sorghum in other years, then, over the long term, the average ET will be lower for biomass sorghum. Thus, our results suggest that, in the Southern Great Plains, rainfed bioenergy production systems based on biomass sorghum may consume less water per unit land area than systems based on perennial grasses.

ACKNOWLEDGMENTS

REFERENCES

Allen, R.G., L.S. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration—Guidelines for computing crop water requirements. Irrigation and Drainage Paper No. 56. FAO, Rome.

Angus, J., R. Gault, M. Peoples, M. Stapper, and A. Van Herwaarden. 2001. Soil water extraction by dryland crops, annual pastures, and lucerne in south-eastern Australia. Aust. J. Agric. Res. 52:183-192.

Basara, J.B., J.N. Maybourn, C.M. Peirano, J.E. Tate, P.J. Brown, J.D. Hoey, and B.R. Smith. 2013. Drought and associated impacts in the Great Plains of the United States—A review. International Journal of Geosciences 4:72-81.

Burba, G.G., and S.B. Verma. 2005. Seasonal and interannual variability in evapotranspiration of native tallgrass prairie and cultivated wheat ecosystems. Agr. Forest Meteorol. 135:190-201.

Dane, J.H., and J.W. Hopmans. 2002. Pressure plate extractor. p. 688-690. *In* J.H. Dane and G.C. Topp, (ed.) Methods of soil analysis. Part 4. Physical methods. SSSA Book Ser. 5. SSSA, Madison, WI.

Enloe, S.F., J.M. DiTomaso, S.B. Orloff, and D.J. Drake. 2004. Soil water dynamics differ among rangeland plant communities dominated by yellow starthistle (*Centaurea solstitialis*), annual grasses, or perennial grasses. Weed Sci. 52:929-935.

Evett, S., J. Tolk, and T. Howell. 2003. A depth control stand for improved accuracy with the neutron probe. Vadose Zone J. 2:642-649.

Evett, S., N. Ibragimov, B. Kamilov, Y. Esanbekov, M. Sarimsakov, J. Shadmanov, R. Mirhashimov, R. Musaev, T. Radjabov, and B. Muhammadiev. 2007. Neutron moisture meter calibration in six soils of Uzbekistan affected by carbonate accumulation. Vadose Zone J. 6:406-412.

Gavlak, R., D. Horneck, R.O. Miller, and J. Kotuby-Amacher. 2003. Soil, plant and water reference methods for the Western Region. 2nd ed. Western Regional Ext. Publ. 125. Colorado State Univ., Ft. Collins.

Gee, G.W., J.W. Bauder, and A. Klute. 1986. Particle-size analysis. p. 383-411. *In* A. Klute, (ed.) Methods of soil analysis. Part 1. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Georgescu, M., D.B. Lobell, and C.B. Field. 2011. Direct climate effects of perennial bioenergy crops in the United States. Proc. Natl. Acad. Sci., USA. 108:4307-4312

Grossman, R., and T. Reinsch. 2002. 2.1 Bulk Density and Linear Extensibility. p. 201-228. *In* J.H. Dane and G.C. Topp, (ed.) Methods of Soil Analysis. Part 4. Physical methods. SSSA Book Ser. 5. SSSA, Madison, WI.

Hao, B., Q. Xue, B.W. Bean, W.L. Rooney, and J.D. Becker. 2014. Biomass production, water and nitrogen use efficiency in photoperiod-sensitive sorghum in the Texas High Plains. Biomass Bioenerg. 62:108-116.

Hargrove, W. 1986. Winter legumes as a nitrogen source for no-till grain sorghum. Agron. J. 78:70-74.

Henning, J.C. 1993. Big Bluestem, Indiangrass and Switchgrass. Department of Agronomy, Campus Extension, University of Missouri, Columbia, MO.

Hignett, C., and S. Evett. 2002. Neutron thermalization. p. 501-521. *In* J.H. Dane and G.C. Topp, (ed.) Methods of soil analysis. Part 4. Physical methods. SSSA Book Ser. 5. SSSA, Madison, WI.

Kiniry, J., K. Cassida, M. Hussey, J. Muir, W. Ocumpaugh, J. Read, R. Reed, M. Sanderson, B. Venuto, and J. Williams. 2005. Switchgrass simulation by the ALMANAC model at diverse sites in the southern US. Biomass Bioenerg. 29:419-425.

Mann, J.J., J.N. Barney, G.B. Kyser, and J.M. DiTomaso. 2013. Root system dynamics of Miscanthus× giganteus and Panicum virgatum in response to rainfed and irrigated conditions in California. Bioenerg Res. 6:678-687.

McIsaac, G.F., M.B. David, and C.A. Mitchell. 2010. Miscanthus and switchgrass production in central Illinois: impacts on hydrology and inorganic nitrogen leaching. J. Environ. Qual. 39:1790-1799.

McLaughlin, S.B., and L.A. Kszos. 2005. Development of switchgrass (*Panicum virgatum*) as a bioenergy feedstock in the United States. Biomass Bioenerg. 28:515-535.

35

McPherson, R.A., C.A. Fiebrich, K.C. Crawford, R.L. Elliott, J.R. Kilby, D.L. Grimsley,
J.E. Martinez, J.B. Basara, B.G. Illston, and D.A. Morris. 2007. Statewide
monitoring of the mesoscale environment: A technical update on the Oklahoma
Mesonet. J. Atmos. Ocean. Tech. 24:301-321.

Monti, A., and A. Zatta. 2009. Root distribution and soil moisture retrieval in perennial
and annual energy crops in Northern Italy. Agric. Ecosyst. Environ. 132:252-259.

Neukirchen, D., M. Himken, J. Lammel, U. Czypionka-Krause, H.-W. Olfs. 1999. Spatial
and temporal distribution of the root system and root nutrient content on an
established *Miscanthus* crop. Eur. J. Agron. 11:301-309.

Nimmo, J.R., R.W. Healy, and D.A. Stonestrom. 2005. Aquifer recharge. *In* M. Anderson
and J. Bear, (eds.) Encyclopedia of Hydrological Sciences. Part 13. Groundwater.
ed. Wiley, Chichester, UK. 4: 2229-2246.

Oklahoma Climatological Survey. 2014. Climate Trends. Climate Facts by County.
Oklahoma Climatol. Surv., Norman.
http://climate.ok.gov/index.php/climate/category/my_county_or_town (accessed
19 Aug. 2014).

Rao, S.C., and B.K. Northup. 2011. Grass Pea (L.) as a pre-plant nitrogen source for
continuous conventionally tilled winter wheat. Crop Sci. 51:1325-1333.

Rooney, W.L., J. Blumenthal, B. Bean, and J.E. Mullet. 2007. Designing sorghum as a
dedicated bioenergy feedstock. Biofuels, Bioprod. Bioref. 1:147-157.

SAS Institue. 2011. SAS/STAT 9.3 user's guide. SAS Inst., Cary, NC

Schilling, K.E., M.K. Jha, Y.K. Zhang, P.W. Gassman, and C.F. Wolter. 2008. Impact of
land use and land cover change on the water balance of a large agricultural
watershed: Historical effects and future directions. Water Resour. Res.
44:W00A09. doi:10.1029/2007WR006644

Sims, R.E., W. Mabee, J.N. Saddler, and M. Taylor. 2010. An overview of second
generation biofuel technologies. Bioresour. Technol. 101:1570-1580.

Skinner, R.H., and P.R. Adler. 2010. Carbon dioxide and water fluxes from switchgrass
managed for bioenergy production. Agric. Ecosyst. Environ. 138:257-264.

Tilman, D., J. Hill, and C. Lehman. 2006. Carbon-negative biofuels from low-input high-
diversity grassland biomass. Science 314:1598-1600.

Van Genuchten, M.T. 1980. A closed-form equation for predicting the hydraulic
conductivity of unsaturated soils. Soil Sci. Soc. Am. J. 44:892-898.

Wagle, P., and V.G. Kakani. 2014. Growing season variability in evapotranspiration,
ecosystem water use efficiency, and energy partitioning in switchgrass.
Ecohydrol.7: 64-72.

Weaver, J.E. 1954. North American Prairie. Johnsen, Lincoln, Nebr.

Wu, Y., and S. Liu. 2012. Impacts of biofuels production alternatives on water quantity
and quality in the Iowa River Basin. Biomass Bioenerg. 36:182-191.

Table 2.1 Selected soil physical properties with depth at the two experimental sites

Depth	Sand	Clay	Silt	ρ_b[†]	θ_{wp}[¶]	ρ_b	θ_{wp}
				Stillwater, OK		Chickasha, OK	
		%		$g\ cm^{-3}$	$cm^3\ cm^{-3}$	$g\ cm^{-3}$	$cm^3\ cm^{-3}$
0 – 0.2	12	29	59	1.63	0.15	1.43	0.10
0.2 – 0.4	11	34	55	1.63	0.16	1.43	0.12
0.4 – 0.6	12	35	53	1.67	0.14	1.39	0.13
0.6 – 0.8	17	32	51	1.60	0.13	1.35	0.08
0.8 – 1.0	29	27	44	1.63	0.11	1.29	0.06
1.0 – 1.2	29	26	45	1.60	0.12	1.39	0.07
1.2 – 1.4	22	28	50	1.54	0.13	1.40	0.08
1.4 – 1.6	16	27	57	1.45	0.13	1.41	0.10
1.6 – 2.0	10	32	58	1.53	0.16	1.40	0.09
2.0 – 2.2						1.39	0.10
2.2 – 2.4						1.37	0.08
2.4 – 2.6						1.37	0.12

† Bulk density

¶ Volumetric water content at -1500 kPa

Table 2.2 Long term (1961 to 2010) average and study period 6 month precipitation totals at Stillwater and Chickasha, OK.

	Stillwater, OK				Chickasha, OK		
	Long term	2011	2012	2013	Long term	2012	2013
	mm						
Apr - Sept	575	316	346	664	530	508	714
Oct - Mar	304	368	178		311	196	

Table 2.3 Calibration equations for converting the neutron probe count ratio (CR) to volumetric soil water content (θ) for the surface and subsurface soil profiles at Stillwater, OK and Chickasha, OK.

location	Soil layers	Calibration equation	R^2	RMSE
	m			$m^3 m^{-3}$
Stillwater	0 – 0.2	$\theta = 0.256 * CR - 0.116$	0.99	0.010
Stillwater	0.2 – 2.0	$\theta = 0.221 * CR - 0.089$	0.85	0.032
Chickasha	0 – 0.2	$\theta = 0.247 * CR - 0.076$	0.99	0.013
Chickasha	0.2 – 2.6	$\theta = 0.228* CR - 0.064$	0.77	0.037

Table 2.4 Stillwater site soil water depletion during the growing season and precipitation storage efficiency (PSE) during the dormant season under switchgrass (SWG), biomass sorghum (BMS), and mixed perennial grasses (MXG) with two different N managements; and results of ANOVA showing the p-values on the main effects and their interactions for each year from SAS GLIMMIX procedure for split plot analysis.

			Growing season soil water depletion			Dormant season PSE	
Effects	Crop	Nitrogen	2011	2012	2013	2011/12	2012/13
			――――――― mm ―――――――			―― fraction――	
	SWG	0 N + Winter leg.	164 a[†]	160	4	0.43	0.48 b
		84 kg ha^{-1}	113 b	208	128	0.51	0.78 a
		Mean	*139 B*	*184 B*	*66*	*0.47 AB*	*0.63*
	BMS	0 N + Winter leg.	19	283	93	0.36	0.57
		84 kg ha^{-1}	96	287	79	0.47	0.69
		Mean	*58 C*	*285 A*	*86*	*0.42 B*	*0.63*
	MXG	0 N + Winter leg.	197	209	73	0.62	0.59
		84 kg ha^{-1}	181	225	94	0.52	0.52
		Mean	*189 A*	*217 B*	*84*	*0.57 A*	*0.56*
					ANOVA		
Crop			0.0605	0.0406	ns	0.0526	ns
N			ns	ns	ns	ns	0.0611
Crop*N			0.0451	ns	ns	ns	0.0742

† In the same column, different upper case letters represent significant differences among cropping systems and different lower case letters represent significant differences between N managements within a cropping system at $\alpha = 0.1$.

Table 2.5 Chickasha site growing season soil water depletion and growing season evapotranspiration, 2012 crop year evapotranspiration , and 2012/13 dormant season precipitation storage efficiency (PSE); and the results of ANOVA showing the p-values for the effect of cropping system.

Effects	Crop	Soil water depletion		PSE	Growing season ET		Crop year ET
		2012	2013	2012/13	2012	2013	2012
		mm		fraction	mm		
	SWG	84	28 B†	0.26	629 A	696	846 A
	BMS	111	178 A	0.31	432 B	687	775 B
				ANOVA			
Crop		ns	0.0004	ns	<0.0001	ns	0.0853

† In the same column, different upper case letters represent significant differences between cropping systems at $\alpha = 0.1$.

Table 2.6 Stillwater site growing season evapotranspiration (ET) and crop year ET under switchgrass (SWG), biomass sorghum (BMS), and mixed perennial grasses (MXG) with two different N managements; and the result of ANOVA showing the p-values on the main effects and interactions for each year from SAS GLIMMIX procedure for split plot analysis.

Effects	Crop	Nitrogen	Growing season ET			Crop year ET	
			2011	2012	2013	2011	2012
			——— mm ———			—— fraction——	
	SWG	0 N + Winter leg.	572 a[†]	569	662	695 a	706
		84 kg ha^{-1}	521 b	616	786	627 b	674
		Mean	*547 B*	*593 A*	*724*	*661 A*	*690*
	BMS	0 N + Winter leg.	370	500	696	493	781
		84 kg ha^{-1}	446	504	683	530	717
		Mean	*408 C*	*502 B*	*690*	*512 B*	*749*
	MXG	0 N + Winter leg.	604	617	731	688	726
		84 kg ha^{-1}	588	634	752	692	760
		Mean	*596 A*	*626 A*	*742*	*690 A*	*747*
			ANOVA				
Crop			0.0172	0.0209	ns	0.0111	ns
N			ns	ns	ns	ns	ns
Crop*N			0.0471	ns	ns	0.0863	ns

† In the same column, different upper case letters represent significant differences among cropping systems and different lower case letters represent significant differences between N managements within a cropping system at $\alpha = 0.1$.
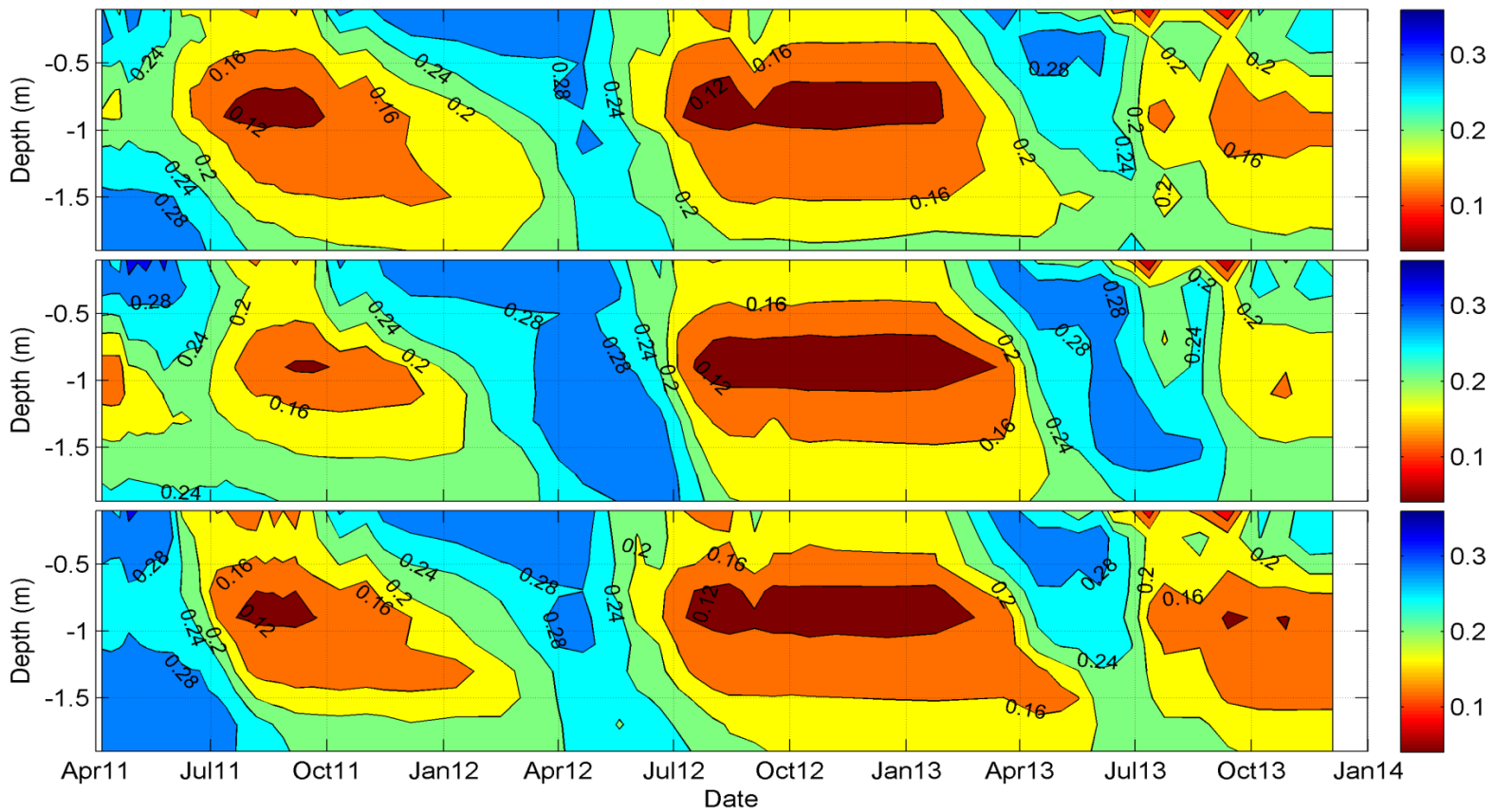
Fig. 2.1 Soil water content distribution (θ) with respect to depth throughout the study period under switchgrass (top), biomass sorghum (middle), and mixed perennial grasses (bottom) at the Stillwater experiment site.
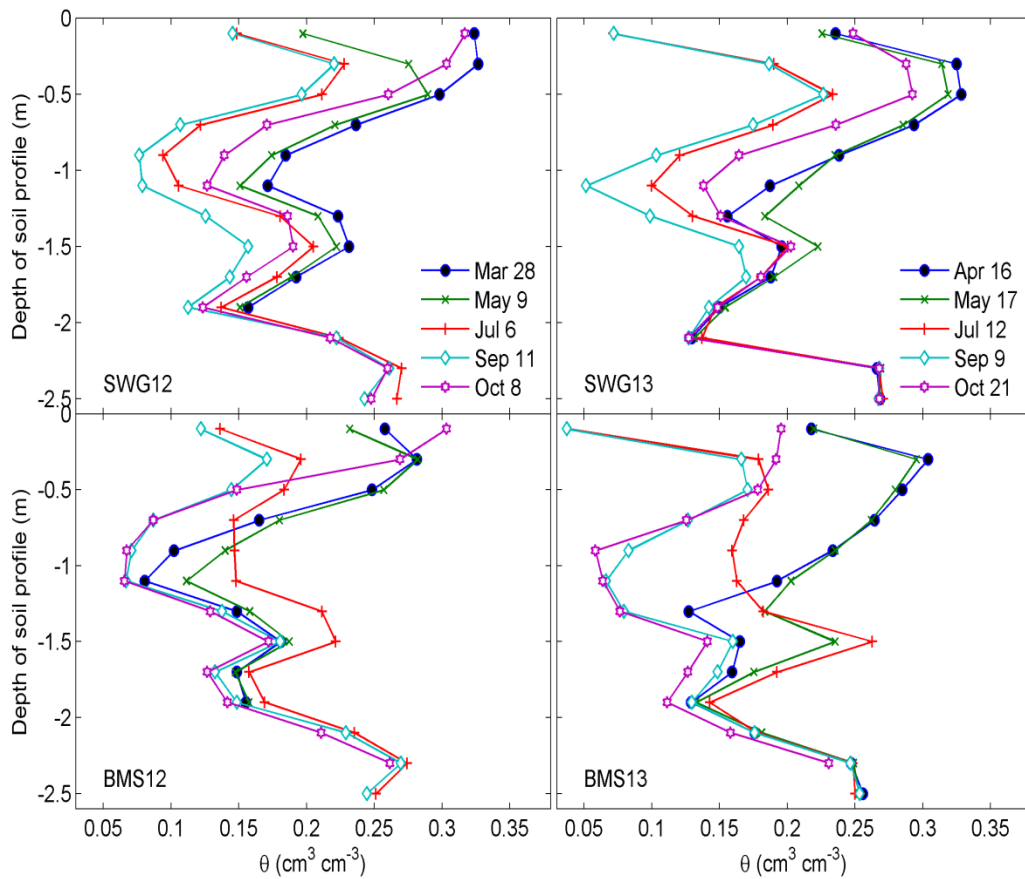
Fig. 2.2 Soil water content (θ) distribution with depth for selected dates under switchgrass (SWG) and biomass sorghum (BMS) during the 2012 and 2013 growing season at the Chickasha site.
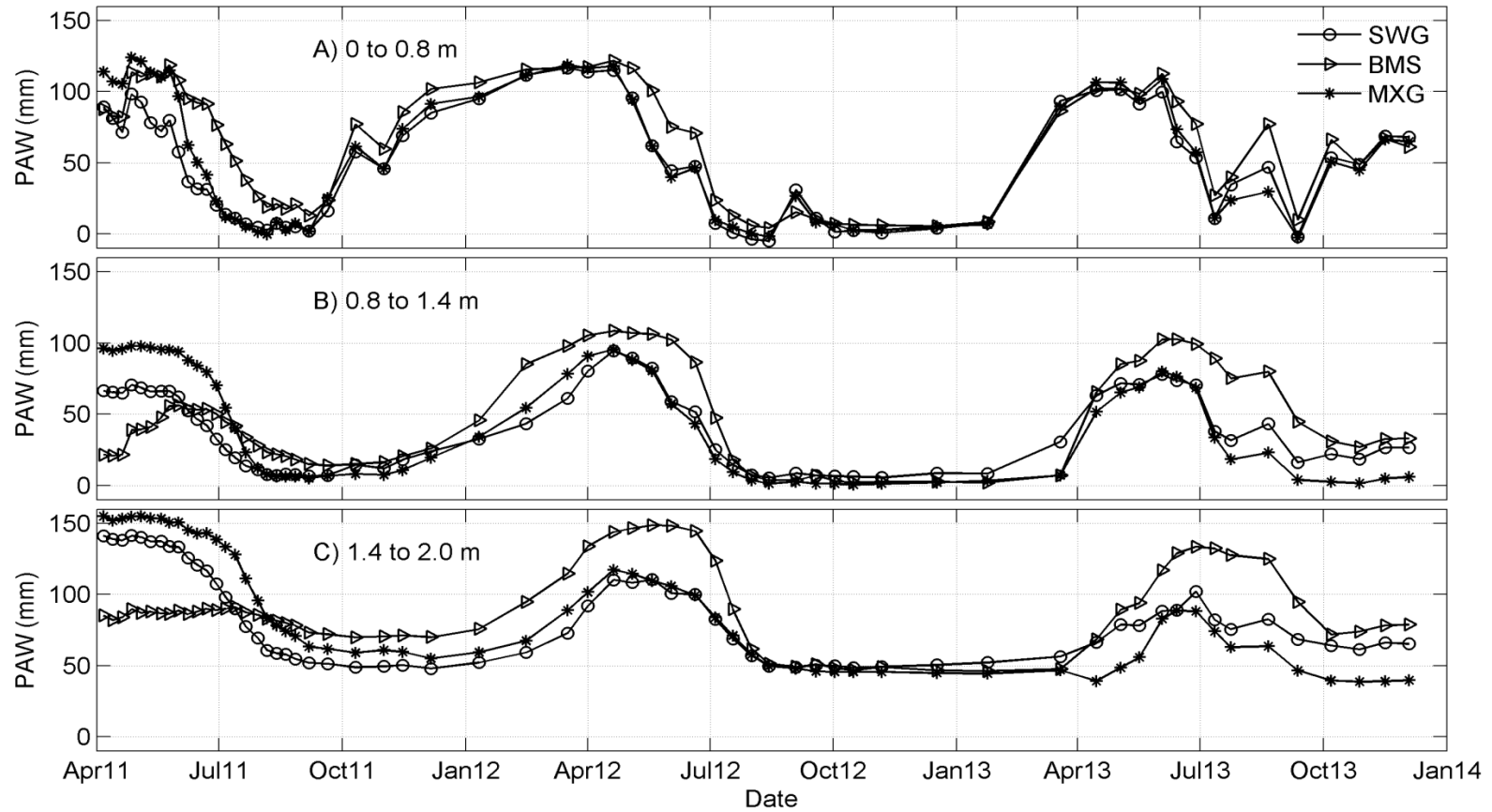
Fig. 2.3 Average plant available water (PAW) for 0 to 0.8 m (a), 0.8 to 1.4 m (b), and 1.4 to 2.0 m (c) during the study period under switchgrass (SWG), biomass sorghum (BMS), and mixed perennial grasses (MXG) at Stillwater, OK.
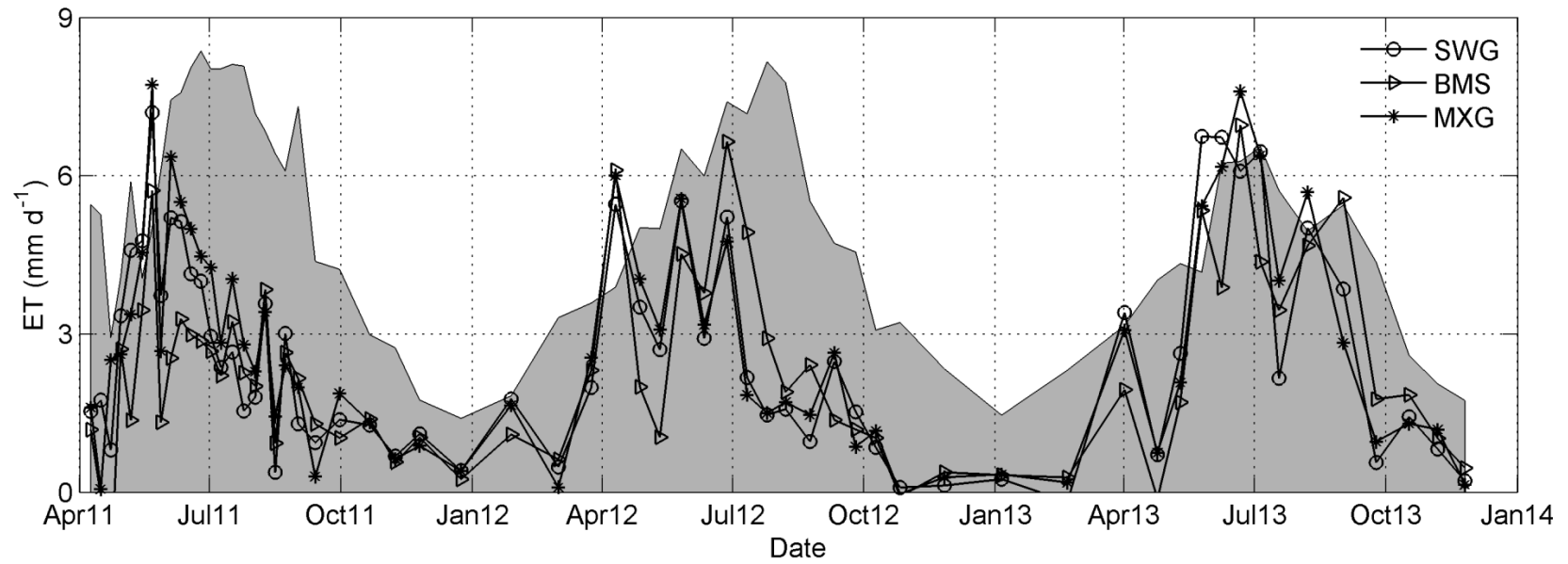
Fig. 2.4 Reference evapotranspiration (shaded region) and average actual evapotranspiration (ET) during the study period under switchgrass (SWG), biomass sorghum (BMS), and mixed perennial grasses (MXG) at Stillwater, OK.

CHAPTER III

EVAPOTRANSPIRATION PARTITIONING AND WATER USE EFFICIENCY

OF SWITCHGRASS AND BIOMASS SORGHUM MANAGED FOR BIOFUEL

Yohannes Tadesse Yima, Tyson E. Ochsner, and Vijaya Gopal Kakani

ABSTRACT

Switchgrass (*Panicum virgatum* L.) and biomass sorghum (*Sorghum bicolor* L. Moench) are two candidate bioenergy crops for the US Southern Great Plains (SGP) region. In this water-limited region, there is a need to partition evapotranspiration (ET) and to determine the water use efficiency (WUE) of these potential feedstocks. Both crops were grown in a field plot experiment at Stillwater, OK. Soil water content measurements were made by neutron probe every two weeks to a depth of 2.0 m in 0.2-m intervals over the course of three growing seasons. Growing season ET was estimated as the difference between growing season precipitation and change in root zone soil water storage. Evapotranspiration was partitioned by measuring canopy interception using interception trays, and estimating soil evaporation using the FAO-56 dual crop coefficient method. Transpiration was calculated as ET minus soil evaporation and canopy interception. Transpiration was the largest component of ET; however, soil evaporation and canopy

interception accounted for 28% of growing season ET for switchgrass and 42% for biomass sorghum. Although the non-productive losses were greater from biomass sorghum, WUE values of 9.5 – 48.7 kg ha^{-1} mm^{-1} based on ET and 22.1 – 83.1 kg ha^{-1} mm^{-1} based on transpiration were observed for biomass sorghum, which were greater than the WUE values of switchgrass, 8.3 – 21.2 kg ha^{-1} mm^{-1} based on ET and 11.7 – 27.6 kg ha^{-1} mm^{-1} based on transpiration. These results demonstrate that biomass sorghum is a candidate feedstock with potential to achieve greater WUE than switchgrass at this location; however, other factors such as economics and ecosystem services should also be considered.

Abbreviations: ET, evapotranspiration; E_S, soil evaporation; WUE_{ET}, evapotranspiration water use efficiency; WUE_T, transpiration water use efficiency; SGP, Southern Great Plains

INTRODUCTION

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

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

biomass yield to transpiration and to find ways to maximize productive water use by minimizing non-productive losses.

The interception component of ET is the amount of rainfall (or irrigation) retained by and evaporated from the plant canopy and plant residue. Interception can significantly reduce the amount of water reaching the soil surface for infiltration; therefore, it is important to consider interception separately from total ET (Savenije, 2004). The majority of studies on interception have been concentrated on tree species, and only a limited number of reports are available for grasses and row crops. Gilliam et al. (1987) reported a mean interception of 38% of growing season rainfall for unburned tallgrass prairies and 19% for annually burned tallgrass prairies in Kansas. For switchgrass in England, Finch et al. (2004) observed a growing season rainfall interception of 54% in 2002 and 47% in 2003, but their study considered only rainfall events of ≤ 10 mm. A study of rainfall interception by another candidate bioenergy crop, miscanthus (*Miscanthus x giganteus*), was performed by Finch and Riche (2010), and they found an interception loss of ~25% of growing season rainfall. Clearly rainfall interception can be a significant component of ET, but we are not aware of any published reports on interception by switchgrass or biomass sorghum managed as bioenergy feedstocks.

Another significant non-productive loss of soil water occurs through soil evaporation, which can account for 20 to 30% of growing season ET for annual crops (Allen, 2011). Garfalo and Rinaldi (2013) estimated 10 to 44% of seasonal water use being lost as soil evaporation under biomass sorghum. They used the ratio of the intercept and slope of the linear regression between ET and above-ground dry biomass as their estimate of soil evaporation. These relatively large soil evaporation values highlight the

importance of accurately quantifying this component of ET for accurate representation of the soil water balance. However, we are not aware of any other detailed studies on soil water evaporation under switchgrass or biomass sorghum.

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

Water use efficiency (WUE), the ratio of carbon assimilated or biomass produced to the amount of water used, is an important indicator which can be used to evaluate how efficiently bioenergy crops utilize available water. The WUE can be defined based on carbon dioxide assimilation, above-ground biomass, or crop yield; and the water consumption can be represented as transpiration, ET, or total water input for the system. Moreover, the time scale for calculating WUE can be instantaneous, daily, or seasonal (Sinclair et al., 1984). In part because of these varying definitions, previous studies on the WUE of switchgrass have produced a wide range of results. Byrd and May (2000) estimated values ranging between 43 to 85 kg ha^{-1} of total biomass (root plus shoot) per mm of water transpired in an outdoor pot experiment for different cultivars of switchgrass grown under varying water and N regimes. Xu et al. (2006) determined the

WUE of switchgrass seedlings in a growth chamber. They calculated the WUE as total biomass per mm of water transpired and found values of 52.4 kg ha^{-1} mm^{-1} for dry and 54.6 kg ha^{-1} mm^{-1} for wet conditions. They also found values of 14.5 and 18.4 kg ha^{-1} of shoot (i.e. above-ground) biomass per mm of water transpired in dry and wet conditions, respectively. Kiniry et al. (2008) simulated WUE values for switchgrass between 30 and 50 kg ha^{-1} of above-ground biomass per mm of water transpired using the ALMANAC model, significantly higher than the values estimated by Xu et al. (2006). From the above mentioned WUE studies, it is evident that the range of reported values for switchgrass WUE is wide and the WUE on an above-ground biomass basis is particularly uncertain.

The majority of studies on the WUE of sorghum cultivars have focused on yield response to different irrigation amount and frequencies. Aishah et al. (2011) calculated the WUE of forage sorghum in their study of yield response to salinity and irrigation frequencies in Malaysia. They obtained values ranging between 58.8 and 68.8 kg ha^{-1} of dry forage yield per mm of water applied through irrigation. Saeed and El-Nadi (1998), working in Sudan, reported WUE values from 65 to 86 kg ha^{-1} of dry forage yield per mm of ET. Garofalo and Rinaldi (2013), in a Mediterranean environment, reported WUE values of biomass sorghum between 40 and 85 kg ha^{-1} mm^{-1} at different irrigation regimes. In Texas, Hao et al. (2014) reported WUE values at different irrigation levels for photoperiod-sensitive sorghum ranging from 30 to 47 kg ha^{-1} of above-ground dry biomass per mm of ET. There are limited reports on WUE values for biomass sorghum under rainfed conditions, and we are not aware of any prior estimates of WUE for biomass sorghum based on transpiration.

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

MATERIALS AND METHODS

Study site and experimental design

A plot scale study was conducted from 2010 through 2013 at the Oklahoma State University, Efaw Research Farm (36.13° N, 97.10° W) near Stillwater, OK. The soil is a deep and well-drained Easpur loam (fine-loamy, mixed, superactive, thermic Fluventic Haplustoll). The area has an average annual precipitation of 880 mm, and the average daily minimum and maximum temperatures are 8.6°C and 21.9°C (Oklahoma Climatological Survey, 2014). 'Alamo' switchgrass and 'ES5200' biomass sorghum were established in the spring of 2010 in a randomized complete block design with three replications. The study period comprises three growing seasons from 2011 to 2013. Growing seasons are from greening of switchgrass or planting of biomass sorghum to harvest. Greening of switchgrass occurred between mid-March and mid-April, while biomass sorghum was planted between April 20 and May 12. Harvest of both crops occurred between November 16 and December 4. Urea ammonium nitrate (UAN)

solution was applied in a band at a rate of 84 kg N ha^{-1} to all plots. Additional soil and

agronomic information for the site was reported by Yimam et al. (2014).

Measurement and estimation of ET components

Growing season ET was determined from 2011 to 2013 using the soil water

balance approach based on measurements of precipitation and change in soil water

storage in the root zone. Soil water storage to 2-m depth was determined every two weeks

during the growing season using neutron probe measurements (CPN 503 HydroProbe,

InstroTek Inc., Raleigh, NC) in 0.2-m intervals. Precipitation data were obtained from a

nearby Oklahoma Mesonet station (McPherson et al., 2007) and a nearby National

Oceanic and Atmospheric Administration (NOAA) station. For our study site, from 2011-

2013, Yimam et al. (2014) estimated deep drainage totals of less than 1% of total

precipitation by using the Darcian method of deep drainage estimation (Nimmo et al.,

2005) and assuming a unit gradient at the bottom of the root zone. In addition, using the

online version of Water Erosion Prediction Project (WEPP) (Frankenberger et al., 2011),

average annual runoff for the study site was estimated to be less than 2% of average

annual precipitation (data not shown). Hence, in this study deep drainage and runoff were

assumed to be negligible. Growing season ET was determined as the difference between

growing season precipitation and change in profile soil water storage in the root zone

between greening and harvest for switchgrass and between planting and harvest for

biomass sorghum.

The interception component measured in this study was canopy interception.

Residue interception was not measured. These crops were grown and managed for

biofuel feedstock production, and during harvest the majority of above-ground biomass was collected, thus residue accumulation was limited. Finch et al. (2004) observed negligible stem flow for switchgrass with values usually < 1% of the total rainfall. Hence, stem flow was not measured in this study. Measurements of throughfall were collected using interception trays. The interception tray design of Brye et al. (2000) was used in this study with some modifications. Loaf pans 305 mm in length, 114 mm in width, and 64 mm in depth (#NLP-12, Winco, Lodi, NJ) were used as interception trays. The interior of each tray was covered, just below the top of the tray wall, with thin styrene foam to reduce evaporation. The styrene foam was fixed to the interior wall of the tray with a gentle slope, leaving only a small space at one end for the water to drain into the bottom of the tray. Above the styrene foam, wire mesh with 6 mm square openings was added to reduce the entrance of litter into the tray. Three trays were placed in each plot to account for spatial variability. The throughfall collected in the trays was measured using a measuring cylinder within 18 hours of each rain event (Brye et al., 2000). Canopy interception was estimated by subtracting throughfall from precipitation.

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

$r^2 = 0.47$ for biomass sorghum) were created to gap fill missing throughfall measurements. The averages of the four largest interception estimates for each crop were used as the interception estimates for rainfall events > 30 mm. For rainfall events of < 2 mm, the rainfall was multiplied by canopy cover (measurements described below) to estimate interception. During the 2011 to 2013 growing seasons, the percentage of rainfall which fell during events with totals < 2 mm was 3%, while 51% of the precipitation fell during events with totals of 2 – 30 mm, and 46% fell in events with totals > 30 mm.

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

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

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

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

where K_{cb} is the basal crop coefficient, $K_{c\ max}$ is the maximum value of K_c following rain or irrigation, K_r is a dimensionless evaporation reduction coefficient [0-1], and f_{ew} is the fraction of the soil surface from which most of the evaporation occurs. As defined in the

FAO-56 dual crop coefficient model, f_{ew} is the fraction of the soil surface that is exposed both to drying and wetting events near the time of solar noon (Allen et al., 1998).

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

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

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

where θ_{FC} and θ_{WP} are the volumetric water content in $m^3\ m^{-3}$ at field capacity and permanent wilting point, respectively, and Z_e is the thickness of the effective surface layer that is dried by evaporation. In this study, Z_e was set equal to 150 mm.

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

$$REW = 20 - 0.15Sa \text{ for } Sa > 80 \tag{4a}$$

$$REW = 11 - 0.06Cl \text{ for } Cl > 50 \tag{4b}$$

$$REW = 8 + 0.08 \, Cl \text{ for } Sa < 80 \text{ and } Cl < 50 \tag{4c}$$

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

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

$$K_{c \, max} = \max\left(\left\{1.2 + [0.04(u_2 - 2) - 0.004(RH_{min} - 45)]\left(\frac{h}{3}\right)^{0.3}\right\}, \, \{K_{cb} + 0.05\}\right) \tag{5}$$

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

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

$$K_r = \min\left[\frac{TEW - D_{e,i-1}}{TEW - REW}, 1.0\right] \tag{6}$$

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

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

$$D_{e,i} = \min\left\{D_{e,i-1} - [(1 - f_b) * P_i + f_b * P_{i+1}] + \frac{E_i}{f_{ew}}, \text{TEW}\right\} \qquad [7]$$

where $D_{e,i-1}$ and $D_{e,i}$ are the cumulative depletion at the end of time step i-1 and i, P_i and

P_{i+1} are the precipitation on date i and i+1, f_b is the fraction of precipitation during a day

that contributes to soil evaporation during the same day (0.5 was used for this study), and

E_i is soil evaporation during day i.

To determine green canopy cover and total canopy cover (i.e. 1- f_{ew}), we used

digital images taken vertically downward at about 1-m height above the canopy. Four

images per plot were taken every two weeks during the growing season. The pictures

were analyzed using SamplePoint software (Booth et al., 2006) to estimate the percentage

of green canopy and total canopy cover. All other calculations were performed in Matlab

(R2013b, The MathWorks, Inc., Natick, MA, USA) including linear interpolation of

green canopy cover, f_{ew}, and crop height to allow continuous daily soil evaporation

estimates.

Calculation of WUE

Several previous WUE studies for switchgrass defined WUE as mg of total

biomass produced (both shoot and root) per g of water transpired. But for our purposes,

we are interested in the harvestable biomass only. Hence, in this study, calculations of

WUE were made using kg ha^{-1} of above-ground dry biomass per mm of ET (WUE$_{ET}$) and

also per mm of transpiration (WUE$_T$). Subsamples of biomass harvested at the center of

the plots were oven dried at ~70°C to determine the above-ground dry biomass per ha.

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

RESULTS AND DISCUSSION

Weather

Monthly anomalies of air temperature and precipitation relative to 50-yr means for the site reflect the diverse weather conditions during the study period (Fig. 3.1). Monthly average air temperatures were above the long-term means for June–August 2011 and March–July 2012. In contrast, April 2013 was colder than the long-term mean. At Stillwater, the long term (50-yrs.) annual average precipitation is 880 mm. The annual precipitation was 590 mm in 2011, 572 mm in 2012, and 918 mm in 2013. The study period included severe growing season drought in 2011, with precipitation below average March–October. There was also a growing season drought in 2012 with precipitation below average May–December, but the impact of this drought was moderated by above average precipitation in the preceding dormant season (February–April). Growing conditions were most favorable in 2013 with above average precipitation April–July.

Canopy Cover and Biomass

There was great year-to-year variation in the amount and timing of canopy cover (Fig. 3.2). In the 2011 growing season, switchgrass had good early growth (>90% cover in June) despite limited rainfall because of relatively high initial plant available water. The maximum canopy cover for biomass sorghum in 2011 was only 70% because of the severe drought and low plant available water at planting (Yimam, et al., 2014). In 2012, switchgrass showed rapid early growth with >95% cover in April due to adequate water availability and above average temperature. Biomass sorghum reached >90% cover in June and had about two months delay relative to switchgrass to reach the maximum cover. In 2011 and 2012, drought induced senescence was observed in both crops beginning in July. In 2013, 100% canopy cover was observed by June for switchgrass and July for biomass sorghum. Water was not a limiting factor in 2013, hence senescence of switchgrass was not observed until late September. We did not measure cover of biomass sorghum after August 2013 because the plants were >3 m in height, and we assumed 100% canopy cover. In summary, there was greater year-to-year variation in the timing of canopy development for switchgrass than for biomass sorghum, but there was greater year-to-year variation in the maximum canopy cover for biomass sorghum than for switchgrass. These differences in amount and timing of canopy cover impacted the ET components (see section 3.3).

Due to the severe drought in 2011, switchgrass and biomass sorghum yields were low, ~ 4.3 Mg ha^{-1} and were not significantly different. Under moderate drought in 2012 yields were higher, ~ 13 Mg ha^{-1} and again not significantly different between cropping systems. However, with good growing conditions in 2013, yield of biomass sorghum was much greater than that of switchgrass (Table 3.1). Biomass sorghum produced an above-

ground dry biomass of 32.5 Mg ha^{-1}, while switchgrass produced only 14.4 Mg ha^{-1}. The maximum yield of biomass sorghum in this study was higher than the yield reported by Hao et al. (2014), who obtained a maximum yield of 24 Mg ha^{-1} under full irrigation in west Texas where the growing season rainfall was between 78 and 227 mm. However, our maximum yield of biomass sorghum was within the range of 18 to 41 Mg ha^{-1} reported by Garofalo and Rinaldi (2013) for different irrigation regimes in a Mediterranean environment. These results show that yield of biomass sorghum was strongly influenced by seasonal water supply, which is consistent with previous observations (Hao et al., 2014; Garofalo and Rinaldi, 2013).

In contrast, switchgrass yield was not as sensitive to water availability. This finding is consistent with those of Wullschleger et al. (2010). They found no strong correlation between yield and growing season precipitation totals for either upland or lowland switchgrass ecotypes, although growing season precipitation totals <600 mm did appear to limit maximum potential yield. The timing of rainfall, however, may play a critical role in determining switchgrass yield. Although growing season rainfall was nearly identical for switchgrass in 2011 and 2012 (Table 3.1), March and April precipitation totaled only 61 mm in 2011 but 254 mm in 2012. This greater early season rainfall in 2012 contributed to switchgrass above-ground dry biomass being ~9 Mg ha^{-1} greater in 2012 than in 2011. Similarly, Lee and Boe (2005) found that early growing season precipitation amount explained >90% of the variation in biomass production for switchgrass in South Dakota. Our switchgrass yields in 2012 and 2013 were within the range of yields reported by Fuentes and Taliaferro. (2002), who observed average Alamo switchgrass yields of 12.8 Mg ha^{-1} at Chickasha, OK and 17 Mg ha^{-1} at Haskell, OK.

Evapotranspiration components

Growing season ET ranged from 521 to 786 mm for switchgrass and from 446 to 683 mm for biomass sorghum (Table 3.2). Total growing season ET varied significantly with year and cropping system, but not with the interactions. The ET was significantly greater for switchgrass than biomass sorghum in 2011 and 2012 growing seasons; whereas, it was similar in 2013, when rainfall was above average. Likewise, Yimam et al. (2014) observed similar ET by annual and perennial bioenergy crops only when rainfall was above average. The ET data presented here are a subset of the data from Yimam et al. (2014). Our growing season ET values for switchgrass were relatively higher than 480 to 610 mm of growing season ET for tallgrass prairie in north-central Oklahoma (Burba and Verma, 2005). The difference might be due to the 84 kg N ha^{-1} input in our experiment. Garofalo and Rinaldi (2013) reported growing season ET of 566 to 891 mm for irrigated biomass sorghum in Southern Italy, which was greater than our growing season ET values for biomass sorghum grown solely under rainfed conditions. Our results were within or greater than the range of 324 to 517 mm growing season ET reported by Hao et al. (2014) for irrigated biomass sorghum in Texas, where the growing season rainfall ranged from 78 to 227 mm.

Time series of ET components for switchgrass and biomass sorghum during the three growing seasons are shown in Fig. 3.3. Transpiration was the predominant component of growing season ET with totals ranging from 366 to 546 mm for switchgrass and from 181 to 417 mm for biomass sorghum (Table 3.2). Kiniry et al. (2008) simulated switchgrass transpiration values ranging from 290 to 399 mm using the ALMANAC model for four locations in the central US, a range which was exceeded by

the 2012 and 2013 switchgrass transpiration totals in our study. We are not aware of any attempts to estimate growing season transpiration in a field experimental setting for switchgrass and biomass sorghum using the soil water budget and evapotranspiration partitioning approaches. In our study, we observed transpiration to ET ratios ranging from 0.70 to 0.76 for switchgrass and from 0.40 to 0.70 for biomass sorghum indicating that the non-productive losses from biomass sorghum were higher than from switchgrass. During the growing seasons interception was greater than soil evaporation for both crops, except in 2011 for biomass sorghum, which failed to exceed 70% canopy cover. Moreover, the differences between interception and soil evaporation were greater for switchgrass than biomass.

The difference in non-productive losses between switchgrass and biomass sorghum was mainly due to soil evaporation (E_s), even though it was the smallest component of ET. Growing season soil evaporation ranged from 28 to 69 mm for switchgrass and from 53 to 153 mm for biomass sorghum and was significantly higher under biomass sorghum compared with switchgrass each season (Table 3.2). The E_s/ ET ratio for switchgrass ranged from 0.05 to 0.09, while for biomass sorghum it ranged from 0.11 to 0.34. Le et al. (2011) used a simulation model to estimate ET partitioning for switchgrass and predicted that soil evaporation would account for 6% of the total ET, an estimate consistent with ours. For biomass sorghum, Garofalo and Rinaldi (2013) estimated 10 to 44% of seasonal water use being lost as E_s, and our results fall in that range

Most of the soil evaporation was observed during the early growing season, when percent canopy cover was relatively low and energy was available for evaporation at the

soil surface (Fig 3.3). After canopy cover reached 80%, soil evaporation was minimal. This result is consistent with many other studies which have shown the importance of canopy cover in determining the amount of soil evaporation during the growing season (e.g. Denmead et al., 1996; Todd et al., 1991; Wang and Liu, 2007). For switchgrass, the percentage of total growing season soil evaporation which occurred during the first month after greening was 39% in 2011, 72% in 2012, and 83% in 2013. For biomass sorghum, the percentage of total growing season soil evaporation which occurred during the first month after planting was 62% in 2011, 73% in 2012, and 80% in 2013. These differences across the years mainly depended on crop growth conditions, canopy development, and surface moisture conditions.

Growing season interception losses ranged from 103 to 171 mm for switchgrass and from 99 to 160 mm for biomass sorghum (Table 3.2). Since switchgrass canopy cover developed earlier than that of biomass sorghum, the amount of canopy interception by switchgrass was greater than that of biomass sorghum two out of three growing seasons (Table 3.2). The percentage of growing season rainfall intercepted by switchgrass ranged from 25 to 31%, and biomass sorghum intercepted 27 to 45% of growing season rainfall. The switchgrass interception in our study was greater than the 66 mm predicted in the simulations of Le et al. (2011) but similar to the results of Finch and Riche (2010), who reported interception loss of 24 to 25% for miscanthus in England. For rainfall events of less than 10 mm, Finch et al. (2004) observed 47 to 54% of the precipitation being intercepted by switchgrass. Similarly, we found 43 to 51 % of rainfall intercepted by switchgrass for rainfall amounts of less than 10 mm. These relatively high percentages are expected because the smaller the rainfall event, the larger the percentage lost to

interception (Thurow et al., 1987). We are not aware of any prior reports of rainfall interception for biomass sorghum. Bui and Box (1992) demonstrated that stem flow can be high for grain sorghum, and biomass sorghum may also have generated stem flow which was not measured in this study. If so, then our interception estimates for biomass sorghum may be somewhat inflated.

Evapotranspiration and Transpiration Water Use Efficiencies (WUE$_{ET}$ and WUE$_{T}$)

The seasonal WUE expressed as above-ground dry biomass per unit ET (WUE$_{ET}$) ranged from 8.3 to 21.2 kg ha^{-1} mm^{-1} for switchgrass and from 9.5 to 48.7 kg ha^{-1} mm^{-1} for biomass sorghum (Fig. 3.4). Seasonal WUE expressed as above-ground dry biomass per unit transpiration (WUE$_{T}$) ranged from 11.7 to 27.6 kg ha^{-1} mm^{-1} for switchgrass and from 22.1 to 83.1 kg ha^{-1} mm^{-1} for biomass sorghum (Fig. 3.4). The difference between WUE$_{ET}$ and WUE$_{T}$ was due to the non-productive losses (interception and soil evaporation). Since the non-productive losses from biomass sorghum were higher than from switchgrass, we observed a larger difference between WUE$_{ET}$ and WUE$_{T}$ for biomass sorghum than for switchgrass.

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

The difference in WUE values within a cropping system among years was mainly due to the influence of climatic conditions on ET, transpiration, and especially on biomass production. Switchgrass had significantly smaller WUE_{ET} and WUE_T in 2011 compared with 2012 and 2013. However, there was no significant difference in WUE values between 2012 and 2013. In 2011, switchgrass was in its 2nd year of establishment; hence, it may have allocated a relatively large portion of assimilated carbon to its roots; whereas, in 2012 and 2013, the switchgrass stand had reached maturity and may have reduced the share of assimilated carbon allocated to the root system. This reduction of root to shoot ratio for switchgrass as it matures was reviewed by Zegada-Lizarazu et al. (2012).

The WUE values of biomass sorghum differed significantly among years where the largest value was observed in 2013 and smallest values in 2011. In 2011, a partial crop failure due to the severe drought impacted the yield of biomass sorghum whereas in 2013, the area received above average rainfall resulting in greater biomass yield (Table 3.1). Greater water availability in 2013 may also have favored above-ground biomass production over root growth; higher temperatures in 2011 and 2012 may have resulted in higher respiration, which could have reduced biomass production; and a lower vapor pressure deficit in 2013 may also have contributed to the increased WUE. Still, the greater WUE for biomass sorghum in 2013 than in 2011 or 2012 was mainly due to the significant increase in above-ground biomass rather than reduction of evapotranspiration or transpiration. Increased WUE due to increase in biomass as opposed to reduction in water use has also been observed by previous researchers (e.g. Koshi et al., 1982; Hendrickson et al., 2013; Hao et al., 2014).

The WUE_{ET} values in this study for switchgrass (8.3 to 21.2 kg ha^{-1} mm^{-1}) were higher than the results of Koshi et al. (1982), who reported values between 3 to 8 kg ha^{-1} mm^{-1} for different harvest and water regimes. In that study under dryland conditions in Big Spring, Texas, the average biomass was < 3 Mg ha^{-1}. Our estimated WUE_{ET} were also higher than the 9.7 ± 0.4 kg ha^{-1} mm^{-1} observed in Illinois, where the switchgrass used more water but had lower yield (Hickman et al., 2010). Our switchgrass WUE_{ET} values are higher than those of Koshi et al. (1982) and Hickman et al. (2010) mainly as a result of the relatively high switchgrass biomass yields in the 2012 and 2013 growing seasons. VanLoocke et al. (2012), using the Agro-IBIS model, simulated annual (not growing season) WUE_{ET} values for switchgrass in the Midwest US ranging from ~5 to 15 kg ha^{-1} mm^{-1}. That range of values is quite similar to the one we observed, considering that dormant season ET represents ~15% of the annual ET for switchgrass at our study site (Yimam et al., 2014).

Values of WUE_T for switchgrass (11.7 to 27.6 kg ha^{-1} mm^{-1}) in this field study were comparable with 14.5 to 18.4 kg ha^{-1} mm^{-1} measured in a seedling experiment by Xu et al. (2006), but well below the values of 30 to 50 kg ha^{-1} mm^{-1} estimated by Kiniry et al. (2008) using the ALMANAC model. To our knowledge, there are no prior reported WUE_T values for switchgrass based on field measurements of mature switchgrass stands.

Our WUE_{ET} values for biomass sorghum (9.5 to 48.7 kg ha^{-1} mm^{-1}) were similar to or lower than the values reported by Hao et al. (2014) in Texas (30 to 47 kg ha^{-1} mm^{-1}); by Narayanan et al. (2013) in Kansas (33.9 – 76.3 kg ha^{-1} mm^{-1}); and by Garofalo and Rinaldi (2013) in southern Italy (40 – 85 kg ha^{-1} mm^{-1}). In all of those studies, irrigation was applied to the sorghum whereas our experiment was rainfed. We are not aware of

any prior reports on WUE_T for biomass sorghum. Xin et al. (2009) measured WUE_T values of 47 to 71 kg ha^{-1} mm^{-1} across 25 lines of grain sorghum in a pot experiment, and our results (22.1 to 83.1 kg ha^{-1} mm^{-1}) encompass that range.

CONCLUSION

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

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REFERENCES

Aishah, S., Saberi, H., Halim, R., Zaharah, A., 2011. Yield responses of forage sorghums to salinity and irrigation frequency. Afr. J. Biotechnol. 10, 4114-4120.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration: Guidelines for computing crop water requirements. Irrigation and Drainage Paper No. 56. FAO, Rome, Italy.

Allen, R.G., Pruitt, W.O., Raes, D., Smith, M., Pereira, L.S. , 2005. Estimating evaporation from bare soil and crop coefficient for the initial period using common soil information. J. Irrig. Drain. Eng., 131, 14-23

Allen, R.G., 2011. Skin layer evaporation to account for small precipitation events – an enhancement to the FAO-56 evapotranspiration model. Agr. Water Manage. 99, 8-18

Booth, D.T., Cox, S.E., Berryman, R.D., 2006. Point sampling digital imagery with 'SamplePoint'. Environ. Monit. Assess. 123, 97-108.

Brye, K., Gower, S., Bundy, L., Norman, J., 2000. Water-budget evaluation of prairie and maize ecosystems. Soil Sci. Soc. Am. J. 64, 715-724.

Burba, G.G., Verma, S.B., 2005. Seasonal and interannual variability in evapotranspiration of native tallgrass prairie and cultivated wheat ecosystems. Agric. For. Meteorol. 135, 190-201.

Bui, E.N., Box J.E., 1992. Stemflow, rain throughfall, and erosion under canopies of corn and sorghum. Soil Sci. Soc. Am. J. 56, 242-247

Byrd, G., May, P., 2000. Physiological comparisons of switchgrass cultivars differing in transpiration efficiency. Crop Sci. 40, 1271-1277.

Campbell, G.S., Diaz, R., 1988. Simplified soil-water balance models to predict crop transpiration. ICRISAT, Patancheru, India, pp. 15-25.

Denmead, O., Dunin, F., Leuning, R., Raupach, M., 1996. Measuring and modelling soil evaporation in wheat crops. Phys. Chem. Earth 21, 97-100.

Finch, J., Hall, R., Rosier, P., Clark, D., Stratford, C., Davies, H., Marsh, T., Roberts, J., Riche, A., Christian, D., 2004. The hydrological impacts of energy crop production in the UK. Final report. Department of Trade and Industry, London.

Finch, J., Riche, A., 2010. Interception losses from Miscanthus at a site in south-east England—an application of the Gash model. Hydrol. Process. 24, 2594-2600.

Frankenberger, J.R., Dun, S., Flanagan, D.C., Wu, J.Q., Elliot, W.J., 2011, Development of a GIS interface for WEPP Model application to Great Lakes forested watersheds. In: Flanagan, D.C., Ascough II, J.C., Nieber, J.L. (Eds.), Proceedings of the International Symposium on Erosion and Landscape Evolution (ISELE). ISELE Paper No. 11139. ASABE, September 18-21, 2011, Anchorage, AK.

Fuentes, R.G., Taliaferro, C.M., 2002. Biomass yield stability of switchgrass cultivars. In: Janick, J., Whipkey, A. (Eds.), Trends in new crops and new uses, ASHS Press, Alexandria, VA, pp. 276-282

Garofalo, G., Rinaldi, P., 2013. Water-use efficiency of irrigated biomass sorghum in a Mediterranean environment. Span. J. Agric. Res. 11, 1153-1169.

Gilliam, F.S., Seastedt, T.R., Knapp, A.K., 1987. Canopy rainfall interception and throughfall in burned and unburned tallgrass prairie. Southwest Nat. 32, 267-271.

Hao, B., Xue, Q., Bean, B.W., Rooney, W.L., Becker, J.D., 2014. Biomass production, water and nitrogen use efficiency in photoperiod-sensitive sorghum in the Texas High Plains. Biomass Bioenerg. 62, 108-116.

Hendrickson, J., Schmer, M.R., Sanderson, M.A., 2013. Water use efficiency by switchgrass compared to a native grass or a native grass alfalfa mixture. BioEnergy Research 6, 746-754.

Hickman, G.C., Vanloocke, A., Dohleman, F.G., Bernacchi, C.J., 2010. A comparison of canopy evapotranspiration for maize and two perennial grasses identified as potential bioenergy crops. Glob. Change Biol. Bioenergy 2, 157-168.

Kiniry, J., Lynd, L., Greene, N., Johnson, M.V.V., Casler, M., Laser, M.S., 2008. Biofuels and water use: Comparison of maize and switchgrass and general perspectives. New research on biofuels. Nova Science Publ., New York.

Koshi, P., Stubbendieck, J., Eck, H., McCully, W., 1982. Switchgrasses: Forage yield, forage quality and water-use efficiency. J. Range Manage. 35, 623-627.

Lee, D.K., Boe, A., 2005. Biomass production of switchgrass in central South Dakota. Crop Sci. 45, 2583-2590.

Le, P.V., Kumar, P., Drewry, D.T., 2011. Implications for the hydrological cycle under climate change due to the expansion of bioenergy crops in the Midwestern United States. Proc. Natl. Acad. Sci. U.S.A. 108, 15085-15090.

McLaughlin, S., De La Torre Ugarte, D., Garten, C., Lynd, L., Sanderson, M., Tolbert, V.R., Wolf, D., 2002. High-value renewable energy from prairie grasses. Environ. Sci. Technol. 36, 2122-2129.

McPherson, R.A., Fiebrich, C.A., Crawford, K.C., Elliott, R.L., Kilby, J.R., Grimsley, D.L., Martinez, J.E., Basara, J.B., Illston, B.G., Morris, D.A., 2007. Statewide monitoring of the mesoscale environment: A technical update on the Oklahoma Mesonet. J. Atmos. Ocean. Tech. 24, 301-321.

Narayanan, S., Aiken, R.M., Prasad, V., Xin, Z., Yu, J., 2013. Water and radiation use efficiency of sorghum. Agron. J. 105, 649-656

Nimmo, J.R., Healy, R.W., Stonestrom D.A., 2005. Aquifer recharge. In: Anderson, M., Bear, J. (Eds.), Encyclopedia of Hydrological Sciences, vol. 4. Wiley, Chichester, UK, pp. 2229-2246.

Oklahoma Climatological Survey. 2014. Climate Trends. Climate Facts by County. Oklahoma Climatol. Surv., Norman. http://climate.ok.gov/index.php/climate/category/my_county_or_town (accessed 19 Aug. 2014).

Ritchie, J., Godwin, D., Singh, U., 1989. Soil and weather inputs for the IBSNAT crop models, Proceedings of the IBSNAT Symposium: Decision Support System for

Agrotechnology Transfer: Part I., IBSNAT, Department of Agronomy and Soil Science, College of Tropical Agriculture and Human Resouces, Univeristy of Hawaii, Honolulu, 31-45.

Ritchie, J.T., 1972. Model for predicting evaporation from a row crop with incomplete cover. Water Resour. Res. 8, 1204-1213.

Rooney, W.L., Blumenthal, J., Bean, B., Mullet, J.E., 2007. Designing sorghum as a dedicated bioenergy feedstock. Biofuels Bioprod. Bior. 1, 147-157.

Saeed, I., El-Nadi, A., 1998. Forage sorghum yield and water use efficiency under variable irrigation. Irrigation Sci. 18, 67-71.

Savenije, H.H., 2004. The importance of interception and why we should delete the term evapotranspiration from our vocabulary. Hydrol. Process. 18, 1507-1511.

Sinclair, T.R., Tanner, C., Bennett, J., 1984. Water-use efficiency in crop production. BioScience. 34, 36-40.

Shideed, K., 2005. Assessing on-farm water-use efficiency: A new approach methodology and six case studies. ICARD, Aleppo, Syria.

Thurow, T., Blackburn, W., Warren, S., Taylor Jr, C., 1987. Rainfall interception by midgrass, shortgrass, and live oak mottes. J. Range Manage. 40, 455-460.

Todd, R., Klocke, N., Hergert, G., Parkhurst, A., 1991. Evaporation from soil influenced by crop shading, crop residue, and wetting regime. Trans. ASAE . 34, 461-466.

VanLoocke, A., Twine, T.E., Zeri, M., Bernacchi, C.J., 2012. A regional comparison of water use efficiency for miscanthus, switchgrass and maize. Agric. For. Meteorol. 164, 82-95.

Wang, H., Liu, C., 2007. Soil evaporation and its affecting factors under crop canopy. Commun. soil sci. plan. 38, 259-271.

Wullschleger, S.D., Davis, E.B., Borsuk, M.E., Gunderson, C.A., Lynd, L.R., 2010. Biomass production in switchgrass across the United States: Database description and determinants of yield. Agron. J. 102, 1158-1168.

Xu, B., Li, F., Shan, L., Ma, Y., Ichizen, N., Huang, J., 2006. Gas exchange, biomass partition, and water relationships of three grass seedlings under water stress. Weed Biol. Manag. 6, 79-88.

Xin, Z., Aiken, R., Burke, J., 2009. Genetic diversity of transpiration efficiency in sorghum. Field Crop Res. 111, 74-80.

Yimam, Y., Ochsner, T., Kakani, G., Warren, J., 2014. Soil moisture dynamics and evapotranspiration under annual and perennial bioenergy crops. Soil Sci. Soc. Am. J. 78, 1584-1592.

Zegada-Lizarazu, W., Wullschleger, S.D., Nair, S.S., Monti, A., 2012. Crop physiology. In: Monti, A. (Ed.), Switchgrass: a valuable biomass crop for energy. Springer-Verlag Publ., London, UK, pp. 55-86.

Table 3.1 Above-ground dry biomass, growing season rainfall, and plant available water (PAW) at greening/ planting during 2011, 2012, and 2013 growing seasons by switchgrass (SWG) and biomass sorghum (BMS). Values inside the bracket represent one standard error.

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

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

Table 3.2 Growing season evapotranspiration (ET), canopy rainfall interception (I), soil evaporation (E_s), transpiration (T), and transpiration to ET ratio (T:ET) for switchgrass (SWG) and biomass sorghum (BMS). Values inside the bracket represent one standard error.

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

† Different lower case letters represent significant differences between cropping systems within a year at $\alpha = 0.1$.
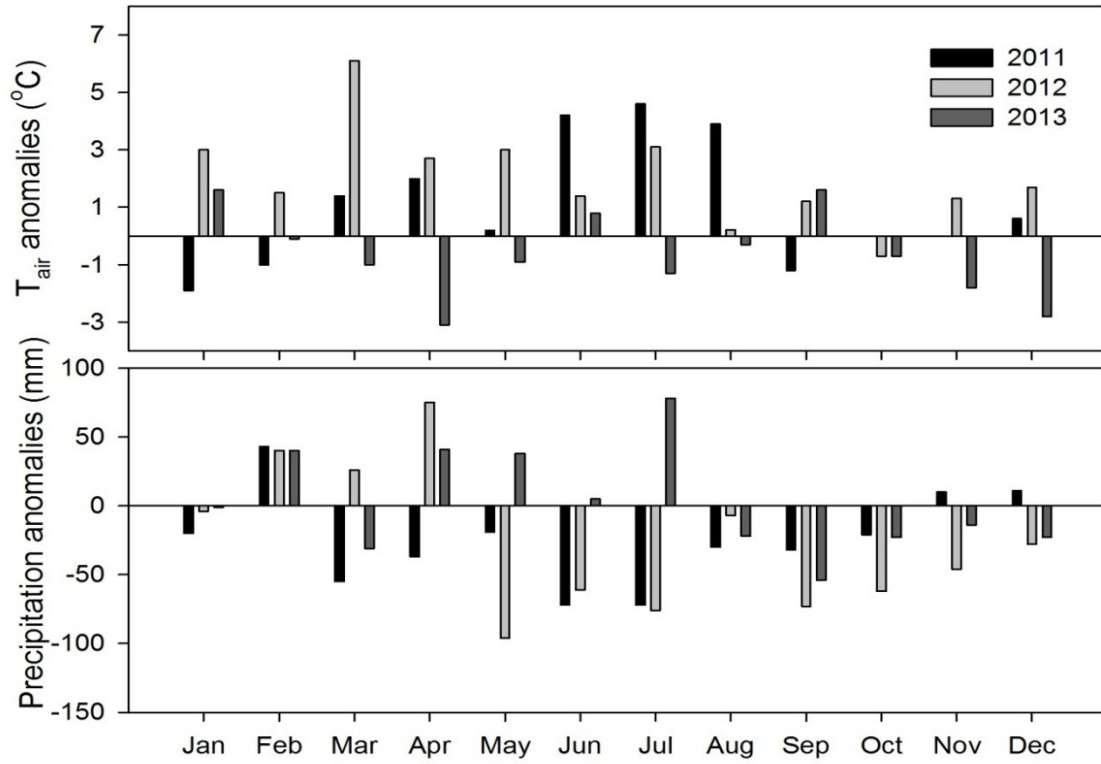
Fig. 3.1 Study period monthly anomalies of air temperature (T_{air}) and precipitation from the long term (50-yr.) average at Stillwater, OK
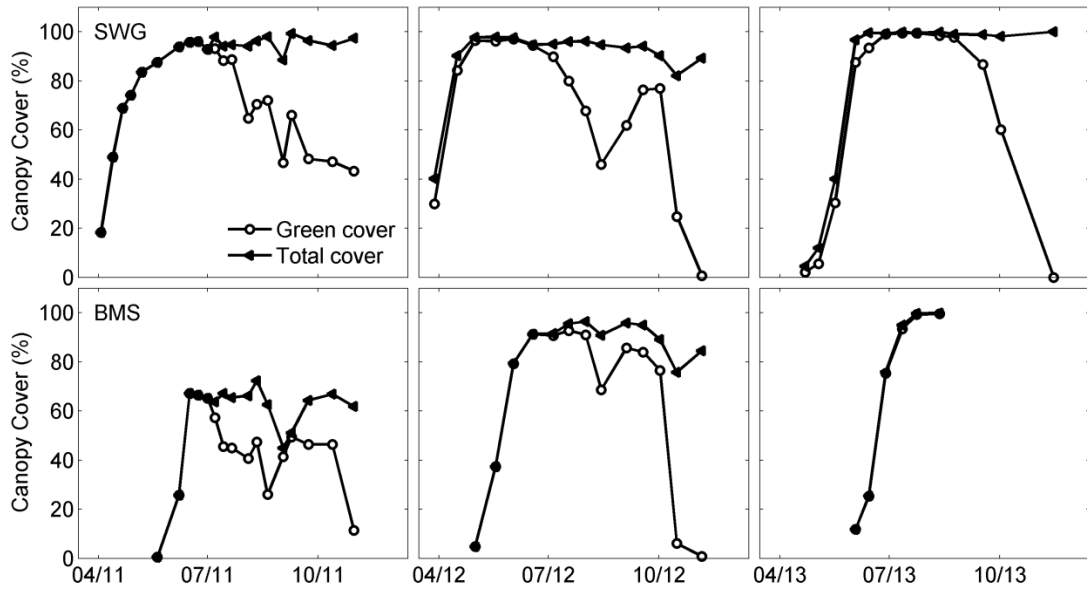
Fig. 3.2 Percent green cover and total canopy cover (both green leaf and senescence) by switchgrass (SWG) and biomass sorghum (BMS) during 2011, 2012, and 2013 growing seasons.
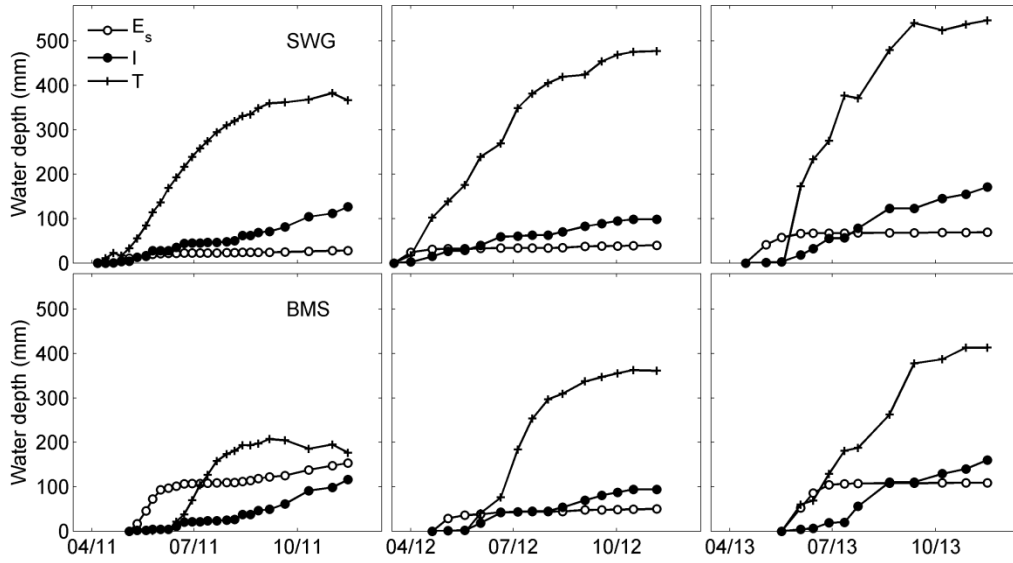
Fig. 3.3 Time series of cumulative soil evaporation (E_s), interception (I), and transpiration (T) by switchgrass (upper panels) and biomass sorghum (lower panels) during the 2011, 2012, and 2013 growing seasons.
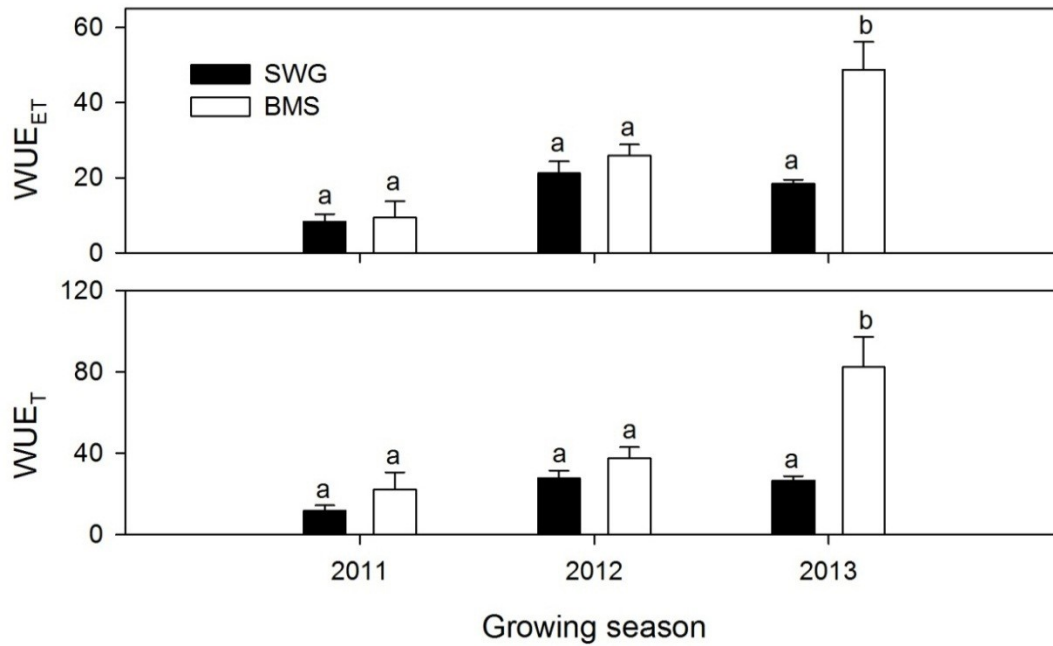
Fig. 3.4 Water use efficiency values based on ET (WUE_{ET}) and based on transpiration (WUE_T) in kg ha^{-1} mm^{-1} for the three growing seasons by switchgrass (SWG) and biomass sorghum (BMS). Letters above bars shows significant difference between species within a year at p $\leq$0.10

CHAPTER IV

GRASSLANDS VERSUS MARGINAL CROPLANDS FOR SWITCHGRASS

PRODUCTION: MODELING BIOMASS AND HYDROLOGIC IMPACTS

A paper submitted to Biomass and Bioenergy

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ABSTRACT

Switchgrass has attracted attention as a promising second generation biofuel feedstock.

Both existing grasslands and marginal croplands have been suggested as targets for

conversion to switchgrass, but the resulting production potentials and hydrologic impacts

are not clear. The objectives of this study were to model switchgrass biomass production

on existing grasslands (scenario-I) and on marginal croplands that have severe to very

severe limitations for crop production (scenario-II) and to evaluate the effects on

evapotranspiration (ET) and streamflow. The Soil and Water Assessment Tool (SWAT)

was applied to the 1063 km^2 Skeleton Creek watershed in north-central Oklahoma, a

watershed dominated by grasslands (34%) and winter wheat cropland (47%). The average

annual simulated switchgrass yield for both scenarios was 12 Mg ha^{-1}. Yield variability

under scenario-I ranged from 6.1 to 15.3 Mg ha^{-1}, while under scenario-II the range was

from 8.2 to 13.8 Mg ha^{-1}. Comparison of average annual ET and streamflow between the

baseline simulation and scenario-I showed that scenario-I had 5.6% (37 mm) higher average annual ET and 27.7% lower streamflow, representing a 40.7 million m^3 yr^{-1} reduction. Compared to the baseline, scenario-II had only 0.5% higher ET and 3.2% lower streamflow, but some monthly impacts were larger. In this watershed, greater water yield reduction per ton of biomass production was predicted under scenario-I than under scenario-II. Our results suggest that, from a hydrologic perspective, it may be preferable to convert marginal cropland to switchgrass production rather than converting existing grasslands.

Key Words: switchgrass, grasslands, marginal croplands, evapotranspiration, streamflow, hydrologic cost-effect ratio

Abbreviations: ET, evapotranspiration; HRU, hydrological response unit; LCC, land capability classification; NSE, Nash-Sutcliffe Efficiency; PB, percentage bias; r^2, coefficient of determination; SGP, Southern Great Plains; SWAT, Soil and Water Assessment Tool

INTRODUCTION

The US has a goal of producing 36 billion gallons of biofuels annually by 2022 [1], primarily as ethanol. Thus far, production of ethanol in the US has been predominantly from corn grain, but future increases in biofuel production are expected to come mostly from cellulosic feedstocks [2]. Switchgrass (*Panicum virgatum*) is considered by some to be a promising cellulosic feedstock crop for much of the US, including the Southern Great Plains (SGP), the focus area for our study [3]. Switchgrass is a warm season C4 perennial grass native to Central and North America. High biomass production, relatively low management requirements, adaptability to poor soils, and drought resistance are some of the reasons switchgrass has been identified as a potential bioenergy crop [4].

Large scale production of bioenergy crops will require alterations in land use and land cover, which may have significant hydrologic effects [5]. Decisions about which energy crops to plant, where to grow them, and how to manage them will be important in determining effects on water resources [6]. For example, Schilling *et al.* [7] predicted a 9.5% increase in ET and a 28% reduction in streamflow upon converting 100% of croplands (about 76% of the watershed) to switchgrass production in the Raccoon River watershed in Iowa, USA. In the Iowa River basin, Wu and Liu [8] simulated an increase in streamflow by converting corn producing lands to switchgrass production; they also predicted a reduction in streamflow by changing grasslands to switchgrass production. A recent study in part of the middle North Canadian River basin in Oklahoma projected an increase in ET by 3.4 to 32% during spring and 1.5 to 18.9% during summer when both winter wheat producing areas and grasslands were converted to switchgrass production

with impacts varying depending on the amount of fertilizer inputs and total area of conversions [9]. These increases in ET were predicted to result in a reduction in streamflow by 5.6 to 20.6% during spring and 6.4 to 31.2% during the summer. Similarly, in the Skeleton Creek watershed, Goldstein and Tarhule [10] predicted an increase in ET and a decrease in runoff during the spring and summer following conversion of 89% of the watershed (currently under grassland, winter wheat, and rye) to switchgrass production. Although there have been several hydrologic modeling studies on land use conversion to switchgrass production, none of them has considered conversion of only marginal croplands.

Some have suggested planting bioenergy crops on marginal lands in order to reduce competition with food crops [11]. But, currently there is no widely accepted definition of marginal lands that would let us identify them on a map. This complicates regional scale studies of bioenergy production and its relation with environmental variables. Previous researchers have used a variety of definitions for marginal lands including: lands that are susceptible to degradation and low inherent productivity, hence high risk for crop production [12]; abandoned agricultural lands and lands reserved for conservation, buffer strips along water bodies and roadway, and contaminated lands [13]; and lands having severe to very severe limitations for production of crops common to the area [14]. In this study, the Natural Resources Conservation Services (USDA-NRCS) land capability classification (LCC) system was used to define marginal cropland. The LCC system classifies lands based on their suitability for cultivation of crops common to the region or for pasture, range, and forest or wildlife habitat. The system has eight classes, ranging from class I, defined as land with only slight limitations that restrict crop

production, to class VIII, which is defined as land that is only suitable for recreation, wildlife, water supply, or aesthetic purposes [15]. In this study we defined marginal cropland as land which has severe (class III) to very severe (class IV) limitations for crop production. A similar approach was used by Graham [14], who considered LCC class III and IV in her estimation of potential land base for bioenergy crop production in the conterminous United States. We are not aware of any prior hydrologic studies in which LCC has been used to guide land use conversion scenarios for bioenergy feedstocks.

Existing grasslands may also be suitable for cellulosic feedstock development [12, 16]. One disadvantage of deriving bioenergy from grassland is the displacement of these lands from their current role of producing forage for grazing animals [17]. Nevertheless, farmers are more willing to replace grasslands instead of croplands with switchgrass [18]. Hence, a comparison among different land use systems and different combination of land uses is important for a practicable bioenergy feedstock production [17]. But, studies of the impacts of bioenergy production on water resources for grassland conversion versus marginal cropland conversion have not been reported in the SGP.

In this study, the Soil and Water Assessment Tool (SWAT) [19] was applied to the Skeleton Creek watershed in north central Oklahoma 1) to estimate the switchgrass production potential on grasslands and marginal croplands and 2) to evaluate the hydrological impacts of converting grasslands versus marginal croplands to switchgrass production.

MATERIALS AND METHODS

Study area

The Skeleton Creek watershed covers a total surface area of 1063 km^2 and lies within three counties (Garfield, Kingfisher and Logan) located in north-central Oklahoma (Fig. 4.1). The watershed was delineated using the USGS streamflow station at Lovell as the outlet for the watershed. Inside the watershed, there is an additional USGS streamflow gauge station at Enid draining 16% of the total area of the watershed. The majority of the watershed has fine surface soil texture, and the soil profile is grouped under taxonomic orders Mollisol and Alfisol. The elevation of the watershed ranges between 280 and 415 m above mean sea level. The watershed is relatively flat with a mean slope of 2.0%. The mean slope of the existing croplands in the watershed is 1.5%; while the grasslands have a mean slope of 2.8%. Winter wheat (*Triticum aestivum* L.), grassland herbaceous, and developed areas together comprise 93% of the total watershed area, representing 47%, 34% and 11%, respectively. In the watershed, 552 km^2 (52% of the total area) are currently under cultivation. About 49% of the cultivated land is marginal cropland in capability classes III and IV, and most of that land is used for the production of winter wheat (Fig. 4.2). About 80% of the grasslands are in land capability class III or higher and are not well suited for crop production. The land cover in the watershed is representative of other watersheds in the SGP where winter wheat and grasslands are predominant [10].

The SWAT model

The Soil and Water Assessment Tool (SWAT) is a physically based, semi-distributed, continuous watershed model. The model was designed to predict the effect of management decisions on water, sediment, nutrient, and pesticide yields in large complex watersheds with varying soils, land use, and management conditions over long periods of time [19]. The major components of the model include hydrology, weather, erosion, soil temperature, crop growth, nutrients, pesticides, and agricultural management practices. The model has been applied around the world for a wide variety of application including simulation of land use change and climate change impacts [20] on major river basins in the US, and other parts of the world. SWAT has also been used to study the effect of bioenergy crop production on the water quantity and quality [e.g. 7, 21, 22]. SWAT simulates the hydrological cycle based on the water balance of the soil profile. The model uses the Erosion Productivity Impact Calculator (EPIC) modeling approach to simulate crop growth [23]. As in EPIC, the development stage of a crop is defined in terms of daily accumulated heat units. For each day of simulation, plant growth is calculated from the daily intercepted photosynthetically active radiation and plant species specific radiation use efficiency. Harvest index is used to calculate yield.

The watershed in SWAT is divided into multiple sub-watersheds or sub-basins which are further divided in to a number of Hydrological Response Units (HRUs). Each HRU is made up of homogeneous land use, management, and soil characteristics. The water balance is the primary driver of the model. In SWAT the water balance is simulated in two separate phases, the land phase and the routing phase. The land phase processes control the flux of water to the main channel in each sub-basin. Once water has reached the stream channel of a watershed, the routing phase controls the processes to the outlet.

In the land phase, SWAT simulates the hydrological cycle for each HRU based on the water balance equation of the soil profile:

$$SW_t = SW_o + \sum(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}) \qquad [1]$$

where SW_t is the final soil water content (mm), SW_o is the initial soil water content (mm), R_{day} is the amount of precipitation for the day (mm), Q_{surf} is the amount of surface runoff for the day (mm), E_a is the amount of evapotranspiration for the day (mm), W_{seep} is the amount of percolation and bypass flow exiting the soil profile bottom for the day (mm), and Q_{gw} is the amount of return flow for the day (mm).

Input data and sources

As a physically based model, SWAT requires a substantial amount of data for calibration and validation. Major input datasets for the model include topography, soil, land use/land cover, weather, and management practices. The geospatial data used in this research include a digital elevation model (DEM), land cover data, and soil data. The 30-m spatial resolution DEM from the National Elevation Dataset (NED) was used to define the topography. The DEM is used to calculate sub-basin parameters like slope, aspect, slope length, and to define the stream networks. The high resolution (1:24,000 scales) Soil Survey Geographic Database (SSURGO) data for the three counties were used to describe the distribution and properties of the soil for the Skeleton Creek watershed. Information about land cover was obtained from two different datasets: the 2006 National Land Cover Dataset (NLCD) (http://www.mrlc.gov/nlcd06_data.php) and the Cropland Data Layer (CDL) (http://nassgeodata.gmu.edu/CropScape/). The CDL was merged with the NLCD to determine the type of crops grown on the "cultivated crops" class of the

NLCD. A map of non-irrigated Land Capability Classifications (LCC) for the watershed was created using the SSURGO dataset. The map showed the capability class for each mapping unit on the SSURGO soil map. By overlying this map with the land cover map it was possible to identify class III and IV lands which were being used for crop production.

Daily values of precipitation, maximum and minimum air temperature, solar radiation, relative humidity and wind speed were collected from Oklahoma Mesonet [24] stations that are found inside and close to the watershed. For sensitivity analysis, calibration, and validation, daily streamflow data from two gauge stations (Fig. 4.1) were obtained from USGS water information system (http://waterdata.usgs.gov/nwis/sw). Thirteen years (from 01/01/1999 to 12/31/2011) of weather and flow data were considered. The first three years were used for model "warm up" followed by six years for calibration and the final four years for validation.

Plant growth parameters

The default parameters for Alamo switchgrass in the SWAT crop growth database were used with some modifications based on recent literature. The initial LAI was changed from 0 to 0.5 [-], the initial biomass was changed from 0 to 500 kg ha^{-1} [21], and the radiation use efficiency was changed from 47 to 43 (kg ha^{-1})/ (MJ m^{-2}) [25]. Based on plot studies at various sites in Oklahoma, 85 kg ha^{-1} yr^{-1} of N fertilization was assumed for the simulation of switchgrass harvested as bioenergy feedstock (V.G. Kakani, personal communication). Winter wheat parameters were calibrated to match average grain yield in the region (~ 2 Mg ha^{-1}; [26]) by changing radiation use efficiency from 30

to 16 (kg ha^{-1}) / (MJ m^{-1}), maximum LAI from 4 to 3.5, and harvest index from 0.40 to 0.34.

Streamflow calibration and validation

The SWAT model was calibrated for the streamflow of the Skeleton Creek watershed from 2002 to 2007, and validated from 2008 to 2011 at the two gauge stations: Enid (upper gauge station) and Lovell (catchment outlet). The evaluation process consisted of three phases: sensitivity analysis, manual and auto-calibration, and validation. An automatic sensitivity analysis embedded in SWAT2005 was used to select key parameters to be used for calibration. The sensitivity tool is based on a Latin Hypercube (LH) One-factor-At-a Time (OAT) sampling technique [27]. Then, using the most sensitive parameters, the model was manually calibrated for the watershed by choosing parameter values that resulted in reasonable agreement between observed and simulated monthly flows for the two stations. After manual calibration, the SWAT2005 auto-calibration was employed. After calibration was completed using the 2002 – 2007 data, the model was validated using the 2008 – 2011 data. The simulated monthly flow was compared with the observed flow at the two stations using three statistical tests: Nash-Sutcliffe Efficiency (NSE) [28], percentage bias (PB), and coefficient of determination (r^2).

Land use change scenarios

The baseline scenario was created using the merged NLCD and CDL land cover data for the watershed. In addition to the baseline, two scenarios were developed based on our research objectives. Scenario-I simulates conversion of the NLCD's "grassland/

herbaceous" land cover to switchgrass production. Around 376 km^2 or 35% of the watershed was converted to switchgrass under scenario-I. Scenario-II simulates switchgrass production on class III and IV croplands. Around 289 km^2 or 27% of the watershed was converted to switchgrass under scenario-II. To compare the hydrologic impacts of these two conversion scenarios, we defined the *hydrologic cost-effect ratio* at the HRU level as the reduction in the water yield (m^3) from the HRU relative to the baseline scenario divided by the switchgrass biomass production (Mg) for the HRU. Cost-effect ratios are often used in economic analyses to compare the relative merits of various courses of action, and cost-effect ratios have been employed in some previous hydrologic studies [29, 30]. Panagopoulos *et al.* [31] used a cost-effect ratio together with SWAT simulations to compare agricultural best management practices for a catchment in Greece.

RESULTS

Streamflow calibration and validation

Sensitivity rankings and final calibration values for key parameters are shown in Table 4.1. In the Skeleton Creek watershed, monthly streamflow predictions were most sensitive to curve number (Cn2). Soil evaporation compensation factor (Esco) was ranked second, and baseflow alpha factor (Alpha_Bf) was third in the sensitivity ranking. For the calibration period, NSE, PBIAS, and r^2 were 0.87, + 6.5%, and 0.91, respectively for the gauge at Enid, and 0.91, -1.6%, and 0.91 at Lovell. The NSE, PBIAS, and r^2 for the validation period were 0.79, - 1.4%, and 0.79 at Enid, and 0.66, - 12.8%, and 0.70 at

Lovell. According to the performance ratings of Moriasi *et al.* [32], model performance is good when NSE is greater than 0.65 and PBIAS < ± 15%, and very good when the NSE is > 0.75 and PBIAS < ± 10%. By those standards, the performance of the calibrated model was good to very good. In addition to these statistical coefficients, from visual comparison it is clear that monthly simulated streamflow matched well with the observed streamflow at the two gauge stations during both calibration and validation (Fig. 4.3). Thus, the SWAT model for the Skeleton Creek watershed was demonstrated to provide a reasonable hydrologic framework for testing our scenarios of changing grasslands to switchgrass (scenario-I) and marginal croplands to switchgrass (scenario-II).

Biomass production

For both scenarios, switchgrass biomass production was simulated for 10 years (2002 – 2011). On average, the annual switchgrass yield from the conversion of grasslands was 12.0 Mg ha^{-1}. Biomass yield varied from 6.5 Mg ha^{-1} (usually around the crest of the sub-watersheds) to 15.1 Mg ha^{-1} on grasslands closer to the stream channels (Fig. 4.4a). The average annual switchgrass production on marginal croplands was also 12.0 Mg ha^{-1}, varying from 8.2 Mg ha^{-1} in the north-central part of the watershed to 13.8 Mg ha^{-1} in the south-eastern part of the watershed (Fig. 4.4b). For comparison, under the baseline scenario, the simulated average above ground biomass for wheat on marginal croplands was 6.2 Mg ha^{-1} and the simulated average grass yield from existing grasslands was 1.8 Mg ha^{-1}. The simulated switchgrass yields were within the range of what has been observed in field trials at Chickasha, OK (13.5 Mg ha^{-1}; [33]) and at Stillwater, OK (12.1 ± 4.5 Mg ha^{-1}; [25]). In addition, our results agreed well with previous SWAT

simulations of switchgrass production for north central Oklahoma by Baskaran *et al.* [21] in their simulation for the whole US.

Hydrologic impacts

In the Skeleton Creek watershed, under the baseline condition, evaluation of water balance components showed a lower ET and higher water yield from grasslands compared with marginal croplands. On average, percentage of precipitation used for ET was 74% for grasslands and 88% for marginal croplands. Most of the remaining percentage of precipitation, 25% for grasslands and 11% for marginal croplands, was water yield to the stream. Thus, about 50% of the streamflow was predicted to come from grasslands covering only 34% of the area of the watershed. This result is due, in part, to the fact that the existing grasslands in the watershed have steeper slopes (mean 2.8%) than the marginal croplands (mean 2.0%).

Conversion of existing grasslands to switchgrass (scenario-I) was predicted to increase ET in the Skeleton Creek watershed for every month except August (Fig. 4.5a). Under the baseline condition, HRUs under grasslands had relatively low ET because they produced little biomass, but when grasslands were converted to switchgrass production with 85 kg of N ha^{-1} fertilizer, the model predicted a 5.6% increase in annual ET under scenario-I compared to baseline (Table 4.2). This increase in ET led to a greater than 20% reduction in simulated streamflow for every month of the year (Fig. 4.5b).

In the watershed, the dominant crop produced on marginal croplands was winter wheat. Changing this to a summer crop (switchgrass) led to a partial shift in evapotranspiration from winter to summer (Fig. 4.6a), although the difference in annual

95

average ET was small (Table 4.2). During summer months, ET was up to 17% greater under scenario-II compared with the baseline because switchgrass was in its active growing period, and the winter wheat crop was under senescence or already harvested. The annual streamflow from the watershed was lower by 3.2% under scenario-II compared to the baseline (Table 4.2). The percentage reduction in streamflow was greatest during late summer and early fall, but never exceeded 7% under scenario-II compared to the baseline. For all the months, there was a simulated reduction in surface flow and an increase in base flow (data not shown). But, the reduction in surface flow offset the increase in base flow which yielded a reduced total streamflow.

Tradeoff between switchgrass production and water yield reduction

Maps of the hydrologic cost-effect ratio for scenarios I and II highlight the differing outcomes for grassland versus marginal cropland conversion (Fig. 4.7). The water yield reduction (cost) per ton of biomass (effect) for the grassland conversion scenario reached as high as 170 m^3 Mg^{-1} in the upper portion of the watershed (Fig. 4.7a) and was substantially higher than the cost-effect ratio for marginal cropland conversion (Fig. 4.7b). On average, in the Skeleton Creek watershed, to produce one ton of switchgrass on grasslands, the model predicted water yield reductions of 95 m^3, while this value was only 17 m^3 for the production of one ton of switchgrass on marginal croplands.

DISCUSSION

The quest to produce cellulosic ethanol from plant biomass motivated us to investigate the interactions between bioenergy cropping systems and water resources. We

used the SWAT model to evaluate the hydrologic effects of two land use conversion scenarios for bioenergy cropping systems in the Skeleton Creek watershed in north-central Oklahoma. The simulations showed that, in this watershed, the average biomass produced following conversion of existing grasslands or marginal croplands to switchgrass was similar (12 Mg ha^{-1}) but with a wider range under grasslands. This yield level might be economically viable if there were a biorefinery nearby. Debnath et al. [34] showed the potential environmental benefits of switchgrass over no-till winter wheat production on marginal croplands and calculated the farm gate breakeven prices in Oklahoma. For an average biomass yield of 9 Mg ha^{-1}, they calculated a breakeven price of $59.92 on LCC III by considering only internal breakeven prices and $27.09 by considering both internal prices and environmental benefits. McLaughlin et al. [3] projected a conversion of 16.9 mha of land to switchgrass at a national level with average annual yield of 9.4 Mg ha^{-1} and farm gate price of $44 Mg^{-1}. At 12 Mg ha^{-1} of switchgrass production, the Skeleton Creek watershed would produce an average annual switchgrass biomass of 435,000 Mg if existing grasslands were converted to switchgrass and 351,000 Mg if marginal croplands were converted. These total biomass amounts are equal to or greater than the biomass feedstock needs of currently planned cellulosic biofuel plants. As an example, Abengoa Bioenergy Biomass of Kansas has a goal to produce 25 million gallons of ethanol using around 350,000 Mg of biomass annually (http://www.abengoabioenergy.com/web/en/2g_hugoton_project/general_information/).

Converting existing grasslands to switchgrass production reduced simulated annual water yield to the streams by 27.7%, because switchgrass increased ET (by about 5.6%) and produced more biomass compared to the baseline scenario. Goldstein and

Tarhule [10] also predicted reduced streamflow and increased ET in the Skeleton Creek watershed due to switchgrass production, but their conversion scenario involved 89% of the watershed area (both grassland and cropland) being converted to switchgrass. It is not clear what driving factors would be necessary to result in such a dramatic land use change. In contrast, our scenarios involved conversion of 27-36% of the watershed to switchgrass and were predicted to produce adequate biomass to support a biorefinery. Wu and Liu [8] predicted a reduction in annual water yield to the stream by 2.1% by converting native grasslands (representing only 5.7% of the watershed area) to switchgrass production in the Iowa River basin. Clearly, at the watershed level, percent increases in ET and reduction in streamflow depend on the fraction of the watershed converted to switchgrass production, thus the conversion scenarios used in hydrologic studies should be critically evaluated.

In the Skeleton Creek watershed under the baseline scenario, grasslands were predicted to route a greater proportion of precipitation to streamflow (25%) than did marginal croplands (11%). The grasslands had steeper slopes on average than the marginal croplands, and evapotranspiration from the existing grasslands was less than that from marginal croplands, in part because the unfertilized grasslands produced less biomass. Previous studies showed that conversion of native grasslands to croplands reduced the ET and subsequently increased streamflow [35, 36]. Extrapolating those findings might lead one to the erroneous conclusion that the existing grasslands in the watershed contribute less to streamflow generation than do the croplands. Our results show that is not the case. Grasslands and marginal croplands occupy fundamentally different areas in the watershed, having different soil types and land surface

characteristics and different management practices. Hence, the surface runoff production mechanisms for these two land use types are different.

Conversion of marginal croplands representing about one quarter of the watershed area to switchgrass was predicted to reduce the annual streamflow by only 3.2%. The effect of converting cropland to switchgrass may be dependent on the amount of biomass produced by the switchgrass relative to that produced by the displaced crops. For example, Wu and Liu [8] predicted an increase in annual average water yield of 1.7% when converting corn (*Zea mays*) croplands to switchgrass because biomass production from the corn was higher than that from switchgrass. But in the Skeleton Creek watershed the story is different, because the dominant crop, winter wheat, produced on average 6.2 Mg ha^{-1} above ground biomass on marginal cropland whereas the switchgrass was predicted to produce 12 Mg ha^{-1} on that same land. Converting the marginal cropland resulted in a significant shift in ET from fall and winter months to spring and summer months. This shift resulted in June through October streamflow reductions. These seasonal changes highlight the importance of considering the shorter time scale variability of water balance components rather than looking only at the annual average. This may be particularly important to maintain year-round "environmental flows", which are the minimum streamflow levels required to achieve desired ecological objectives [37].

As shown in Fig. 4.7, the streamflow reduction for the production of a unit of biomass, i.e. the hydrologic cost-effect ratio, was higher for the case of grassland conversion than marginal cropland conversion. This is consistent with the findings of Goldstein *et al.* [9] who reported larger hydrologic impacts when converting grasslands

99

versus winter wheat to switchgrass production in the SGP. However, their study did not normalize the hydrologic impacts by the amount of switchgrass produced to facilitate comparisons between scenarios. Policy makers may need to consider the tradeoff between bioenergy feedstock production and reduction of streamflow and prioritize areas accordingly. Our results show that if the goal is to avoid streamflow reduction, planting switchgrass on marginal croplands may be preferable to converting grasslands to switchgrass. Marginal croplands are currently used for cultivation of food crops, predominantly winter wheat in this area, even though these lands have severe to very severe limitations according to the LCC system. Conversion of these marginal croplands to bioenergy crops may raise controversial issues of land for food versus for fuel. However, even the grasslands are part of our food production system, as many are used for cattle grazing. If we pre-emptively eliminate marginal cropland from consideration for biofuel production, our results show that we may be increasing the probability of undesirable hydrologic impacts. Therefore, comprehensive assessments of bioenergy systems should include careful consideration of the impacts of land conversion on the hydrological regime.

ACKNOWLEDGEMENTS

REFERENCES

[1] U.S. Congress. Energy independence and security act of 2007 (HR 6. 110th congress. 1st session. December 2007); 2007.

[2] Johnson JM, Coleman MD, Gesch R, Jaradat A, Mitchell R, Reicosky D, et al. Biomass-bioenergy crops in the United States: A changing paradigm. Americas J Plant Sci Biotech 2007;1(1):1-28.

[3] McLaughlin S, De La Torre Ugarte D, Garten C, Lynd L, Sanderson M, Tolbert VR, et al. High-value renewable energy from prairie grasses. Environ Sci Technol 2002;36(10):2122-9.

[4] McLaughlin SB, Adams Kszos L. Development of switchgrass (*Panicum virgatum*) as a bioenergy feedstock in the United States. Biomass Bioenergy 2005;28(6):515-35.

[5] Berndes G. Bioenergy and water - the implications of large-scale bioenergy production for water use and supply. Global Environ Chang 2002;12(4):253-71.

[6] Dale VH, Kline KL, Wright LL, Perlack RD, Downing M, Graham RL. Interactions among bioenergy feedstock choices, landscape dynamics, and land use. Ecol Appl 2011;21(4):1039-54.

[7] Schilling KE, Jha MK, Zhang YK, Gassman PW, Wolter CF. Impact of land use and land cover change on the water balance of a large agricultural watershed: Historical effects and future directions. Water Resour Res 2008;44(7):doi:10.1029/2007WR006644.

[8] Wu Y, Liu S. Impacts of biofuels production alternatives on water quantity and quality in the Iowa River Basin. Biomass Bioenergy 2011;36:182-91.

[9] Goldstein JC, Tarhule A, Brauer D. Simulating the hydrologic response of a semiarid watershed to switchgrass cultivation. Hydrol Res 2014;45:99-114.

[10] Goldstein JC, Tarhule A. Evaluating the impacts of climate change and switchgrass production on a semiarid basin. Hydrol Process 2014:doi: 10.1002/hyp.10159.

[11] Zhang X, Izaurralde RC, Manowitz D, West T, Post W, Thomson AM, et al. An integrative modeling framework to evaluate the productivity and sustainability of biofuel crop production systems. GCB Bioenergy 2010;2(5):258-77.

[12] Cai X, Zhang X, Wang D. Land availability for biofuel production. Environ Sci Technol 2011;45(1):334–9.

[13] Gopalakrishnan G, Negri MC, Wang M, Wu M, Snyder SW, Lafreniere L. Biofuels, land, and water: a systems approach to sustainability. Environ Sci Technol 2009;43:6094–100.

[14] Graham RL. An analysis of the potential land base for energy crops in the conterminous United States. Biomass Bioenergy 1994;6(3):175-89.

[15] Klingebiel AA, Montgomery PH. Land-capability classification: Soil Conservation Service, US Department of Agriculture 1961.

[16] Gu Y, Boyte SP, Wylie BK, Tieszen LL. Identifying grasslands suitable for cellulosic feedstock crops in the Greater Platte River Basin: dynamic modeling of ecosystem performance with 250 m eMODIS. GCB Bioenergy 2012;4(1):96-106.

[17] Ceotto E. Grasslands for bioenergy production: a review. Agron Sustain Develop 2008;28(1):47-55.

[18] Bransby D. Interest among Alabama farmers in growing switchgrass for energy. Paper presented at BioEnergy '98: expanding bioenergy partnerships, Madison, Wisconsin 1998:4-8.

[19] Neitsch S, Arnold J, Kiniry J, Williams J. Soil and water assessment tool theoretical documentation, version 2009. Texas, USA. 2011.

[20] Gassman PW, Reyes MR, Green CH, Arnold JG. The soil and water assessment tool: historical development, applications, and future research directions: Center for Agricultural and Rural Development, Iowa State University 2007.

[21] Baskaran LM, Jager Y, Schweizer PE, Srinivasan R. Progress toward evaluating the sustainability of switchgrass production as a bioenergy crop using the SWAT model. Trans ASAE 2010;53(5):1547–56.

[22] Wu Y, Liu S, Li Z. Identifying potential areas for biofuel production and evaluating the environmental effects: a case study of the James River Basin in the Midwestern United States. GCB Bioenergy 2012;4(6):875-88.

[23] Williams J, Jones C, Dyke PT. Modeling approach to determining the relationship between erosion and soil productivity. Trans ASAE 1984;27(1):129-44.

[24] McPherson RA, Fiebrich CA, Crawford KC, Kilby JR, Grimsley DL, Martinez JE, et al. Statewide monitoring of the mesoscale environment: A technical update on the Oklahoma Mesonet. J Atmos ocean Tech 2007;24(3):301-21.

[25] Kiniry J, Anderson L, Johnson M-V, Behrman K, Brakie M, Burner D, et al. Perennial Biomass Grasses and the Mason–Dixon Line: Comparative Productivity across Latitudes in the Southern Great Plains. BioEnergy Res 2013;6(1):276-91.

[26] Patrignani A, Lollato RP, Ochsner TE, Godsey CB, Edwards J. Yield Gap and Production Gap of Rainfed Winter Wheat in the Southern Great Plains. Agron J 2014;doi:10.2134/agronj14.0011

[27] Van Griensven A. Sensitivity, auto-calibration, uncertainty and model evaluation in SWAT2005. Available at: http://www.biomath.ugent.be/~ann/swat_manuals/SWAT2005_manual_sens_cal_unc.pdf (accessed 27 February 2012). 2005.

[28] Nash J, Sutcliffe J. River flow forecasting through conceptual models part I—A discussion of principles. J Hydrol 1970;10(3):282-90.

[29] Fröschl L, Pierrard R, Schönbäck W. Cost-efficient choice of measures in agriculture to reduce the nitrogen load flowing from the Danube River into the Black Sea: An analysis for Austria, Bulgaria, Hungary and Romania. Ecol Econ 2008;68(1):96-105.

[30] Shaviv A, Sinai G. Application of conditioner solution by subsurface emitters for stabilizing the surrounding soil. J Irrigat Drain Eng 2004;130(6):485-90.

[31] Panagopoulos Y, Makropoulos C, Mimikou M. Reducing surface water pollution through the assessment of the cost-effectiveness of BMPs at different spatial scales. J Environ Manage 2011;92(10):2823-35.

[32] Moriasi D, Arnold J, Van Liew M, Bingner R, Harmel R, Veith T. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Trans ASABE 2007;50(3):885-900.

[33] Fuentes RG, Taliaferro CM. Biomass yield stability of switchgrass cultivars. In: Janick J, Whipkey A, editors. Trends in New Crops and New Uses, Alexandria, VA: ASHS Press; 2002, p. 276–282

[34] Debnath D, Stoecker AL, Epplin FM. Impact of Environmental Values on the Breakeven Price of Switchgrass. 2013 Annual Meeting, February 2-5, 2013, Orlando, Florida: Southern Agricultural Economics Association; 2013.

[35] Scanlon BR, Jolly I, Sophocleous M, Zhang L. Global impacts of conversions from natural to agricultural ecosystems on water resources: Quantity versus quality. Water Resour Res 2007;43:doi:10.1029/2006WR005486.

[36] Wilcox BP. Does rangeland degradation have implications for global streamflow? Hydrol Process 2007;21(21):2961-4.

[37] Acreman M, Dunbar MJ. Defining environmental river flow requirements–a review. Hydrol Earth Syst Sc 2004;8(5):861-76.

Table 4.1 Sensitivity analysis and final calibration results for parameters influencing predicted streamflow for the upper basin (above Enid gauge station) and lower basin (between Enid and Lovell gauge stations).

Parameter Code	Description	Sensitivity ranking		Parameter changed to	
		Upper basin	Lower basin	Upper basin	Lower basin
Alpha_Bf[a]	Baseflow alpha factor (d^{-1})	3	3	0.10	0.18
Ch_K2[a]	Channel effective hydraulic conductivity (mm h^{-1})	9	5	5.62	3.12
Cn2[b]	Initial SCS CN II value	1	1	1.07	1.04
Esco[a]	Soil evaporation compensation factor	2	2	0.72	0.76
Gwqmn[a]	Threshold water depth in the shallow aquifer for flow (mm)	7	6	17.58	6.90
Revapmn[a]	Threshold water depth in the shallow aquifer for "revap" (mm)	10	7	33.04	55.35
Sol_Awc[b]	Available water capacity (mm H2O mm^{-1} soil)	5	4	1.018	1.085
Sol_Z[b]	Soil depth (mm)	6	8	1.028	1.021
Surlag[a]	Surface runoff lag time (d)	4	10	1.58	1.58

The parameter variation methods were *a* = replacement of initial parameter values with the new values, and *b* = multiplying the initial value by the calibration values

Table 4.2 Summary of annual water balance during the simulation period (2002 through 2011) for the baseline condition, scenario-I (grassland conversion to switchgrass), and scenario-II (marginal cropland conversion to switchgrass) along with the area converted and switchgrass produced under each scenario.

Scenarios	Precipitation	ET	Streamflow	Area converted	Biomass produced
		mm		ha	Mg
Baseline	806	660	138		
Scenario I	806	697	100	37,600	435,000
Scenario II	806	663	134	28,900	351,000
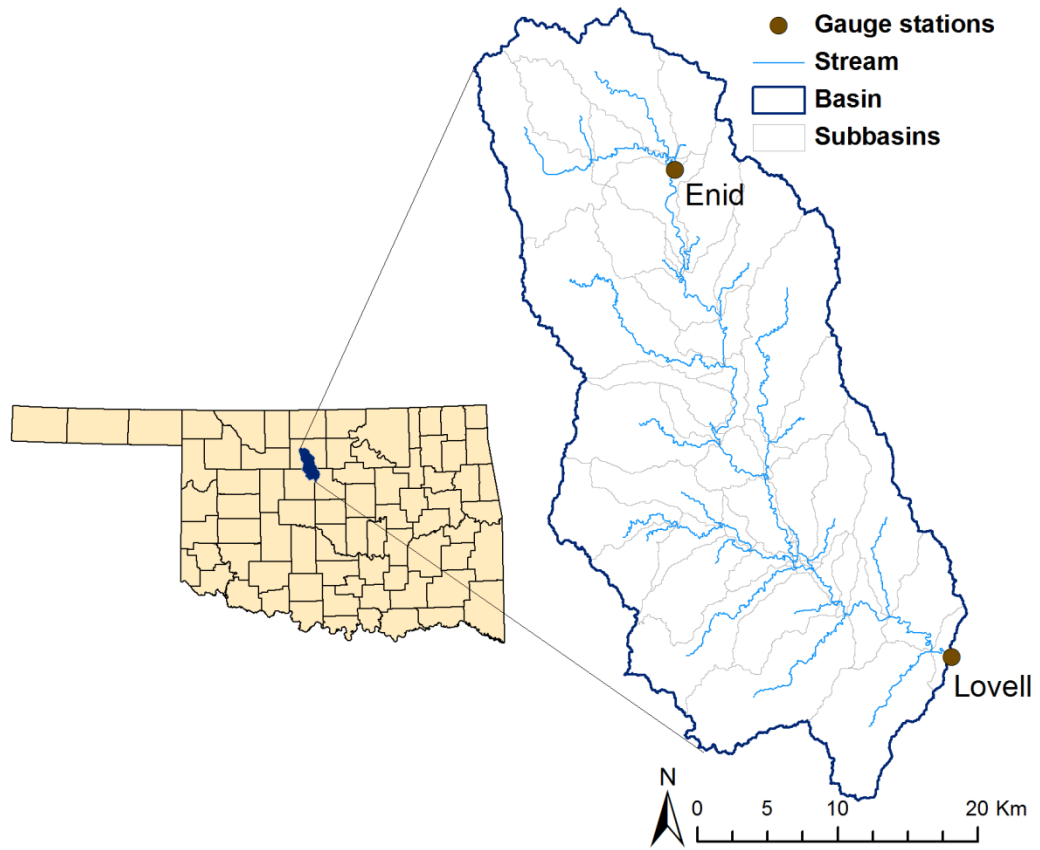
Fig. 4.1 Location of Skeleton Creek watershed in north central Oklahoma and the locations of two stream gauge stations.
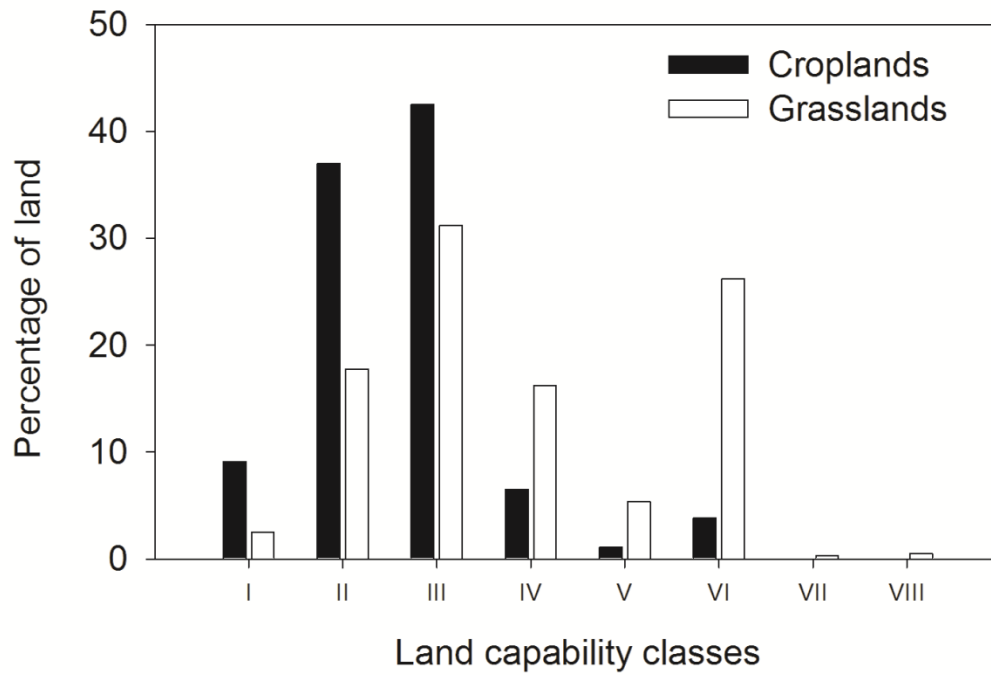
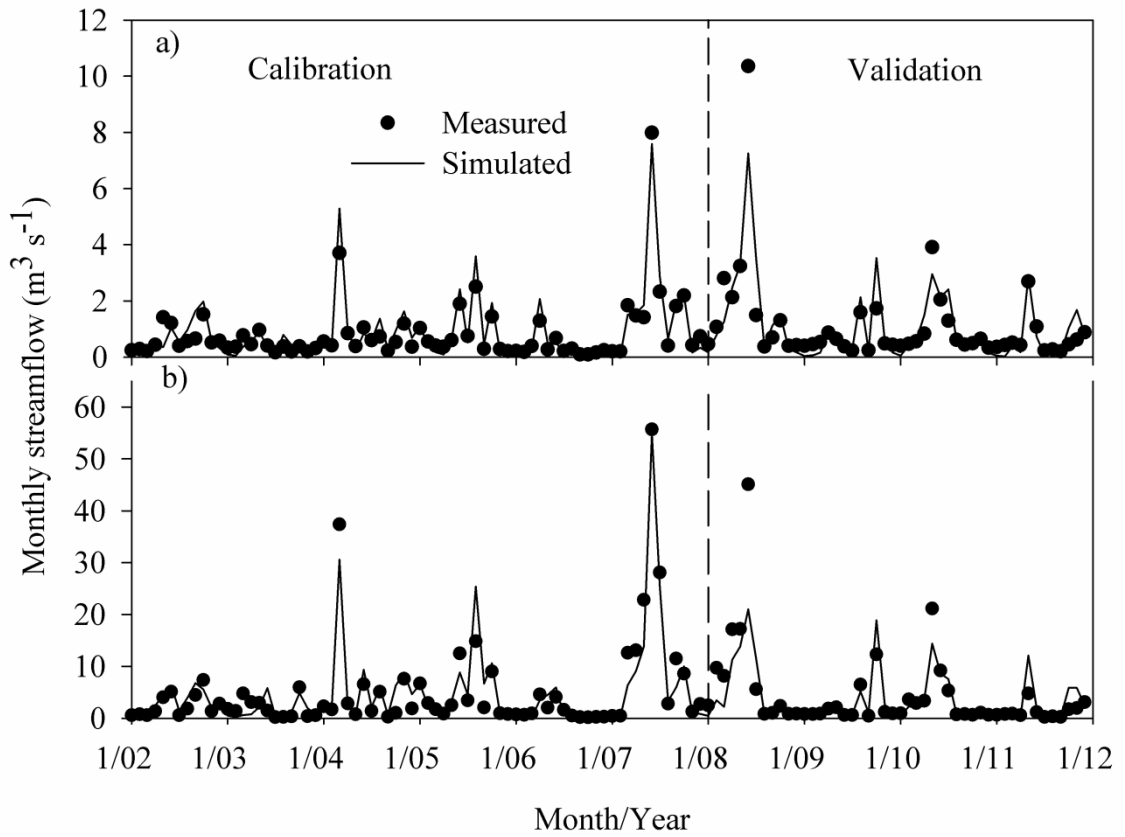Fig. 4.2 Percentages of croplands and grasslands in NRC land capability classes I through VIII.

Fig. 4.3 Comparison of observed and simulated monthly mean streamflow at Enid, OK (a) and Lovell, OK (b) during six years of calibration (2002-2007) and four years of validation (2008-2011).
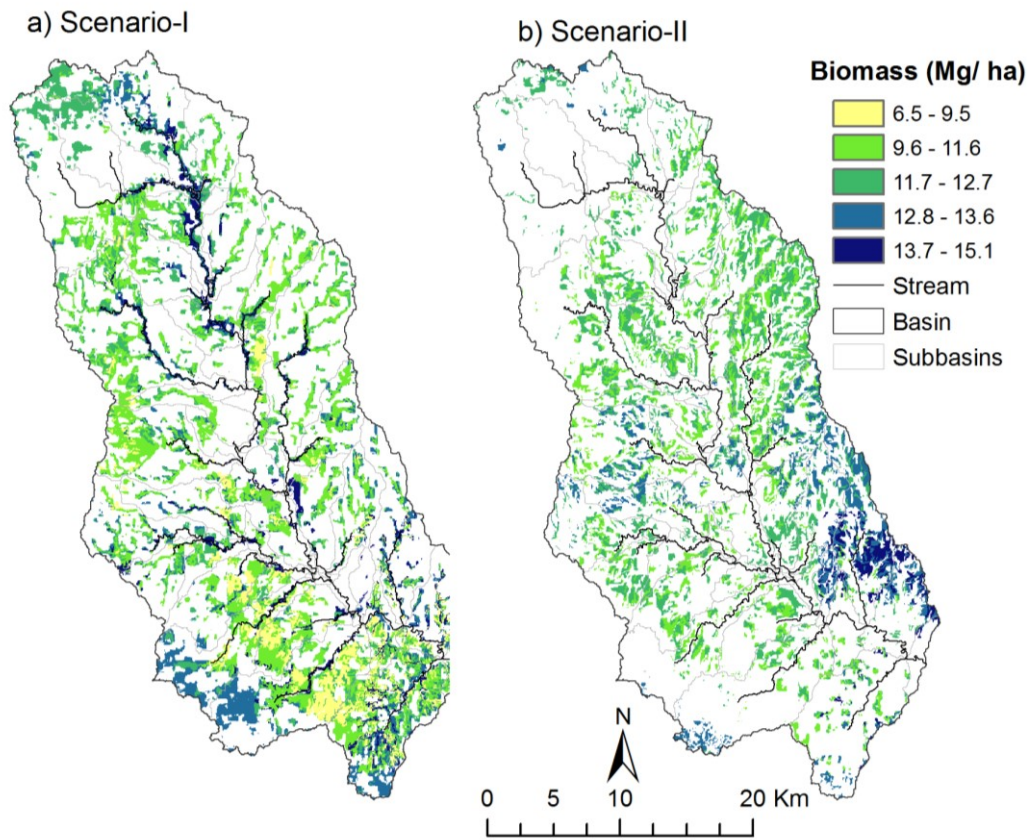
Fig. 4.4 Simulated average annual switchgrass production for 2002-2011 for conversion of grasslands (a) and marginal croplands (b).
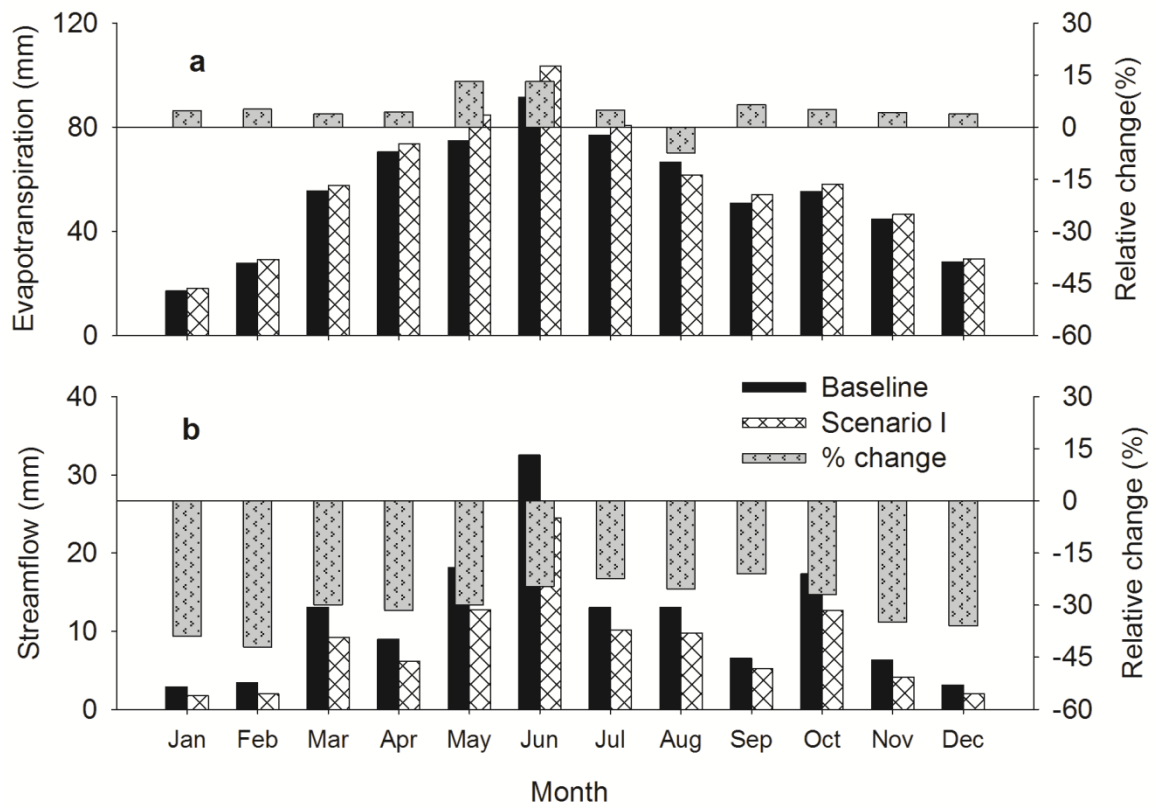
Fig. 4.5 Simulated average monthly evapotranspiration (a) and streamflow (b) for 2002-2011 for the baseline and scenario-I (grassland conversion to switchgrass).
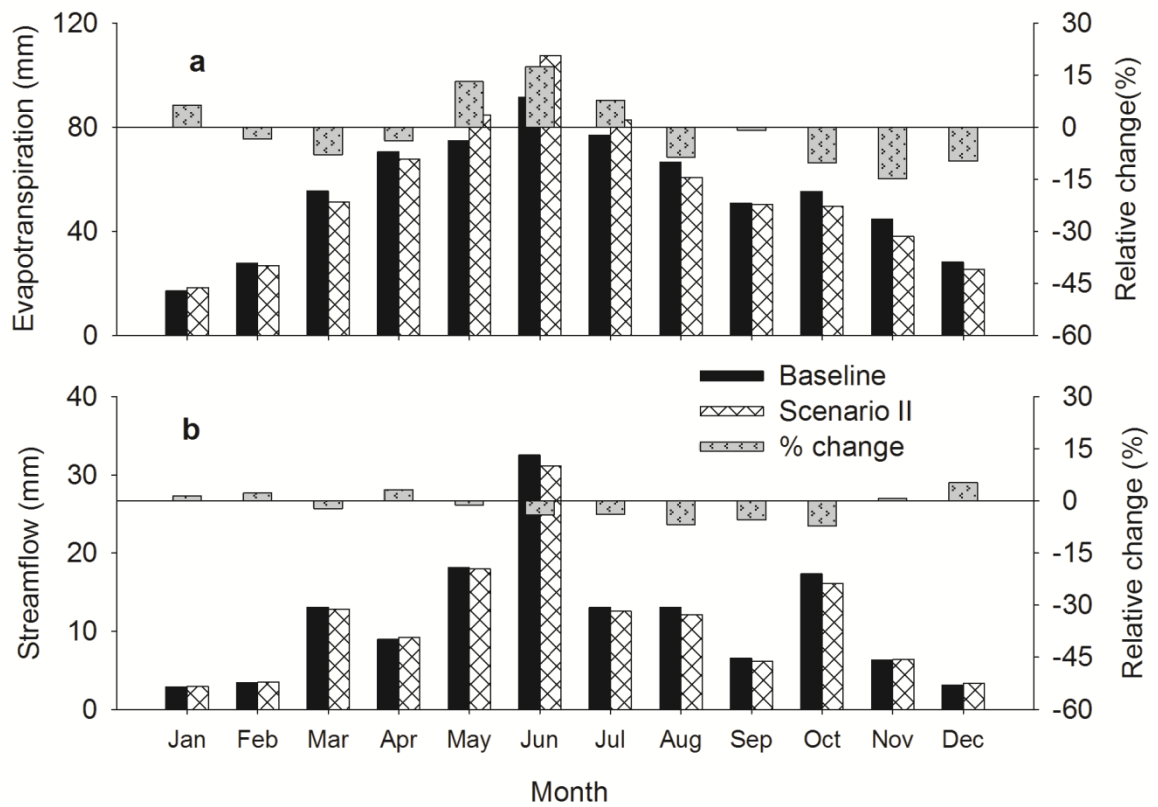
Fig. 4.6 Simulated average monthly evapotranspiration (a) and streamflow (b) for 2002-

2011 for the baseline and scenario-II (marginal cropland conversion to switchgrass).
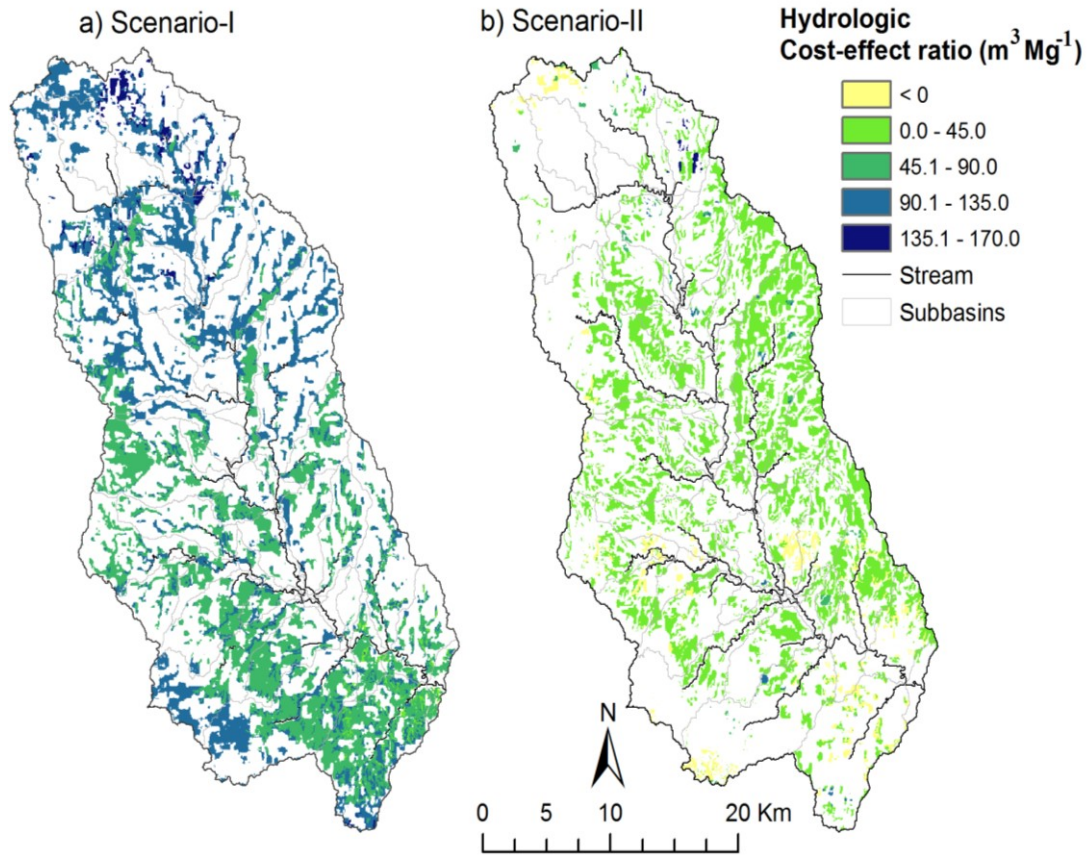
Fig. 4.7 Map of hydrologic cost-effect ratio for each HRU defined as average annual water yield reduction relative to the baseline scenario divided by the switchgrass production for each HRU for the case of grassland conversion (a) and marginal cropland conversion (b).

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