PARAMETERIZATION AND APPLICATION OF THE AQUACROP MODEL FOR SIMULATING BIOENERGY CROPS IN OKLAHOMA

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CHAPTER I

INTRODUCTION

Global demand for food is expected to double within the coming 50 years and global demand for transportation fuels is expected to increase even more rapidly. Increasing use of biofuels is driving scientists to search for ways to balance the needs for both food and fuel. Maize (*Zea mays* L.) is the primary feedstock for US biofuel production, but competing feed and food demands and declining water and land resources limit its potential expansion (Solomon et al., 2007). One alternative is cellulosic ethanol, which is ethanol produced from cellulosic feedstock rather than grain (Johnson et al., 2007). The AbenGoa biorefinery under construction in southwest Kansas will use cellulosic feedstock from southern Kansas and the Oklahoma Panhandle for ethanol production. Those regions are underlain by the High Plains Aquifer which supports extensive irrigated corn and wheat production. But, the ongoing depletion of groundwater in the region calls into a question the sustainability of the current cropping system (McGuire, 2009). To produce sufficient feedstock for ethanol production while sustaining the aquifer will be a major challenge. Forage sorghum (*Sorghum bicolor* L.) and switchgrass (*Panicum virgatum* L.) are considered as good candidates for cellulosic feedstock production. Proponents claim that these crops require less water than corn (Cook et al., 2000). However, few studies, and none in the southern Great Plains, have directly compared the productivity of forage sorghum, switchgrass, and corn in a water-limited environment. There is a clear need to determine if, and at what level, declining water availability would favor a shift in the cropping systems of the semi-arid southern Great Plains from corn to cellulosic feedstocks. The recently developed AquaCrop model is suitable for that analysis because it is specifically designed to predict crop response under water limitations (Steduto et al., 2009). However, AquaCrop calibration parameters have yet to be developed for cellulosic feedstocks like forage sorghum and switchgrass. Thus, calibration of the model is needed to enable analysis of these crops within the context of ethanol production.

Nature, scope and objectives of the research

The long term goal of our research is to discover ways to maintain agricultural productivity and overcome the otherwise unavoidable grip of water scarcity. The main objective of this study is to compare forage sorghum, switchgrass, and corn performance under full irrigation, deficit irrigation, and rainfed conditions in the Oklahoma Panhandle. Comparing the water productivity and water use of forage sorghum, switchgrass, and corn will help us to decide if these cellulosic feedstocks have a promising future for ethanol production in the southern Great Plains. Groundwater level declines of up to 14 feet have been reported from pre-development to 2005 in this region of the High Plains Aquifer (McGuire, 2009). The central hypothesis of the study is that as water availability declines, the most productive crop will shift from being corn to forage sorghum and finally to switchgrass. The following specific aims are proposed as part of this project:

Specific aim 1: Parameterize the AquaCrop model to accurately simulate forage sorghum and switchgrass growth across a range of water limitations. Field data from locations with widely varying climates and soil types will be used to calibrate and validate the model.

Specific aim 2: Compare the performance of forage sorghum, switchgrass, and corn under full irrigation, deficit irrigation, and rainfed conditions in the Oklahoma Panhandle. Forage sorghum, switchgrass, and corn yields will be simulated for ten years (2002-2011) under full irrigation, deficit irrigation, and rainfed conditions at Goodwell, OK.

Expected Results and Benefits

The High Plains aquifer experiences ongoing water depletion, but still it is a focus area for bioenergy feedstock production. The results of this research will determine if cellulosic feedstock production can be a part of a more sustainable system which will prolong the life of the aquifer and the vitality of the region. The model parameters we calibrate for switchgrass and forage sorghum will be of use to other researchers studying bioenergy cropping systems.

Related research and significance of the proposed work

Corn is currently a primary crop in the region. Crop survey data by National Agricultural Statistics Service (NASS) from Texas County, in the Oklahoma Panhandle, show that from an area of 81,633 harvested acres (out of which 66,291 acres were irrigated), 15804459 bushels of corn was produced in 2007. This implies that the land has high productivity for corn (approx. 200 bushels acre^{-1}) but over time, with decreasing level of groundwater, the same yield levels may not be achieved. There is a need to look for alternative cropping patterns which can better survive the grip of declining water levels.

High biomass forage sorghum holds promise as a cellulosic feedstock crop due to its high yield potential and vegetative growth habit, which allows more flexible management of the crop. Unger (1988) reported forage sorghum yields up to 11.24 Mg ha^{-1} in Bushland, Texas in 1984 which shows that the crop has a scope in the region. McCollum et al. (2005) reported that forage sorghum near College Station, Texas produced yields equal to or greater than that of corn while using 33% less water. In Iowa, Hallam et al. (2001) compared perennial grasses with annual row crops and found that forage sorghum had the highest yield potential, averaging over 35 Mg ha^{-1} (dry weight basis). However, the performance of forage sorghum under drier conditions is uncertain.

Switchgrass is another prime candidate for feedstock production because of its demonstrated high productivity across a wide geographic range, suitability for marginal quality land, low water and nutrient requirements, and positive environmental benefits (McLaughlin et al., 2005). Cook and Beyea (2000) observed that the conversion of land from annual crops to native perennial grasses like switchgrass added an average of 1.1 Mg C ha^{-1} yr^{-1} to the soil. It has been projected that replacing annual crops with perennial biomass crops would reduce run-off while decreasing soil erosion and improving water quality (Hill, 2007). Switchgrass is widely adapted, has high biomass production, high C-4 photosynthetic efficiency, and efficient use of water and nitrogen. Switchgrass can yield up to 25 Mg ha^{-1} yr^{-1} depending on latitude, nutrition and other factors (Yuan et al., 2008). In an experiment conducted by Koshi et al. (1982) at Big Spring, Texas, the three strains of switchgrass produced about 2 Mg ha^{-1} yr^{-1} of good quality forage under non-irrigated conditions and 6.7 Mg ha^{-1} yr^{-1} under full irrigation. In this experiment, maximum production was obtained with 117 cm yr^{-1} of consumptive water use but maximum water use efficiency was obtained with about 86 cm yr^{-1} of water use. Water affects not only switchgrass yield, but also establishment. Greenhouse studies in Texas indicate that a rainfall frequency of at least once every 7-10 days is critical to early seedling survival under south-western climatic conditions (Hussey et al., 2002). The alkaline conditions of surface soil, such as those found in areas of the Oklahoma Panhandle, could increase stress due to low moisture availability and make the timing of switchgrass planting of critical importance to seedling survival. Switchgrass has demonstrated good physiological resilience evidenced by a high capability to respond to favorable growing conditions that followed extreme droughts (<15 cm rain from April to September) and low yields on individual years in Texas (Hussey et al., 2002). Measurements of leaf level water use efficiency indicate that switchgrass, as expected, uses relatively low levels of water, and that the highest yielding switchgrass varieties had the highest water use efficiencies. While transpiration and photosynthesis were closely related, it was the balance of carbon assimilated per unit of water transpired, the water use efficiency, which appeared to be most closely linked to higher biomass yield (Wullschleger et al., 1996)

The AquaCrop model will be used in the study to simulate and compare yields of corn, forage sorghum, and switchgrass (Steduto et al., 2009). The AquaCrop model evolved from the influential Doorenbos and Kassam (1979) approach for predicting yield response to water. AquaCrop is a canopy-level and water driven model, mainly focused on simulating the crop biomass and harvestable yield in response to available water. Maximum canopy coverage is an important parameter of AquaCrop, but it is equally dependent on canopy growth rate as modulated by stresses. AquaCrop model distinguishes four water stress effects: on leaf growth, stomatal conductance, canopy senescence, and harvest index (HI) (Steduto et al., 2009). Except HI, these effects are manifested through their individual stress coefficient Ks, an indicator of the relative intensity of the effect. The Ks values are a function of soil water depletion. The model requires estimates of the total available water (TAW) capacity for the soil and adjusts the Ks values based on the fraction of the TAW which has been depleted (p). The relation of Ks vs. fractional depletion (p) is usually not linear due to plant acclimation and adaptation to the stress, and also due to the nonlinearity of the matric potential vs. volumetric soil water content relationships.

The research needs a modeling study to simulate the results over a longer period of time i.e. ten years which is otherwise, not feasible under my project. The choice of AquaCrop model over other crop growth models is because this model is water- driven unlike most of the other models which are radiation driven. So, it may have an inherent advantage over them to meet our goal. It calculates biomass in terms of water productivity which is an important key to our results. Moreover, it is easier to parameterize AquaCrop than other comprehensive models since it needs fewer parameters. Heng et al. (2009) have validated the AquaCrop model for corn under deficit irrigation conditions.

Methods and procedures

Parameterize the Aquacrop model to accurately simulate forage sorghum and switchgrass growth across a range of water limitations: Field studies were conducted at three locations across Oklahoma: Stillwater, Woodward, and Chickasha. Forage sorghum, switchgrass, and mixed perennial grasses were grown in randomized block design plots. The AquaCrop model needs four types of data to run a simulation study. These data sets are climate, crop, management, and soil. The weather data for the 2011 growing season was obtained from the Oklahoma Mesonet stations located nearest to each of the field sites. Stillwater had a wetter climate with good rainfall and relatively low moisture stress while Chickasha and Woodward experienced drier conditions. The management practices and the crop parameters such as estimated dates for developmental growth stages and planting density were recorded from the field experiments. The canopy expansion rate, canopy stress coefficients and canopy decline coefficients were calibrated to match the observed dynamics of canopy growth for forage sorghum and switchgrass at three field sites with varying levels of water stress.

The soil parameters such as field capacity, permanent wilting point, total available water, and saturated hydraulic conductivity were measured in the lab. Soil samples were taken using a hydraulic sampler with a 3.5 inch outer diameter steel sampling tube. Soil segments were cut for 0-20, 20-40, 40-60, 60-80, and 80-100 cm intervals. These intact samples were used in Tempe cells to determine the soil moisture retained at -33kPa (Dane et al., 1965). The pressure plate method was used to determine the soil moisture retained at -1500 kPa (Dane et al., 1965). Saturated hydraulic conductivity was measured for intact samples from each soil layer using the constant head tank method by Reynolds and Elrick (1983) in Methods of Soil Analysis.

Crop data such as seeding rate, planting density, and developmental stages such as dates of emergence, floral initiation, and physiological were recorded and used as inputs for the model simulation. The model requires an estimate of the maximum rooting depth of the crop. Rooting depth was estimated by using water depletion measurements monitored with a neutron probe. AquaCrop uses canopy coverage rather than leaf area index (LAI) to partition the crop water use into evaporation and transpiration. By taking overhead photographs of crop cover with the optical plane of the camera parallel to the ground surface a few days after emergence, an approximate initial canopy coverage (CC_o) was estimated (Hsiao et al., 2009). In switchgrass, the regrowth of green leaves from the dormant crown was considered as emergence in the next season. The pictures were taken looking vertically downward, approximately 1.5 m above the canopy, using automatic exposure. The green canopy coverage was estimated using SamplePoint software, a manual image classification tool (Booth et al., 2006).

The canopy cover was plotted against time throughout the growing season at the experiment locations to find the canopy growth in relation to water stress conditions. The crops at the Stillwater location had the least water stress. So, the data from that site were used to calibrate the canopy growth rate parameters for forage sorghum and switchgrass to achieve the best match between measured and observed canopy cover dynamics. For calibrating the water stress effect, water stress threshold levels had to be defined. The water stress coefficients Ks are functions of water content in the root zone, expressed as a fractional depletion (p) of the total available water. Parameter estimation was accomplished by a manual trial and error approach. A similar approach has been used successfully to calibrate AquaCrop for deficit irrigation of cotton (Farahani et al., 2009).

Compare the performance of forage sorghum, switchgrass, and corn under full irrigation, deficit irrigation, and rainfed conditions in the Oklahoma Panhandle.

Forage sorghum, switchgrass, and corn yields were simulated for ten years (2002-2011) under full irrigation, deficit irrigation, and rainfed conditions at Goodwell, Oklahoma using the calibrated AquaCrop model. The soil data were based on samples taken at the Oklahoma

Panhandle Research and Extension Center, and weather data were obtained from the Goodwell Mesonet station for the growing season of each of the crop. The planting date for forage sorghum was set as 5 May, while switchgrass was assumed to break dormancy on 17 March based on observations at Stillwater, Oklahoma. Irrigation in AquaCrop was simulated by selecting an allowable depletion level of the root zone at which irrigation should be triggered. In this study, the irrigation scheduling for full and deficit irrigation treatments will be at 50% and 70% depletion of available water capacity respectively.

The AquaCrop model calculates biomass based on the crop's normalized water productivity. Water productivity is the amount of biomass produced per unit of water depleted by the crop through transpiration. The biomass yield units were converted into theoretical ethanol yield to bring all the three crops to the same scale of comparison since corn cannot be compared in yield units to forage sorghum and switchgrass as it also has a grain component in it. The yield to water relationship is also described for each crop.

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CHAPTER II

PARAMETERIZATION AND TESTING OF THE AQUACROP MODEL FOR BIOENERGY CROPS: SWITCHGRASS AND FORAGE SORGHUM

Abstract

The recently developed AquaCrop model is specifically designed to predict crop yields as influenced by water stress. It has been parameterized for many cereal crops and vegetable crops but not for simulation of forage crops in general or bioenergy crops in particular. The objective of this study was to parameterize the AquaCrop model for two bioenergy crops, switchgrass and forage sorghum, using field measurements from Stillwater, Oklahoma in 2011. The parameterized model was then validated for additional sites at Chickasha and Woodward, Oklahoma. After parameterization at Stillwater, the simulated canopy cover closely matched the measured canopy cover dynamics with a RMSE of 6% in switchgrass and 5% in forage sorghum. The water stress thresholds for canopy expansion and stomatal conductance were similar for switchgrass and forage sorghum, but senescence was induced at 35% available water depletion for forage sorghum compared to 85% for switchgrass. The maximum rooting depth of switchgrass was estimated at 190 cm and that of forage sorghum at 120 cm. The normalized water productivity of switchgrass was found to be 14 g m^{-2}, approximately half that of forage sorghum which was 27 g m^{-2}. The parameterized model reasonably simulated soil water depletion at Stillwater (RMSE < 34 mm) and canopy cover at Chickasha and Woodward (RMSE < 11%) for both crops.

Introduction

Since its introduction by the UN Food and Agricultural Organization in 2009, AquaCrop has been widely used for research related to agricultural water management. AquaCrop is a canopy-level and water driven model which simulates crop biomass and harvestable yield as constrained by available water (Hsiao et al., 2009). It is specifically designed to predict crop productivity as a function of water stress, which is one of the most difficult relationships to accurately represent in crop modeling (Steduto et al., 2009). AquaCrop evolved from the Doorenbos and Kassam (1979) equation [1], for predicting yield response to water:

$$\left(1-\frac{Y}{Y_x}\right)=K_y\left(1-\frac{ET}{ET_x}\right) \qquad [1]$$

where Y and Y_x are actual and potential yield, ET and ET_x are actual and potential evapotranspiration and K_y is the proportionality factor between relative yield loss and relative reduction in evapotranspiration. AquaCrop improved on the Doorenbos and Kassam (1979) approach by separating ET into evaporation and transpiration. The biomass is then predicted based on cumulative daily transpiration and the crop water productivity. Crop water productivity is defined by Kassam and Smith (2001) at FAO as “Crop yield/water consumptively used in evapotranspiration.” The model was designed to be sufficiently accurate for the development of water management strategies while avoiding the complexity and lack of transparency common among existing crop models. AquaCrop has previously been parameterized for many cereal crops like corn (Hsiao et al., 2009), wheat (Andarzian et al., 2011), and barley (Araya et al., 2010), for cotton (Farahani et al., 2009), for vegetable crops such as quinoa (Geerts et al., 2009), for root and tuber crops and even for oilseed crops like sunflower (Todorovic et al., 2009) and canola (Zeleke et al., 2011).

However, the present day cropping system is shifting from being only food crops to both food and fuel crops. So far, the AquaCrop model has not been parameterized for most of the biomass crops or forage crops, in general, other than corn. Corn is currently the primary biofuel crop in the U.S., but switchgrass and forage sorghum are considered the next best candidates for biofuel production, especially in the water limited areas of the Southern Great Plains. Previous studies by McCollum et al. (2005) reported that forage sorghum near College Station, Texas produced yields equal to or greater than that of corn while using 33% less water. In Iowa, Hallam et al. (2001) compared perennial grasses with annual row crops and found that forage sorghum had the highest yield potential, averaging over 35 Mg ha^{-1} (dry weight basis). Another study by Rooney et al. (2007) compared the performance of corn, forage sorghum and switchgrass in a wetter climate. The findings of this study have been presented in Table 2.1. However, the performance of these bioenergy crops under drier conditions is still uncertain. It is, therefore, important to parameterize the Aquacrop model for both switchgrass and forage sorghum to accurately simulate crop growth in response to water stress.

The parameterization of the model involves adjusting some conservative parameters which remain fixed for a species and some site-specific parameters which are influenced by local climate, soil, and management. Canopy development coefficients including the maximum canopy coverage (CC_x), canopy growth coefficient (CGC), and canopy decline coefficient (CDC) are key among these conservative parameters. The crop water productivity (WP*) normalized by the reference evapotranspiration (ET_o), is another important conservative parameter influencing the predicted yields (Steduto et al., 2009). The AquaCrop model distinguishes four water stress effects: on leaf expansion, stomatal conductance, canopy senescence, and harvest index (Steduto et al., 2009). Except harvest index, these effects are manifested through their individual stress coefficient, Ks, an indicator of the relative intensity of the effect. The Ks values are a function of soil water depletion and are reflected in the canopy growth of the crop. The model requires estimates of the total available water (TAW) capacity for the soil and adjusts the Ks values based on the fraction of the TAW which has been depleted (p). Water stress affecting leaf expansion begins when the fraction of TAW depleted exceeds an upper threshold ($p\ upper_{exp}$), and leaf expansion ceases when the fractional depletion exceed a lower threshold (p $lower_{exp}$). Likewise, there are upper thresholds for water stress affecting stomatal conductance and canopy senescence, and the corresponding lower thresholds are defined by the permanent wilting point of the soil. The objective of this study is to parameterize the canopy coefficients, the water productivity, and stress thresholds in the AquaCrop model to allow optimal simulation of the growth of forage sorghum and switchgrass across a range of water limitations.

Materials and Methods

Locations

The field experiment used here for model parameterization was established in 2010 at the Efaw research farm near Stillwater, Oklahoma (36°07'50" N, 97°06'17" W), 268.83 m above sea level. The site has a humid subtropical climate in the Köppen classification system with summer temperatures rising to more than 38°C and winter low temperatures reaching -7°C. Data from 2011 growing season were used in the study to parameterize the AquaCrop model. The maximum and minimum temperatures for 2011 were 40°C and -6.3°C, respectively, with a total of 350 mm of rainfall. The dominant soil series at the site is the Pulaski series which is a fine sandy loam to silt loam with 0-1% of slope. The soils were well drained, in general, with a deep water table.

Similar field experiments were established at two other locations in Oklahoma in 2010 and provide data to validate the parameterized model. One validation experiment was located at the South-central Research Station near Chickasha, Oklahoma. The dominant soil series at the site is Teller series with 1-3% of slope. The soils are well drained with a typical soil profile having a loamy texture. The other validation experiment was located at the Southern Plains Research Station near Woodward, Oklahoma. The dominant soil series found at the site is Devol series with well drained sandy loam soils on a 0-3% slope. The weather data for the three experimental sites is presented in Table 2.2.

Agronomic Management

At each location, forage sorghum, switchgrass, and mixed grasses were established in 2010 under rainfed conditions in a randomized complete block design. There were three replications at Stillwater and four at Woodward and Chickasha. Forage sorghum is planted each subsequent spring in the same plots. Planting and harvest dates are specified in Table 2.3. In 2011, switchgrass broke dormancy in the second half of March. The mixed grasses were included in the experiment because some studies have reported higher yields for mixed stands than for monocultures on marginal soils (Tilman et al., 2006). Mixed grasses are not considered in the present study.

Supporting Data

Weather data were collected from the Oklahoma Mesonet station closest to each experiment location (McPherson et al., 2007). Daily observations of maximum temperature (°C), minimum temperature (^{o}C), average relative humidity (%), daily rainfall (mm), total solar radiation (MJ/m^{2}), and wind speed at 2 m height (m sec^{-1}) were obtained from the Mesonet system for 2011. This information was then used in a Penman-Monteith equation (Allen et al., 1998) based ET_o calculator, which estimates a daily value of reference evapotranspiration throughout the crop season (Annandale et al., 2002). The values were included in the AquaCrop climate file, a user-specific file which also includes temperature, rainfall, and CO_2 concentration data.

The soil input file for Aquacrop requires four parameters for each soil layer: soil texture, volumetric water content at saturation, field capacity (FC), permanent wilting point (PWP), and saturated hydraulic conductivity**.** Soil samples were collected at the beginning of the cropping season in 2010, using a hydraulic sampler with an 8.89 cm outer diameter steel sampling tube which resulted in 7.47 cm diameter samples. Soil segments were cut for 0-20, 20-40, 40-60, 60-

80, and 80-100 cm intervals. Triplicate samples were obtained for each depth at each location. Soil texture was analyzed using the hydrometer method (Gee et al., 1979). Intact sub-samples were used in Tempe cells (Model 1405, Soil Moisture Equipment Corp., Santa Barbara, CA) at 33 kPa pressure to determine the soil moisture at FC (Dane et al., 1965). Additional sub-samples for each layer were dried, ground, and sieved to pass a 2-mm sieve. These sub-samples were used on pressure plates (Model 1500F1, Soil Moisture Equipment Corp., Santa Barbara, CA) at 1500 kPa pressure to determine the soil moisture at PWP (Dane et al., 1965). Saturated hydraulic conductivity was measured for a second set of intact sub-samples from each soil layer using the constant head tank method by Reynolds and Elrick (1983). The observed soil properties of the study sites are listed in Table 2.4.

The soil water content in the soil profile at Stillwater was determined using neutron probe measurements (Model 503 Hydroprobe, CPN International, Concord, CA) at weekly intervals. Access tubes were installed in the plots and soil moisture readings were taken at 20 cm intervals from 10 cm to 190 cm. A soil specific linear calibration was used to convert neutron count ratio to soil water content (Yohannes Yimam, personal communication).

Visual estimates of canopy cover (CC) were done by digital imagery. By taking overhead photographs of crop cover with the optical plane of the camera parallel to the ground surface a few days after emergence, an approximate initial canopy coverage (CC_o) can be estimated (Hsiao et al., 2009). In switchgrass, the regrowth of green leaves from the dormant crown is considered as emergence in the next season. The pictures were taken looking vertically downward, approximately 1.5 m above the canopy, using automatic exposure. The canopy coverage was estimated using SamplePoint, a software to get percent canopy cover (Booth et al., 2006). The canopy cover of the crops, switchgrass and forage sorghum, was monitored every 15 days throughout the growing season. The crops were mechanically harvested using a swather. The harvestable yield was collected from the center rows of each plot. The residual biomass was also collected from four 0.09 m^2 quadrats in each plot to estimate the harvest index of the crops. For the purposes of this study, harvest index was defined as the ratio of the harvested biomass to the total above ground biomass produced in the growing season.

Parameterization of the Model

Conservative Parameters

The calibration of the model was accomplished primarily by comparing measured and simulated canopy cover development throughout the growing season. AquaCrop uses CC instead of leaf area index (LAI) in part because CC directly influences both evaporation and transpiration. Canopy cover is affected by species specific conservative parameters such as (a) CGC which describes the daily percent increase in CC during the growth of the crop, (b) CDC which corresponds to the daily percent reduction in CC towards maturity of the crop, and (c) the water stress upper and lower threshold values, and shape factors for leaf expansion, stomatal conductance, and senescence.

The water stress coefficients, Ks, are functions of water content in the root zone, expressed as a fractional depletion (p) of the total available water. The leaf expansion Ks, Ks_{exp}, in relation to fractional depletion is a convex curve (Steduto et al., 2009). The convex nature is the consequence of adjustments by the crop to cope with the developing water stress that improve with time its resistance to stress (Steduto et al., 2009). Figure 2.1 illustrates the stress coefficients for leaf expansion, stomatal conductance, and canopy senescence as functions of fractional depletion of TAW. Points *a* and *b* are the upper and lower thresholds for water stress effects on leaf expansion, point *c* is the upper threshold for stomatal conductance and point *d* is the upper threshold for senescence. The lower threshold of stomatal conductance and senescence were fixed at PWP. The points *a, b, c, d* were calibrated for forage sorghum and switchgrass.

For switchgrass, the start of the growing season was approximated as the date when the first signs of green-up were observed at the Stillwater location. For both crops, the days required for 90% emergence, for maximum canopy, for beginning of senescence, and for maturity were adjusted based on observed canopy cover throughout the season. Maximum canopy cover, which is the potential canopy reached by the crop under optimal environmental conditions given the actual plant density, was set at 99% for both crops. Senescence of the crop here refers to the time when the canopy starts declining as the crop approaches maturity. This culminates in physiological maturity of the crop when the crop is ready to harvest. These physiological development stages were estimated in terms of calendar days for both switchgrass and forage sorghum.

A critical conservative parameter within AquaCrop is the normalized water productivity, WP*, defined as

$$WP^* = \frac{B}{\sum \left(Tr / ET_o \right)} \qquad [2]$$

where B is the above ground biomass, Tr is the daily transpiration and ET_o is the reference evapotranspiration for the location (Steduto et al., 2009).The normalized water productivity was adjusted to match the simulated yield with the measured yield for the Stillwater location. The other conservative parameters were adjusted to reproduce field observed CC and soil water depletion at the Stillwater location. A manual trial and error approach was used (Farahani et al., 2009), adjusting one parameter at a time. The Woodward and Chickasha locations were used as validation sites for the conservative parameters determined at Stillwater.

Site Specific Parameters

While some parameters are crop specific, some vary according to the site management. These parameters may be affected by factors such as planting density, irrigation, initial soil water content, and fertilizer application rates.

Initial canopy cover (CC_o) is a vital parameter for simulating the canopy development of the crop. Initial canopy cover is dependent on the planting density, and plant cover per seedling. Other factors that may affect initial canopy cover include prevailing temperature conditions, soil moisture conditions, and planting depth. The initial canopy cover in the model was adjusted based on the field observations of the canopy cover at the beginning of the growing season. Initial canopy cover at Stillwater location was set at 0.48% in switchgrass and 0.23% in forage sorghum. A similar approach was used to adjust CC_o at the validation sites. At Chickasha and Woodward, CC_o in switchgrass was adjusted to 0.10% and 0.21% respectively. In forage sorghum, CC_o was adjusted to the default minimum which is 0.10%. When the initial canopy cover of a crop is higher, it can reach maximum canopy cover sooner and avoid heat and water stress later in the season.

Rooting depth is also a site specific parameter. The time to reach the maximum rooting depth generally coincides with the start of canopy senescence under optimal conditions. However, under stressed conditions, canopy senescence may occur earlier while the roots may continue to grow. Soil moisture data from the Stillwater location were used to estimate the maximum rooting depth of the crops. There was evidence of soil water depletion to a depth of 190 cm under switchgrass and 120 cm in forage sorghum. The same values were used for the other two locations.

The initial soil water content plays an important role in the germination and development of the crop, especially under rain fed conditions. Therefore, it is crucial to accurately estimate the initial soil water content at the start of the growing season. Initial soil water content was measured using the neutron probe at the Stillwater location within 1-2 weeks of the start of the growing season for each crop. The initial soil water content at the Woodward and Chickasha locations was set to field capacity.

Harvest index for biomass crops like switchgrass and forage sorghum depends primarily upon harvest procedures such as harvest timing and cutting height. Harvest index for each crop and location was estimated based on harvested yields and above ground biomass and residue remaining after harvest. Since this was the second year of the experiment, some of the biomass and residue was from the prior year. Based on visual estimates at the beginning of the growing season, the carry-over biomass and residue was calculated at 25% of the total measured after harvest in switchgrass and 75% in forage sorghum.

Data Analysis

Model performance was analyzed by comparing simulated results with the measured values. The root mean square error (RMSE) was used to quantify the agreement between the observed and simulated canopy cover and soil water depletion.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(M_i - S_i\right)^2} \qquad [3]$$

where S_i and M_i are the simulated and measured values respectively and *n* is the number of observations. The unit of RMSE is the same as the parameters compared.

The Nash-Sutcliffe model efficiency coefficient (E) is used to quantify the proportion of variability in the observed values that was accounted for by the model (McCuen et al., 2006).

$$E = 1 - \frac{\sum_{i=1}^{n}\left(M_i - S_i\right)^2}{\sum_{i=1}^{n}\left(M_i - \overline{M}\right)^2} \qquad [4]$$

where $\overline{M}$ is the measured mean. An efficiency of 1 (E = 1) corresponds to a perfect match of modeled results to the observed data. An efficiency of 0 (E = 0) indicates that the model predictions are as accurate as the mean of the observed data, whereas an efficiency less than zero (E < 0) occurs when the observed mean is a better predictor than the model.

Results and Discussion

Canopy Development

The canopy cover of switchgrass and forage sorghum at Stillwater were adequately simulated with the parameterized model having a RMSE of 6.5% in switchgrass and 5.6% in forage sorghum (Table 2.6). These RMSE values are comparable to those obtained in AquaCrop parameterizations for other crops. For corn, canopy cover RMSE values ranging from 4.8-11% were obtained by Hsiao et al. (2009). For cotton, Farhani et al. (2009) achieved RMSE for canopy cover of 9.5%. Zeleke et al. (2011) reported a RMSE of 8.4% for canola canopy cover.

Figure 2.2 gives a direct comparison of measured and simulated canopy cover at the Stillwater location. Both measured and simulated canopy for switchgrass exceeded 80% from the first week of May through the end of July. In contrast, forage sorghum canopy cover did not exceed 70% because of water and heat stress, and this limitation was also captured by the model. Based on the Stillwater data, the canopy growth coefficient values for switchgrass and forage sorghum are 13.4% d^{-1} and 19.2% d^{-1}, and the canopy decline coefficient values are 8.0% d^{-1} and 3.0% d^{-1} respectively. Hsiao et al. (2009) estimated canopy growth coefficient for corn, the only C4 crop for which AquaCrop has been previously parameterized, at 1.3% GDD^{-1}. During canopy expansion for switchgrass, the Stillwater location accumulated 7.9 GDD per day assuming a base temperature of 8°C. Dividing the switchgrass canopy growth coefficient by this value gives 1.7% GDD^{-1}, higher than the value previously determined for corn. During canopy expansion for forage sorghum, the Stillwater location accumulated 14.2 GDD per day assuming a base temperature of 10°C. Dividing the forage sorghum canopy growth coefficient by this value gives 1.3% GDD^{-1}, the same as the value previously determined for corn. During the decline of the canopy, switchgrass canopy declined 0.4% GDD^{-1} and forage sorghum declined with 0.2% GDD^{-1}, values which are lower than the 1.06% GDD^{-1} decline coefficient for corn estimated by Hsiao et al. (2009).

Based on the measured switchgrass canopy data from Stillwater, canopy expansion stress threshold has upper and lower bounds at 0.25 and 0.55 which means that switchgrass canopy expansion slows once 25% of the total available water is depleted and stops completely when 55% of the total available water is depleted (Table 2.5). In forage sorghum, canopy expansion is even more sensitive to water stress with an upper threshold of only 15% and the lower threshold of 45% (Table 2.5). Hsiao et al. (2009) has previously calibrated an upper canopy expansion threshold at 0.14 and lower canopy expansion threshold at 0.72 for corn. For stomatal conductance, the upper threshold was adjusted to 0.50 for switchgrass and 0.45 for forage sorghum. For corn, Hsiao et al. (2009) estimated the stomatal conductance upper threshold to be 0.69. Canopy senescence upper threshold values for switchgrass and forage sorghum are 0.85 and 0.35, respectively, compared to 0.69 for corn as previously calibrated by Hsiao et al. (2009).

Once the canopy development parameters were adjusted to match the measured canopy, the water productivity of the switchgrass and forage sorghum was then parameterized to reproduce the harvested yields at the Stillwater location. Previous AquaCrop studies give normalized water productivity values ranging between 30-35 g m^{-2} for C4 crop species (Steduto et al., 2009). In switchgrass, the normalized water productivity for our study was estimated to be 14 g m^{-2}. This value is well below the range of previously suggested values from literature. We hypothesize that this is due to the perennial nature of switchgrass which causes it to allocate more carbon to its root biomass. Recall that water productivity is calculated based only on the above-ground biomass. In forage sorghum, the normalized water productivity was 27 g m^{-2}, almost double that of switchgrass. Hsiao et al. (2009) estimated the water productivity of corn at 33.7 g m^{-2}. One reason the water productivity of forage sorghum fell below the expected range may be the intense drought conditions during the study. Another factor potentially affecting the estimated water productivity of both crops is uncertainty in the measured harvest index values arising from uncertainty about the amount of residue carry-over from the previous year's crop. If the measured harvest index was too high, then the normalized water productivity would be too low.

The canopy growth at the validation sites was simulated using the same conservative parameters as determined for the Stillwater location. For switchgrass at Chickasha and switchgrass and forage sorghum at Woodward, the canopy growth was adequately simulated within an RMSE of 8% (Table 2.6). However, the model performance for forage sorghum at Chickasha was poor with a RMSE of 11%. Figures 2.3 and 2.4 show measured and simulated canopy cover dynamics for Chickasha and Woodward. Due to heat and water stress at these locations, canopy cover did not exceed 40% for either of these crops. The model reasonably simulated the evolution of canopy cover except for forage sorghum at Chickasha where the simulated canopy cover was too high. This overestimate may have resulted from the fact that initial soil water content was lower than the assumed value, i.e. below field capacity. The simulated canopy cover was too low at the end of the season for switchgrass at Chickasha and switchgrass and forage sorghum at Woodward. Previous AquaCrop studies (e.g. Heng et al., 2009) have shown similar excessive canopy decline towards the end of the growing season, and this is one of the areas where AquaCrop model may need improvement.

Biomass and Yield

The residual biomass was collected to estimate the harvest index for all locations. For the Stillwater location, the harvest index for switchgrass was estimated to be 53% while forage sorghum had a harvest index of 74%. At Chickasha, the harvest index was calculated as 67% for switchgrass and 10% for forage sorghum. At Woodward, the harvest index was 33% for switchgrass, but in forage sorghum, there was no harvestable yield. In previous AquaCrop parameterizations, harvest index was considered as a conservative parameter. In this study, however, the harvest index was treated as a site-specific parameter because the harvest index of a forage crop depends on the cutting height of the biomass.

The measured yields and simulated yields were within 0.5 Mg ha^{-1} in both crops at all experiment locations, except switchgrass at Chickasha where the model predicts a yield of 4.64 Mg ha^{-1} against a measured yield of 1.78 Mg ha^{-1}. Table 2.7 shows the comparison of measured and simulated yields and measured harvest index for all locations. The biomass is much lower than the previous studies of forage sorghum in the Texas and Oklahoma which have reported biomass of 28 Mg ha^{-1} (Texas Alliance for Water Conservation). Previous switchgrass studies at Beeville, Texas have reported yields of 14.5 Mg ha^{-1} (Muir et al., 2001).

Soil water depletion

Using neutron probe measurements at the Stillwater location, maximum rooting depth was estimated as the deepest depth which showed substantial soil water depletion during the growing season. The maximum rooting depth was 190 cm in switchgrass and 120 cm in forage sorghum. The measured and simulated trends of soil moisture depletion by both sorghum and switchgrass are displayed in Figure 2.5. The model reasonably simulated soil water depletion throughout the growing season, with a RMSE of 17 mm for switchgrass and 34 mm for forage sorghum (Table 2.6). To put these values in perspective, the total available water for switchgrass was 374 mm and for forage sorghum was 236 mm. AquaCrop slightly over predicted the water depletion in switchgrass late in the growing season and in forage sorghum through the entire season. Forage sorghum had a greater soil water deficit at the beginning of the growing cycle than switchgrass. This can be attributed to the carry-over effect of soil water depletion by the previous year’s forage sorghum crop.

Conclusions

AquaCrop was parameterized for Stillwater and tested at two other locations Chickasha and Woodward and was able to reproduce the measured values within reasonable limits of error. The normalized water productivity of switchgrass was only half that of forage sorghum. This is likely due to the perennial nature of switchgrass which causes it to allocate more carbon to its root biomass. The water productivity is calculated based only on the above-ground biomass. The leaf expansion and stomatal conductance thresholds were similar in both switchgrass and forage sorghum. However, the senescence threshold values were strikingly different. Early senescence due to water stress in forage sorghum starts when only 35% of the available water is depleted whereas in switchgrass, the canopy doesn't begin to senescence until 85% of the available water is depleted. In this sense, switchgrass is more drought tolerant.

Under severe water stress conditions at Chickasha and Woodward, AquaCrop underpredicted green canopy cover towards the end of the growing season. This tendency of AquaCrop to predict senescence which is too rapid has also been shown in prior studies. The lack of initial soil water content measurements at Chickasha and Woodward introduced uncertainty in the yield simulations at these validation sites. Although the model was successfully parameterized and gave reasonable predictions for the validation sites, additional validation site years are still needed. The performance of AquaCrop in these water limited environments was satisfactory suggesting that it may be an effective tool for simulating yields of bioenergy crops.

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Table 2.1: Yield response of corn, forage sorghum, and switchgrass to different nitrogen treatments in Iowa. (Reproduced from Rooney et. al, 2007)

Treatment	Forage Sorghum	Switchgrass	Corn
		$Mg\ ha^{-1}$	
Ames, IA (1989-1992)			
0 kg N ha^{-1}	11.3	5.4	8.3
140 kg N ha^{-1}	14.2	9.3	12.7
Chariton, IA (1990-1992)			
0 kg N ha^{-1}	11.7	7.1	8.9
140 kg N ha^{-1}	14.1	9.3	9.6
College Station, TX (1985)			
0 kg N ha^{-1}	4.6	-	-
112 kg N ha^{-1}	5.9	-	-

Table 2.2: 2011 growing season (March 15- November 30) weather summary for Stillwater, Chickasha, and Woodward locations

Station	Average Daily Maximum Temp.	Average Daily Minimum Temp.	Seasonal Rainfall	Average Daily Relative Humidity	Average Daily Solar Radiation	Average Daily Wind Speed
	————°C	————	Mm	%	MJ m^{-2}	m s^{-1}
Stillwater	28.0	13.6	347	57	19.4	2.7
Chickasha	29.0	13.6	372	56	20.6	3.3
Woodward	27.9	12.9	278	48	21.1	4.1

Table 2.3: Agronomic information for switchgrass and forage sorghum for 2010 and 2011

Station	Crop	2010		2011		
		Planting Date	Harvesting Date	Planting Date	Start of Growing Season	Harvesting Date
Stillwater	Switchgrass	12 May	6 Jan		17 March	16 Nov
	Forage Sorghum	25 May	6 Jan	5 May 5		16 Nov
Chickasha	Switchgrass	21 May	10 Nov		21 March	14 Nov
	Forage Sorghum	21 May	10 Nov	6 May		14 Nov
Woodward	Switchgrass	24 May	22 Nov		24 March	4 Jan
	Forage Sorghum	24 May	22 Nov	3 May		4 Jan

Table 2.4: Soil properties for the experiment locations at Stillwater, Chickasha, and Woodward, Oklahoma.

Site	Depth	Soil texture	Saturated Water Content	Field Capacity	Permanent Wilting Point	Saturated Hydraulic Conductivity
	Cm			$cm^3\ cm^{-3}$		mm day^{-1}
Stillwater	0-20	Silty clay loam	0.48	0.34	0.13	111.2
Stillwater	20-40	Silty clay loam	0.41	0.34	0.16	109.4
Stillwater	40-60	Silty clay loam	0.44	0.37	0.16	105.7
Stillwater	60-80	Silty clay loam	0.44	0.35	0.15	110.2
Stillwater	80-100	Loam	0.39	0.30	0.11	113.2
Chickasha	0-20	Silty Loam	0.43	0.27	0.13	126.3
Chickasha	20-40	Silty Loam	0.42	0.30	0.17	135.7
Chickasha	40-60	Silty Loam	0.45	0.23	0.13	125.4
Chickasha	60-80	Silty Loam	0.42	0.22	0.16	123.1
Chickasha	80-100	Silty Loam	0.41	0.18	0.12	154.0
Woodward	0-20	Loam	0.42	0.26	0.11	147.4
Woodward	20-40	Loam	0.41	0.21	0.11	162.3
Woodward	40-60	Loam	0.40	0.28	0.11	179.1
Woodward	60-80	Loam	0.39	0.17	0.09	188.0
Woodward	80-100	Loam	0.39	0.18	0.09	183.5

Table 2.5: Conservative crop parameters for switchgrass and forage sorghum as parameterized for the Stillwater location.

Conservative Parameters	Switchgrass	Forage Sorghum	Explanation
Crop Growth Coefficient	13.4	19.2	% /day
Crop Decline Coefficient	8.0	3.0	% /day
Crop Coefficient for Transpiration at Maximum Canopy Cover	1.1	1.03	Full canopy transpiration relative to ET_0
Normalized Water Productivity	14	27	g/m^2
Leaf growth threshold p (upper)	0.25	0.15	As fraction of TAW, above this leaf growth is inhibited
Leaf growth threshold p (lower)	0.55	0.45	Leaf growth stops at this p
Leaf growth stress coefficient curve shape	3	2.9	Convex curve
Stomatal conductance threshold p (upper)	0.5	0.45	Above this threshold, stomata begin to close
Stomata stress coefficient curve shape	3	0	Convex curve, 0 curve shape is linear
Senescence stress coefficient p (upper)	0.85	0.35	Above this threshold, early canopy senescence begins
Senescence stress coefficient curve shape	3.0	3.7	Convex curve
Days from Planting to			From 1 day after planting
a) Emergence	2	4	
b) Maximum Canopy Cover	30	53	
c) Maximum rooting depth	89	74	
d) Senescence	124	132	
e) Harvest	197	172	
Rooting Depth	1.9	1.2	meter

Table 2.6: RMSE and Coefficient of Efficiency (E) for measured and simulated canopy cover and soil water depletion at Stillwater, Chickasha, and Woodward.

Crop & Station	Canopy Cover		Soil Moisture	
	RMSE (%)	E	RMSE (mm)	E
Stillwater				
Switchgrass	6.5	0.93	17	0.93
Forage Sorghum	5.6	0.96	34	0.82
Chickasha				
Switchgrass	8.2	-6.95	-	-
Forage Sorghum	10.7	-0.54	-	-
Woodward				
Switchgrass	8.3	0.04	-	-
Forage Sorghum	8.0	0.75	-	-

Table 2.7: Measured and simulated biomass and yield and measured harvest index for switchgrass and forage sorghum at the three experiment locations

Location	Treatment	Measured Harvest Index	Measured Biomass	Simulated Biomass	Measured Yield	Simulated Yield
		%	Mg ha^{-1}			
Stillwater	Switchgrass	53	8.12	8.56	4.34	4.54
Stillwater	Forage Sorghum	74	5.88	6.59	4.36	4.43
Chickasha	Switchgrass	67	2.65	6.92	1.78	4.64
Chickasha	Forage Sorghum	10	1.93	0.20	0.20	0.00
Woodward	Switchgrass	32	3.93	5.31	1.28	1.70
Woodward	Forage Sorghum	00	0.44	0.00	0.00	0.00

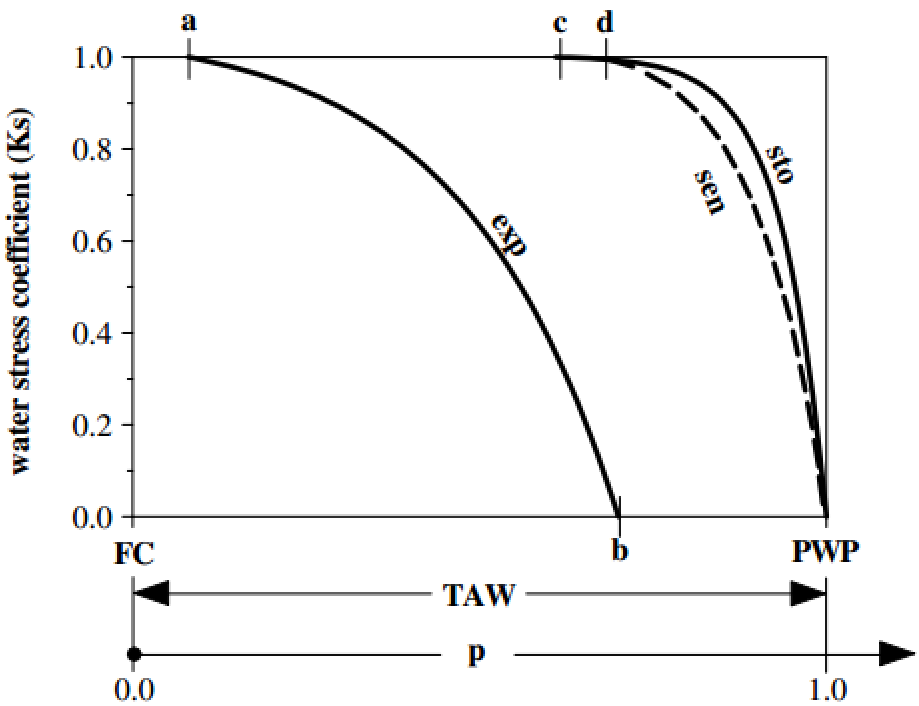


Figure 2.1: Stress coefficients (Ks) for leaf expansion, stomatal conductance, and canopy senescence as functions of soil water depletion (p). (Reproduced from Steduto et al., 2009)

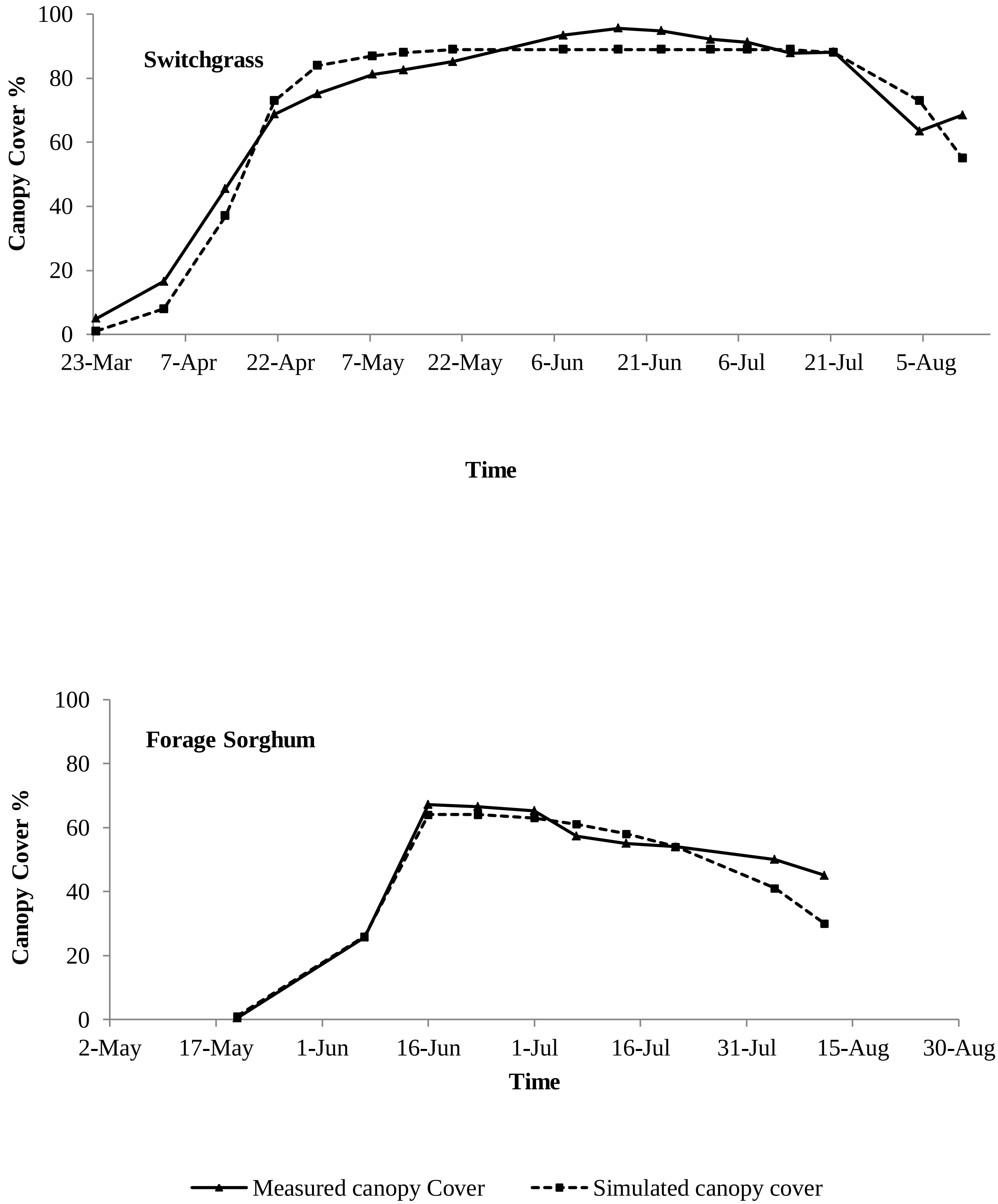


Figure 2.2: Measured and simulated canopy cover for switchgrass and forage sorghum at Stillwater, Oklahoma.

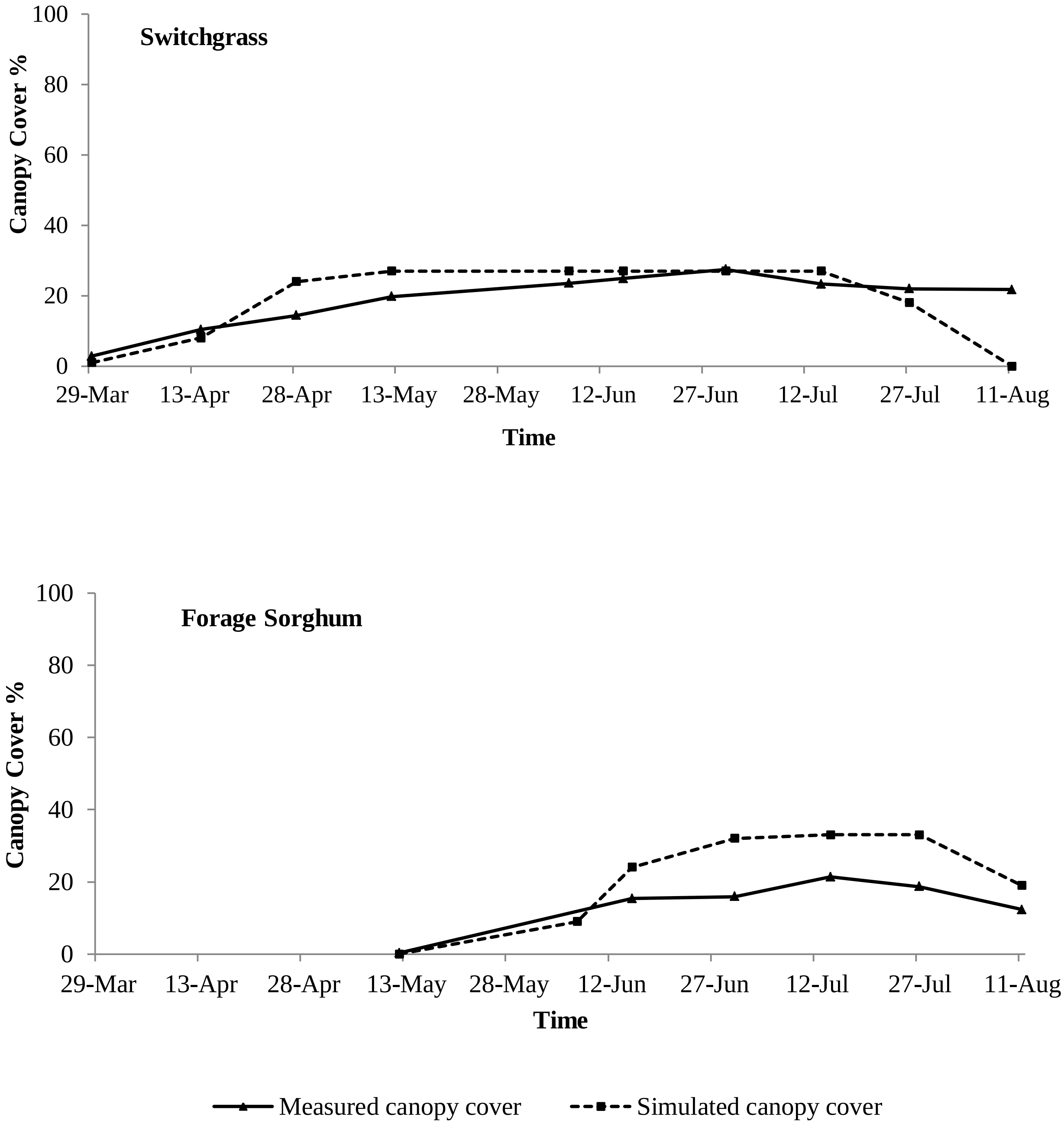


Figure 2.3: Measured and simulated canopy cover for switchgrass and forage sorghum at Chickasha, Oklahoma using conservative parameters determined at the Stillwater location.

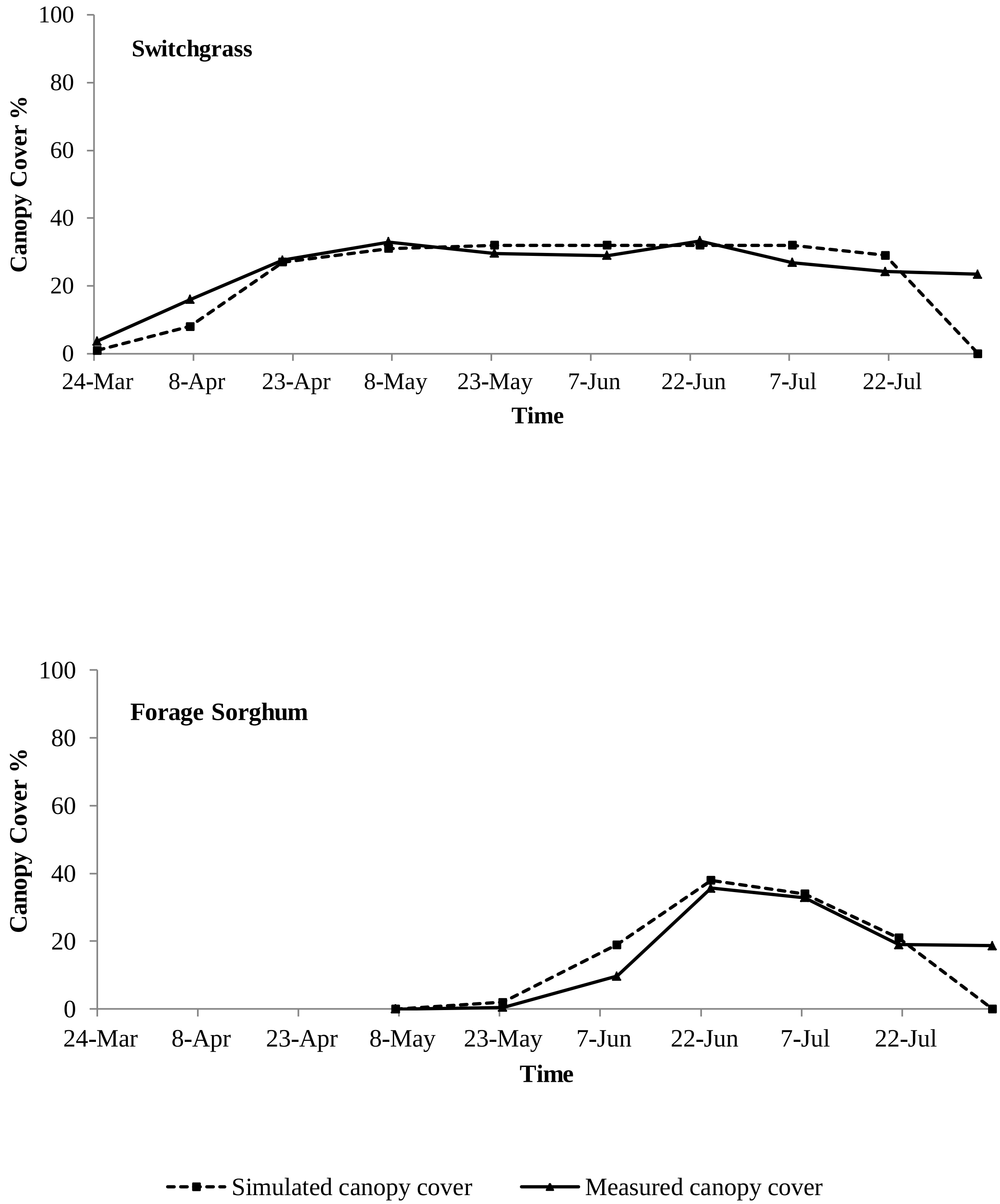
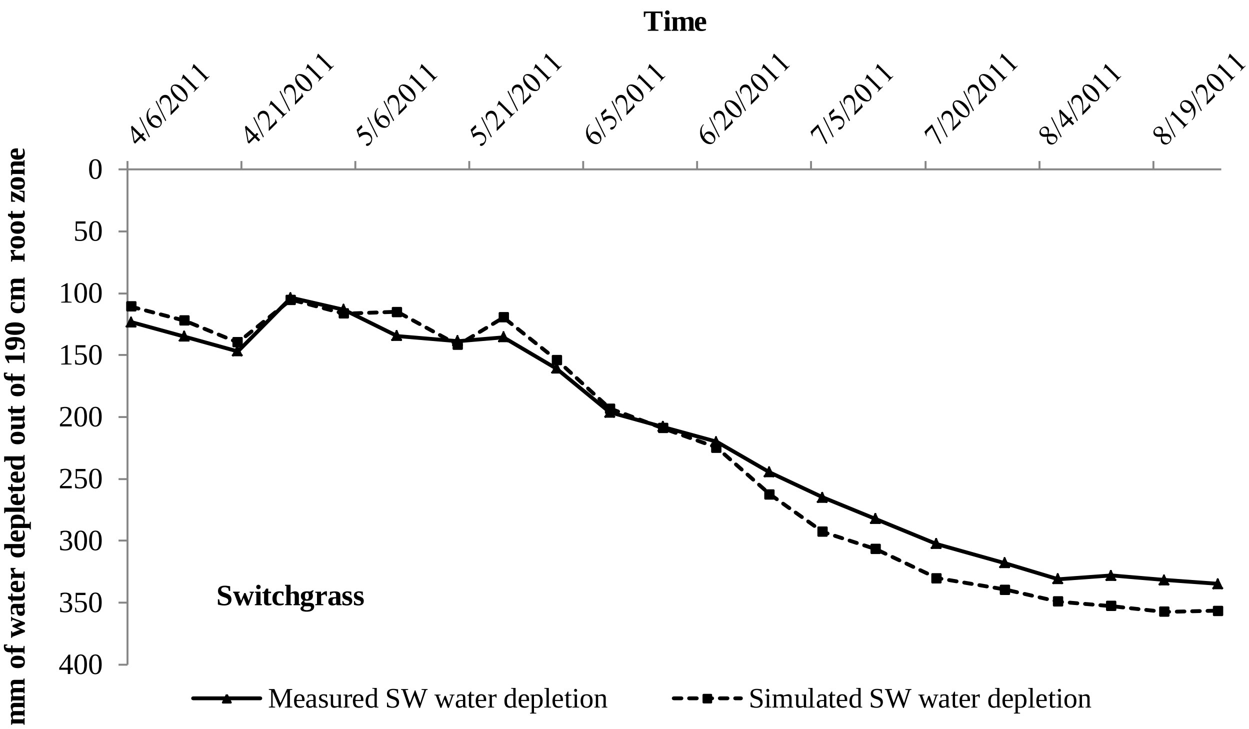


Figure 2.4: Measured and simulated canopy cover for switchgrass and forage sorghum at Woodward, Oklahoma using conservative parameters determined at the Stillwater location



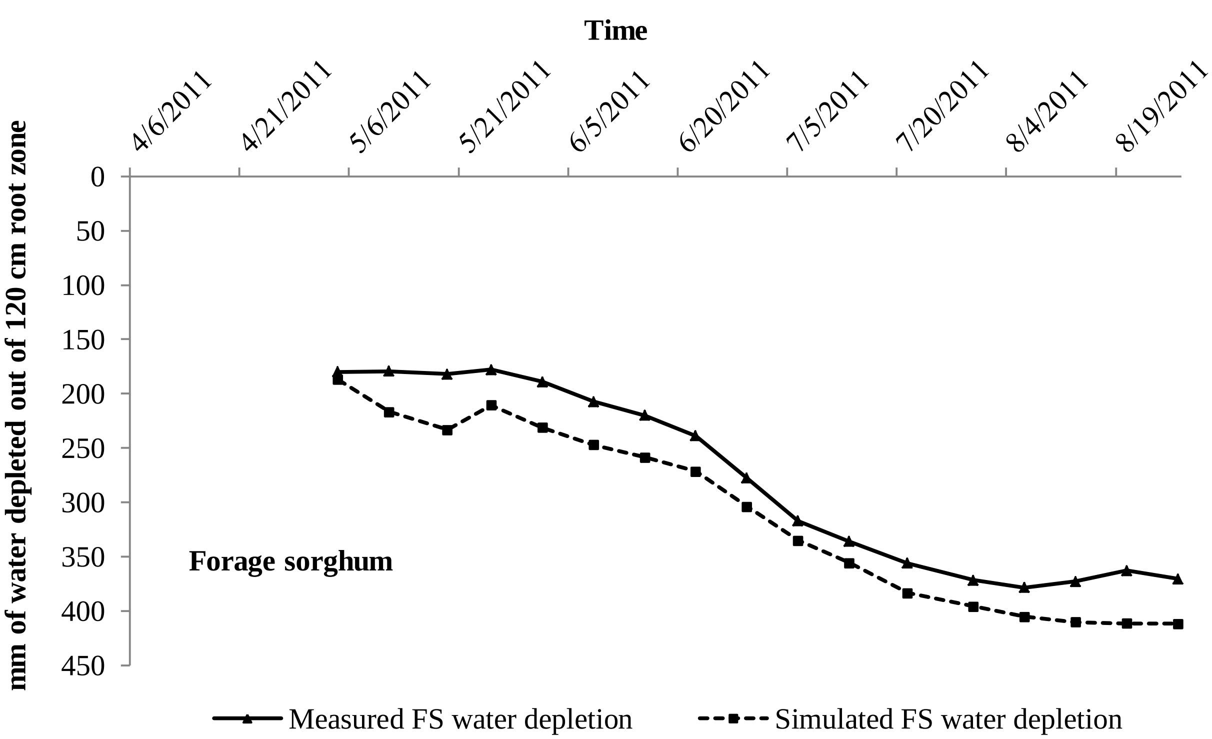


Figure 2.5: Measured and simulated soil water depletion in switchgrass and forage sorghum at Stillwater location.

CHAPTER III

SIMULATION OF BIOENERGY CROPS UNDER IRRIGATED AND RAINFED CONDITIONS IN THE OKLAHOMA PANHANDLE

Abstract

The High Plains aquifer supports extensive irrigated corn and wheat production in the Oklahoma Panhandle, but ongoing groundwater depletion threatens the sustainability of the current cropping system. The development of a cellulosic ethanol production facility in the region may create opportunities for alternative biomass crops such as forage sorghum and switchgrass. The objective of this study was to compare the performance of corn, forage sorghum, and switchgrass under full irrigation, deficit irrigation and rainfed conditions in the Oklahoma Panhandle. The three crop species were simulated using AquaCrop five water levels: rainfed with initial soil moisture conditions of 60% available water capacity, 80% available water capacity, 100% available water capacity, and irrigation treatments of 70% allowable depletion, and of 50% allowable depletion. The simulation study was done over a period of ten years 2002-2011 to assess the long term performance. County average yields were consistent with simulated grain yields for corn under irrigated and rainfed conditions. Forage sorghum produced 30 % higher theoretical ethanol yields than corn under irrigated environments but not under rainfed environments. Switchgrass failed to produce significantly higher theoretical ethanol yields than corn at any water level. Based on this modeling study, forage sorghum may have potential as an alternative to corn in the Oklahoma Panhandle given the advent of cellulosic ethanol production but forage sorghum is unlikely to help meet the challenge of groundwater depletion.

Introduction

Maize (*Zea mays* L.) is the primary feedstock for US biofuel production, but competing feed and food demands and declining water and land resources limit its potential expansion (Johnson et al., 2007). One alternative is cellulosic ethanol, which is ethanol produced from cellulosic feedstock rather than grain. The AbenGoa biorefinery under construction in southwest Kansas will use cellulosic feedstock from southern Kansas and the Oklahoma Panhandle for ethanol production. Those regions are underlain by the High Plains Aquifer which supports extensive irrigated corn and wheat production. According to NASS reports for 2011, there were 76000 ha of harvested corn with an estimated value of $ 61,216,900 in Texas County, which is in the middle of the Oklahoma Panhandle. Likewise, a total of 105,000 ha of wheat were also harvested from the Texas County in 2011. But, the ongoing depletion of groundwater in the region calls into a question the sustainability of the current cropping system. Groundwater level declines of up to 14 feet have been reported from pre-development to 2005 in this region of the High Plains Aquifer (McGuire, 2009). To produce sufficient feedstock for ethanol production while sustaining the aquifer will be a major challenge.

Forage sorghum (*Sorghum bicolor* L.) and switchgrass (*Panicum virgatum* L.) are considered as good candidates for cellulosic feedstock production (Lynd et al., 1991, Solomon et al., 2007). High biomass forage sorghum holds promise as a cellulosic feedstock crop due to its high yield potential and vegetative growth habit, which allows more flexible management of the crop. A previous study reported forage sorghum yields up to 9.5 Mg ha^{-1} under light irrigation to 14.8 Mg ha^{-1} under frequent irrigated treatments in Bushland, Texas in 1984 showing that the crop has good potential in the region (Saeed et al., 1998). McCollum et al. (2005) reported that forage sorghum near College Station, Texas produced yields equal to or greater than those of corn while using 33% less irrigation water. In Iowa, Hallam et al. (2001) compared perennial grasses with annual row crops and found that forage sorghum had the highest yield potential, averaging over 35 Mg ha^{-1} (dry weight basis). However, the performance of forage sorghum under drier conditions is uncertain.

Switchgrass is another prime candidate for feedstock production because of its demonstrated high productivity across a wide geographic range, suitability for marginal quality land, low water and nutrient requirements, and positive environmental benefits (McLaughlin et al., 2005). Cook and Beyea (2000) observed that the conversion of land from annual crops to native perennial grasses like switchgrass added an average of 1.1 Mg C ha^{-1} yr^{-1} to the soil. It has been projected that replacing annual crops with perennial biomass crops would reduce run-off while decreasing soil erosion and improving water quality (Hill, 2007). Switchgrass is widely adapted, has high biomass production, high C-4 photosynthetic efficiency, and efficient use of water and nitrogen. Switchgrass can yield up to 25 Mg ha^{-1} yr^{-1} depending on latitude, nutrition and other factors (Yuan et al., 2008). In an experiment conducted by Koshi et al. (1982) at Big Spring, Texas, the three strains of switchgrass produced about 2 Mg ha^{-1} yr^{-1} of good quality forage under non-irrigated conditions and 6.7 Mg ha^{-1} yr^{-1} under full irrigation. However, few studies, and none in the southern Great Plains, have directly compared the productivity of forage sorghum, switchgrass, and corn in a water-limited environment. There is a clear need to determine if, and at what level, declining water availability would favor a shift in the cropping systems of the semi-arid southern Great Plains from irrigated corn to cellulosic feedstocks.

The objective of this study was to compare the performance of forage sorghum, switchgrass, and corn under full irrigation, deficit irrigation and rainfed conditions in the Oklahoma Panhandle. To represent a wide range of water limitations, rainfed conditions with initial soil water content at 60%, 80%, and 100% available water capacity, were simulated and two irrigation thresholds of 70% and 50% allowable depletion were selected. The three crops, that is, corn, forage sorghum and switchgrass were compared for their simulated biomass, theoretical ethanol yields, and water use over a period of ten years from 2002-2011.

Materials and Methods

Model Description

The recently developed AquaCrop model was selected for this analysis because it is specifically designed to predict crop response under water limitations (Steduto et al., 2009). The calibrated AquaCrop version 3.1+ was used as a tool to perform this study. The AquaCrop model evolved from the influential Doorenbos and Kassam (1979) approach for predicting yield response to water. AquaCrop improved on the Doorenbos and Kassam approach by separating ET into evaporation and transpiration. The biomass is then predicted based on cumulative daily transpiration and the crop water productivity. The model was designed to be sufficiently accurate for the development of water management strategies while avoiding the complexity and lack of transparency common among existing crop models. Aquacrop has previously been parameterized for many cereal crops like corn (Hsiao et al., 2009), wheat (Andarzian et al., 2011), and barley (Araya et al., 2010), for cotton (Farahani et al., 2009), for vegetable crops such as quinoa (Geerts et al., 2009), for root and tuber crops like potato and even for oilseed crops like sunflower (Todorovic et al., 2009) and canola (Zeleke et al., 2011). We have recently parameterized AquaCrop for potential cellulosic feedstock crops, switchgrass and forage sorghum.

Weather and Soil Data

The simulations were based on weather and soil data from the Oklahoma Panhandle Research and Extension Center at Goodwell, Oklahoma (36°35’43”N, 101°38’11”W), elevation 1006 m above sea level. The Goodwell location has a semi-arid climate. The average annual temperature of the region is about 14°C with average daytime highs of 34°C in July and average lows of -7°C in January. Average annual precipitation is 381 mm. Weather data were obtained from the Goodwell Mesonet station (McPherson et al., 2007). Daily maximum and minimum temperatures (°C), average relative humidity (%), wind speed (km d^{-1}) at 2-m height, total solar radiation (MJ m^{-2}), and daily rainfall (mm) were obtained and used in a Penman-Monteith equation based reference evapotranspiration (ET_o) calculator (Annandale et al., 2002). This weather and soil data were then exported to AquaCrop to generate the required climate file.

The soil input file for AquaCrop requires four parameters for each soil layer: soil texture, volumetric water content at saturation, field capacity (FC), and permanent wilting point (PWP), and saturated hydraulic conductivity (K_s). Soil samples were collected in a newly established bioenergy cropping systems experiment at Goodwell, at the beginning of the cropping season in 2010, using a hydraulic sampler with an 8.89 cm outer diameter steel sampling tube which resulted in 7.47 cm diameter samples. Soil segments were cut for 0-20, 20-40, 40-60, 60-80, and 80-100 cm intervals. Triplicate samples were obtained for each depth. Soil texture was analyzed using the hydrometer method (Gee et al., 1979). Intact sub-samples were used in Tempe cells (Model 1405, Soil Moisture Equipment Corp., Santa Barbara, CA) at 33 kPa pressure to determine the soil moisture at FC (Dane et al., 1965). Additional sub-samples for each layer were dried, ground, and sieved to pass a 2-mm sieve. These sub-samples were used on pressure plates (Model 1500F1 Soil Extractor, Soil Moisture Equipment Corp., Santa Barbara, CA) at 1500 kPa pressure to determine the soil moisture at PWP (Dane et al., 1965). Saturated hydraulic conductivity was measured for a second set of intact sub-samples from each soil layer using the constant head tank method by Reynolds and Elrick (1983). The observed soil properties of the study sites are listed in Table 3.1.

Crop parameters

AquaCrop has already been parameterized and tested for corn at various locations by Hsiao et al. (2009). The conservative parameters estimated in that study were used for corn in the present simulation study. These parameters include canopy growth and canopy decline coefficients, crop coefficient for transpiration at maximum canopy, normalized water productivity for biomass, water stress thresholds for canopy expansion, stomatal conductance and canopy senescence, and reference harvest index. The list of the conservative parameters as adopted by Heng et al. (2009) is presented in Table 3.2. For switchgrass and forage sorghum, AquaCrop was parameterized and tested at Oklahoma State University in 2011. The parameterization was accomplished using data from Stillwater, Oklahoma. The resulting conservative parameters were adopted for this study (Table 3.2).

In addition to these conservative parameters, AquaCrop requires some site-specific parameters which vary depending upon location and management practices. Initial canopy cover is a vital parameter for simulating the canopy development of the crop. Initial canopy cover is dependent on the planting density, and plant cover per seedling. Other factors that may affect initial canopy cover include prevailing temperature conditions, soil moisture conditions, and planting depth. Planting dates were chosen based on survey and experimental research data. For corn, it was set to 19 April, forage sorghum to 5 May and in switchgrass, it was marked by the breaking of dormancy and was set to 17 March, for all simulation years. Planting density of corn was adjusted to 75000 plants ha^{-1}, which resulted in an initial canopy cover of 0.5% assuming 6.5 cm^2 plant cover per seedling (Hsiao et al., 2009). The initial canopy cover for switchgrass and forage sorghum was set to the default minimum of the AquaCrop model which is 0.1%. For forage sorghum, that initial canopy cover corresponds to a planting density of approximately 15000 plants ha^{-1}. Simulations run with varying levels of initial canopy cover up to 0.5% showed that forage sorghum and switchgrass yields were not sensitive to this parameter. Maximum rooting depth is another site specific parameter. Maximum rooting depth was set to 150 cm in corn, 120 cm in forage sorghum, and 190 cm in switchgrass.

Water Levels

Water availability is a crucial factor for biomass feedstock production. Corn, forage sorghum, and switchgrass may have inherent differences in water stress tolerance. To represent a range of water limited scenarios, five water levels were chosen. The study simulated both rainfed and irrigated conditions to observe the response of each crop to water availability. Initial soil water contents play an important role especially under rainfed environment. Initial soil water contents of 60%, 80%, and 100% of field capacity were used to span a range of potential rainfed conditions. Preliminary simulations showed that simulated crop yields are negligible for most years at this location when the initial soil water content is less than 60% of field capacity. Under irrigated treatments, two threshold levels, 70% and 50% allowable depletion were selected, corresponding to deficit and full irrigation, respectively.

Biomass and Yield

Texas County corn yield data were obtained from the National Agricultural Statistics Service (NASS) for the years 2002-2008 for both irrigated and rainfed corn separately. For the years 2009-2011, only combined irrigated and rainfed yield data were available. The combined data are likely a reasonable approximation of the irrigated yields because only a small fraction of corn acres in the region are rainfed. Forage sorghum and switchgrass have only biomass yield based on their harvest indices which depend on the cutting height of the biomass. Harvest indices for forage sorghum and switchgrass were set to 73% and 54% respectively, based on the harvesting procedure followed at the Stillwater location. For corn, however, the yield is a summation of grain yield and stover yield. The simulated grain yield was calculated using a harvest index value of 48% as given by Heng et al. (2009). This grain yield was subtracted from the simulated total biomass and 50% of the remaining biomass was estimated to be the harvested stover yield. Harvest of 100% of the corn stover would not be practical or sustainable.

Ethanol Yields

To compare the performance of corn, forage sorghum, and switchgrass as bioenergy crops the biomass yields were converted into theoretical ethanol yields. Corn yield was partitioned into grain yield and corn stover, which is the cellulosic feedstock. In forage sorghum and switchgrass, however, only cellulosic feedstock was produced. The theoretical ethanol yield conversion factors for corn and switchgrass were taken from the National Renewable Energy Laboratory (NREL) report by Humbird et al. (2011), assuming enzymatic hydrolysis to convert lignocellulosic feedstock into ethanol. Based on the NREL feedstock composition analysis, corn stover has 36% cellulose and 23% hemicellulose, switchgrass has 33% cellulose and 26% hemicellulose, while forage sorghum has 34% cellulose and 16% hemicellulose. This results in conversion factors for corn and switchgrass set at 333 L Mg^{-1} but a lower value of 283 L Mg^{-1} for forage sorghum because of its lower hemicellulose composition. The conversion factor for forage sorghum was provided by Dr. Gopal Kakani at Oklahoma State University, Stillwater (personal communication). The conversion factor for translating corn grain yield to ethanol was 300 L Mg^{-1} (Pimentel et al., 2008).

Data Analysis

Analysis of variance (ANOVA) was used to determine the effects of water levels, year, and crop species on theoretical ethanol yields. Crop species and water levels were considered fixed factors and year was treated as a random factor. Two way interactions between the three factors were also included in the model. Mean separation was accomplished by Tukey's least significant difference with $\alpha = 0.05$. Statistical calculations were performed in Matlab (Mathworks Inc., Natick, Massachusetts).

Results and Discussion

Weather Data

The weather of a simulated environment has a crucial impact on the performance of the model and the performance of the crop. The growing season weather data for the simulation years 2002-2011 (Table 3.3) displayed wide variation between seasons for the Goodwell location. The average daily maximum temperatures ranged from a low of 24°C in 2004 and 2006 to a high of 27°C in 2011. The average daily minimum temperature was around 9°C, for all growing seasons except 2006, which experienced a low average minimum temperature of 7°C. The growing season rainfall varied from a high of 499 mm in 2004 to an exceptionally low value of 186 mm in 2011. Serious drought conditions were widespread across the Southern Great Plains during 2010-2011. The relative humidity of the site was low, around 55% for most years and 45% in 2011. The daily solar radiation at Goodwell was high with a daily average of 20-21 MJ m^{-2} for most growing seasons. The region also experienced high speed winds averaging about 4.5 m s^{-1} throughout the growing season. A combination of all these factors led to high evaporative demand in the growing season. Reference evapotranspiration for most seasons averaged about 5.5 mm d^{-1}. In 2011, however, the reference evapotranspiration value was unusually high, about 6.6 mm d^{-1}.

Corn Yields Validation

Corn grain yields were simulated for both rainfed and irrigated conditions and the results were compared to the survey yield data to check the accuracy of the model. To represent a wide range of conditions, rainfed simulations were run for initial conditions of 60%, 80% and 100% available water capacity. The measured survey yields were expected to fall within the yield range predicted using these initial conditions. The County average yields were, in fact, within the limits of the simulated yields for the 60% and 100% available water capacity initial conditions for five out of seven years. In 2003, the model performance was poor, as it predicted the yield to be zero at all three rainfed water levels while the County average yield for that year was approximately 4 Mg ha^{-1} (Fig. 3.1). The reason for this discrepancy is unknown. The irrigated yield simulations were done for 50% allowable depletion (full irrigation) and 70% allowable depletion (deficit irrigation). The simulated yield predictions closely matched the survey yield data (Fig. 3.2). However, the model slightly overpredicted the yields in most years. In 2003 and 2011, the simulated yields were about 2 Mg ha^{-1} higher than the measured yield values (Fig. 3.2). Simulated yields were similar for full and deficit irrigation.

Biomass and Yield

Under rainfed conditions with a dry soil profile at the start of the growing season, switchgrass proved to produce the highest biomass among the three crops. Switchgrass had an average biomass of 3.78 Mg ha^{-1} for the 60% available water capacity initial conditions, whereas corn and forage sorghum biomass averaged under 3 Mg ha^{-1}. However, corn and forage sorghum performed better than switchgrass in 2004, which was a high rainfall year (data not shown). Forage sorghum yielded the highest under irrigated treatments with an average biomass of 36 Mg ha^{-1} (Table 3.4). That simulated biomass is higher than in previous studies of forage sorghum in Texas, which have reported biomass of 28 Mg ha^{-1} (Texas Alliance for Water Conservation). Irrigated corn produced an average biomass of 23 Mg ha^{-1}. Switchgrass was not as responsive to irrigation as corn and forage sorghum. The switchgrass biomass under both full and deficit irrigated conditions averaged 8 Mg ha^{-1}. Previous rainfed switchgrass studies at Beeville, Texas have reported high yields of 14.5 Mg ha^{-1} in response to nitrogen and phosphorus applications (Muir et al., 2001). Appendix 1 lists biomass and yield predictions for all water treatments for corn, forage sorghum, and switchgrass across ten years, 2002-2011.

Ethanol Yield Analysis

The ethanol yield comparisons across crops, treatments, and years were done using analysis of variance (ANOVA) (Table 3.5). The water levels and crop species had significant effects on the ethanol yields while year did not. The rainfed water levels of 60% available water capacity to 100% available water capacity had a striking effect on the crop yields and therefore, ethanol yield. Under irrigation, the crops show only a slight difference between full and deficit irrigation thresholds, but both were significantly higher than rainfed yields. Based on the results of the ANOVA, the ethanol yields were averaged across the years and the least significant difference was calculated for the condensed data (Table 3.6).

For corn, forage sorghum and switchgrass, there were no significant differences in ethanol yields between deficit and full irrigation treatments (Table 3.6). For corn, the rainfed with 100% available water capacity yielded the next highest followed by 80% available water capacity and then 60% available water capacity. The same pattern was followed by forage sorghum under the rainfed environment. In switchgrass, however, there was no significant difference between 80% and 100% AWC for rainfed conditions. Comparing the ethanol yields across crop species within water levels, there was no significant difference between corn, forage sorghum and switchgrass for 60% AWC rainfed conditions. For 80% AWC rainfed conditions, corn and forage sorghum ethanol yields were significantly higher than those of switchgrass. For 100% AWC rainfed conditions, significant differences were seen between all three crops with corn yielding the highest and switchgrass yielding the lowest. For full and deficit irrigation, forage sorghum yielded the highest, followed by corn, and then switchgrass. The ethanol yields fall in the range of previously reported corn ethanol yields of about 3200 L ha^{-1} by Pimental et al. (2003) and 544 L ha^{-1} switchgrass ethanol yields as reported by Hill et al. (2006).

Water Use

Water use in the growing season indicates a clear difference in the growth behavior of the three crops. The water use amounts exceed 1000 mm under irrigated conditions for all crops, the highest being in corn with a total evapotranspiration water use of 1069 mm (Table 3.7). This value is higher than the previously reported corn evapotranspiration study by Payero et al. in

(2009) of up to 633 mm under deficit irrigation. The simulated net irrigation amount applied for both full and deficit irrigation was approximately 800 mm which is higher than previously used irrigation requirements up to 541 mm (Lamm et al., 2003). Under rainfed conditions, corn and forage sorghum had less transpiration therefore, produced little biomass and yield. The corn evapotranspiration values under rainfed are within range of previously reported data by Grassini et al. in (2009) who reported evapotranspiration values between 130–225 mm under rainfed corn. Switchgrass had higher evapotranspiration than corn and forage sorghum under rainfed conditions. Brown et al. (2000) have reported switchgrass evapotranspiration values of up to 800 mm. Evaporation was lowest in switchgrass, which can be attributed to its achieving higher canopy cover earlier in the growing season due to its perennial nature.

Conclusions

AquaCrop was able to adequately predict corn yields under both irrigated and rainfed conditions in the Oklahoma Panhandle. Under irrigated conditions, simulated ethanol yields from forage sorghum were 30 % higher than those from corn and 82 % higher than those from switchgrass. However, the simulated forage sorghum biomass was higher than expected for the region, thus further study is needed. Switchgrass failed to produce significantly higher theoretical ethanol yields than corn or forage sorghum at any simulated water level under irrigated or rainfed conditions. This study provides no evidence that switchgrass could compete with corn at any future level of diminished water availability in the High Plains aquifer. However, no economic analysis has been attempted here. Admittedly, ecological considerations might favor switchgrass to be the alternative of corn. A long term field validation study is needed to definitively understand the performance and adaptability of biofuel feedstock crops in the region. Until these long term data are available, AquaCrop can be a helpful tool in assessing and comparing the water use and productivity of these crops.

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Table 3.1: Soil properties for the Goodwell location.

Depth	Soil texture	Saturated Water Content	Field Capacity	Permanent Wilting Point	Saturated Hydraulic Conductivity
		$cm^3\ cm^{-3}$			$mm\ day^{-1}$
0-20	Silty clay	0.42	0.46	0.25	104
20-40	Silty clay	0.41	0.46	0.28	108
40-60	Silty clay	0.46	0.40	0.26	109
60-80	Silty clay	0.41	0.35	0.23	103
80-100	Silty clay	0.37	0.33	0.18	104

Table 3.2: Conservative crop parameters for switchgrass and forage sorghum as parameterized for the Stillwater location. Conservative crop parameters for corn adopted from Heng et al. (2009).

Conservative Parameters	Corn	Switchgrass	Forage Sorghum	Explanation
Crop growth coefficient	1.3	13.4	19.2	% d^{-1}; for corn, % GDD^{-1}
Crop decline coefficient	1.06	8.0	3.0	% d^{-1}; for corn, % GDD^{-1}
Crop coefficient for transpiration at maximum canopy cover	1.03	1.1	1.03	Full canopy transpiration relative to reference ET
Normalized water productivity	33.7	14	27	g m^{-2}
Leaf growth threshold p (upper)	0.14	0.25	0.15	As fraction of TAW, above this leaf growth is inhibited
Leaf growth threshold p (lower)	0.72	0.55	0.45	Leaf growth stops at this p
Leaf growth stress coefficient curve shape	2.9	3	2.9	Convex curve
Stomatal conductance threshold p (upper)	0.69	0.5	0.45	Above this threshold, stomata begin to close
Stomatal stress coefficient curve shape	6.0	3	0	Convex curve, 0 curve shape is linear
Senescence stress coefficient p (upper)	0.69	0.85	0.35	Above this threshold, early canopy senescence begins
Senescence stress coefficient curve shape	2.7	3.0	3.7	Convex curve
Days from planting to				From 1 day after planting
a) Emergence	140	2	4	For corn, the values are in GDD
b) Maximum canopy cover	550	30	53	
c) Maximum rooting depth	800	89	74	
d) Senescence	1400	124	132	
e) Harvest	1700	197	172	
Rooting depth	1.5	1.9	1.2	meter

Table 3.3: Goodwell weather summary for the growing season for simulation years 2002-2011.

Year	Average Daily Max. Temp.	Average Daily Min. Temp.	Seasonal Rainfall	Relative Humidity	Solar Radiation	Wind Speed	ETo
	°C		mm	%	MJ m^{-2}	m s^{-1}	mm d^{-1}
2002	25	9.0	313	49	20.7	4.7	5.6
2003	25	9.4	363	55	20.4	4.1	5.4
2004	24	9.5	499	61	16.9	4.2	4.6
2005	25	9.2	332	57	20.3	4.3	5.3
2006	24	7.4	386	50	17.0	4.2	5.7
2007	26	9.2	256	58	21.3	4.1	5.3
2008	25	8.7	453	55	20.5	4.5	5.5
2009	25	8.5	320	58	20.1	4.2	5.2
2010	26	9.2	457	57	21.4	4.3	5.5
2011	27	9.6	186	45	22.5	4.6	6.6

Table 3.4: Average simulated biomass across years 2002-2011 for corn, forage sorghum, and switchgrass under different water levels at Goodwell, Oklahoma. The values in parentheses are standard deviations.

Species	**Average Biomass**				
	Rainfed 60% Available Water Capacity	**Rainfed 80% Available Water Capacity**	**Rainfed 100% Available Water Capacity**	**70% Allowable Depletion**	**50% Allowable Depletion**
	Mg ha^{-1}				
Corn	2.55(2.55)	6.44(5.12)	9.83(5.58)	23.29(0.76)	23.81(0.83)
Forage sorghum	1.28(1.59)	5.41(2.88)	7.33(3.27)	36.05(0.44)	36.02(0.52)
Switchgrass	3.78(1.08)	4.91(0.99)	5.59(0.89)	7.96(0.11)	7.96(0.11)

Table 3.5: ANOVA between all treatments (species, year, water levels) at Goodwell, OK

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob > F
Species	1.56×10^{8}	2	7.8×10^{7}	140.4	0
Year	9.75×10^{6}	9	1.1×10^{6}	1.46	0.2134
Water Level	4.48×10^{8}	4	1.1×10^{8}	364.71	0
Species*Year	1.00×10^{7}	18	5.5×10^{5}	4.68	0
Species*Water Level	2.02×10^{8}	8	2.5×10^{7}	212.74	0
Year*Water Level	1.10×10^{7}	36	3.1×10^{5}	2.58	0.0003
Error	8.55×10^{6}	72	1.2×10^{5}		
Total	8.45×10^{8}	149			

Table 3.6: Predicted mean ethanol yields for corn (grain plus 50% stover), forage sorghum, and switchgrass at Goodwell, Oklahoma from 2002-2011

Species	**Water Level**				
	Rainfed			**Irrigated**	
	60% Available Water Capacity	**80% Available Water Capacity**	**100% Available Water Capacity**	**70% Allowable Depletion**	**50% Allowable Depletion**
	L ha^{-1}				
Corn	534aD	1333aC	2028aB	4987bA	4945bA
Forage Sorghum	245aD	1031aC	1397bB	7111aA	7142aA
Switchgrass	589aC	847bB	904cB	1277cA	1275cA

*A, B, C, D show a significant difference of ethanol yields across the water levels for a crop.
a, b, c indicate the significant difference of ethanol yields across crop species at a particular water level.

Table 3.7: Comparison of average growing water use and irrigation amounts for corn, forage sorghum and switchgrass at five water levels at Goodwell, OK from 2002-2011.

Species	Water Level	Average Evaporation	Average Transpiration	Total ET	Irrigation Applied
		mm			
Corn	RF60	195	24	261	
Corn	RF80	219	82	303	
Corn	RF100	198	143	351	
Corn	DEP70	264	777	1043	854
Corn	DEP50	293	774	1069	892
Forage Sorghum	RF60	232	16	276	
Forage Sorghum	RF80	262	68	330	
Forage Sorghum	RF100	235	83	347	
Forage Sorghum	DEP70	194	827	1047	820
Forage Sorghum	DEP50	223	824	1020	858
Switchgrass	RF60	185	221	425	
Switchgrass	RF80	158	292	471	
Switchgrass	RF100	135	335	490	
Switchgrass	DEP70	126	866	1034	764
Switchgrass	DEP50	148	866	1011	813

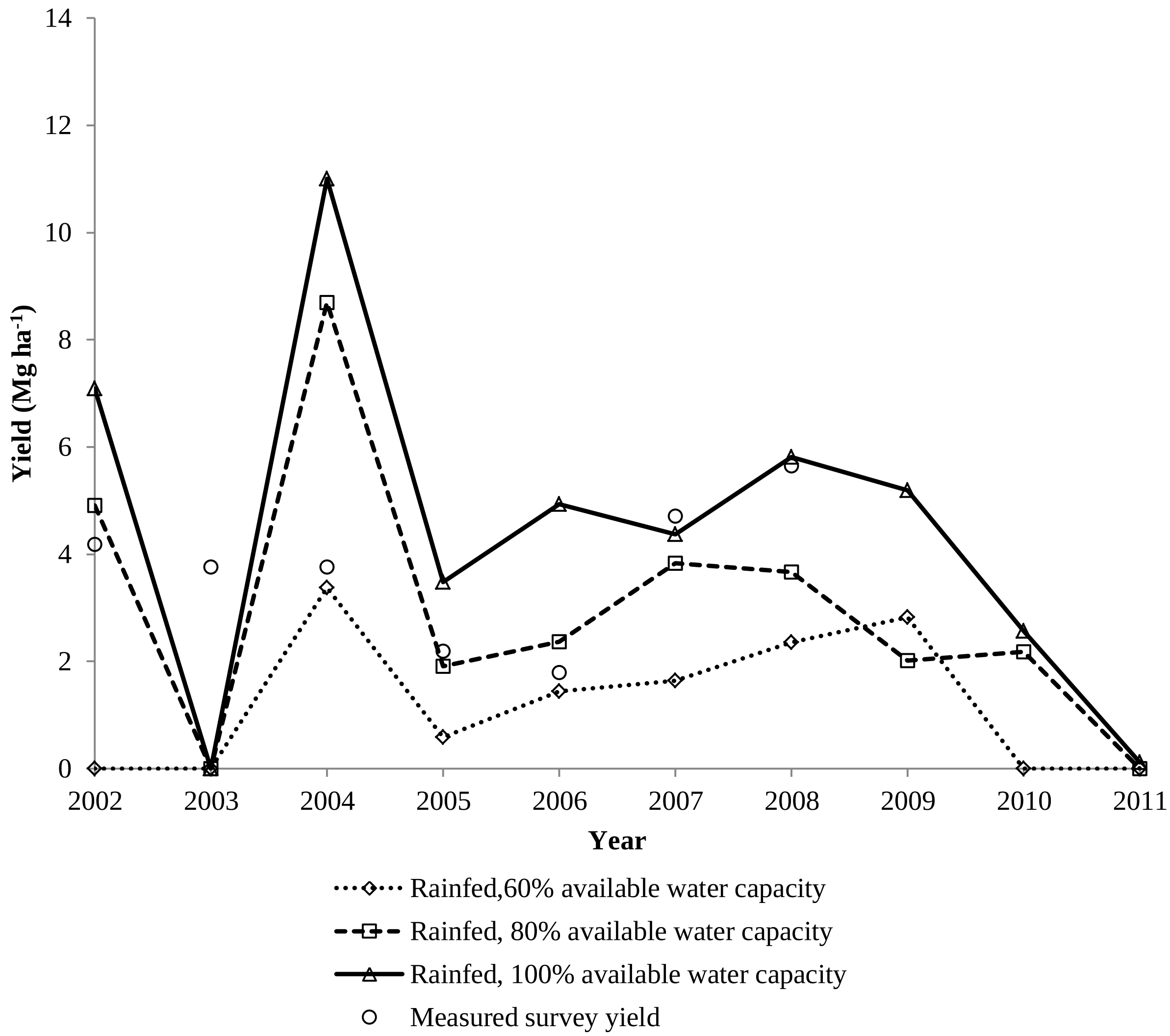

Figure 3.1: Simulated and County average corn grain yields under rainfed conditions at Goodwell, Oklahoma for years 2002-2011. Simulations were performed with initial soil moisture conditions set to 60%, 80% and 100% of the soil's available water capacity.

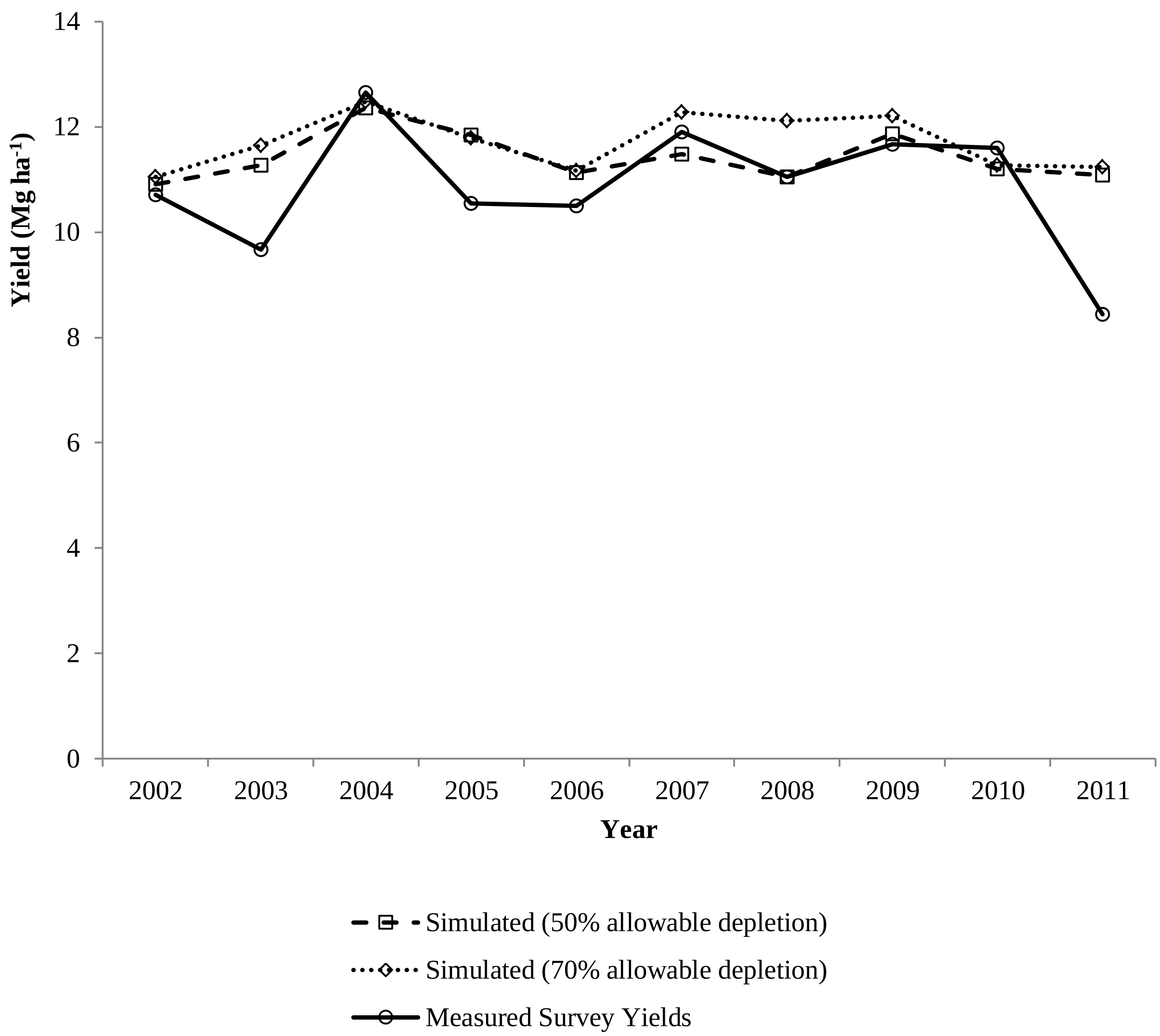

Figure 3.2: County average and simulated yields for irrigated corn at Goodwell, Oklahoma for years 2002-2011

Appendix 1: Biomass and yield of (a) corn (b) forage sorghum and (c) switchgrass in response to different water levels at Goodwell, Oklahoma

Year	Rainfed 60%		Rainfed 80%		Rainfed 100%		Irrigated 50%		Irrigated 70%	
	Biomass	Yield	Biomass	Yield	Biomass	Yield	Biomass	Yield	Biomass	Yield
	ton ha^{-1}									
2002	0	0	10.28	4.91	13.77	7.09	22.64	10.90	22.25	11.04
2003	0	0	0.00	0.00	2.15	0.00	23.61	11.27	22.87	11.64
2004	7.01	3.38	18.63	8.69	22.99	11.01	25.37	12.35	24.99	12.48
2005	1.27	0.59	3.92	1.91	7.25	3.48	24.53	11.84	24.15	11.79
2006	3.01	1.44	4.90	2.36	10.16	4.93	22.93	11.13	22.85	11.17
2007	3.47	1.64	7.88	3.83	10.41	4.37	24.08	11.49	23.37	12.28
2008	4.90	2.35	7.77	3.67	10.60	5.81	24.62	11.05	23.26	12.11
2009	5.86	2.83	6.52	2.02	11.61	5.19	24.11	11.86	23.61	12.21
2010	0	0	4.51	2.18	5.44	2.57	23.31	11.21	22.95	11.27
2011	0	0	0	0	3.97	0.12	22.91	11.08	22.57	11.24

Year	Rainfed 60%		Rainfed 80%		Rainfed 100%		Irrigated 50%		Irrigated 70%	
	Biomass	Yield	Biomass	Yield	Biomass	Yield	Biomass	Yield	Biomass	Yield
	ton ha^{-1}									
2002	0.00	0.07	3.20	2.36	5.52	4.08	35.29	26.97	35.46	26.63
2003	3.56	2.65	6.19	4.58	7.80	5.73	35.28	26.50	35.55	27.18
2004	0.00	0.00	12.91	9.52	16.04	11.92	35.98	26.71	35.67	27.34
2005	0.03	0.02	4.46	3.35	6.15	4.57	35.95	27.09	36.04	27.09
2006	2.73	2.02	5.07	3.74	5.95	4.40	35.47	28.69	35.75	28.66
2007	2.57	1.90	5.32	3.92	7.25	5.38	36.57	27.11	36.43	27.30
2008	0.00	0.00	5.92	4.40	8.81	6.51	36.20	28.36	36.25	28.45
2009	0.03	0.02	3.73	2.76	5.73	4.26	36.66	27.53	36.57	27.78
2010	3.84	2.84	6.01	4.49	7.15	5.27	36.79	28.01	36.85	27.86
2011	0.00	0.00	1.33	0.96	2.89	2.16	35.99	29.35	35.95	29.23

Year	Rainfed 60%		Rainfed 80%		Rainfed 100%		Irrigated 50%		Irrigated 70%	
	Biomass	Yield	Biomass	Yield	Biomass	Yield	Biomass	Yield	Biomass	Yield
	ton ha^{-1}									
2002	2.81	1.49	4.02	2.13	4.68	2.48	7.78	4.12	7.76	4.11
2003	4.76	2.52	5.80	3.07	6.28	3.33	7.83	4.15	7.82	4.15
2004	3.45	1.83	4.69	4.28	5.53	2.93	7.87	4.17	7.86	4.17
2005	4.36	2.31	5.80	3.07	6.35	3.37	7.91	4.19	7.90	4.19
2006	3.44	1.28	4.39	2.49	5.18	2.76	7.95	4.21	7.95	4.21
2007	5.62	2.98	6.37	3.38	6.76	3.78	7.99	4.23	7.98	4.23
2008	2.83	1.50	4.15	2.20	4.95	2.62	8.02	4.25	8.02	4.25
2009	3.84	2.04	4.88	2.59	5.73	3.04	8.06	4.27	8.05	4.21
2010	4.82	2.55	5.92	3.14	6.64	3.52	8.10	4.29	8.10	4.30
2011	1.82	0.97	3.07	1.63	3.84	2.04	8.14	4.31	8.13	4.31

VITA

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Scope and Method of Study: The results of this modeling study can help researchers determine if cellulosic feedstock production can be a part of a more sustainable system which will prolong the life of the High Plains aquifer and the vitality of the region. The model parameters we calibrate for switchgrass and forage sorghum will be of use to other researchers studying bioenergy cropping systems.

Findings and Conclusions: The objective of this study was to parameterize the AquaCrop model for two bioenergy crops, switchgrass and forage sorghum, using field measurements from Stillwater, Oklahoma in 2011. The parameterized model was then validated for additional sites at Chickasha and Woodward, Oklahoma. After parameterization at Stillwater, the simulated canopy cover closely matched the measured canopy cover dynamics with a RMSE of 6% in switchgrass and 5% in forage sorghum. The water stress thresholds for canopy expansion and stomatal conductance were similar for switchgrass and forage sorghum, but senescence was induced at 35% available water depletion for forage sorghum compared to 85% for switchgrass. The maximum rooting depth of switchgrass was estimated at 190 cm and that of forage sorghum at 120 cm. The normalized water productivity of switchgrass was found to be 14 g m^{-2}, approximately half that of forage sorghum which was 27 g m^{-2}. The parameterized model reasonably simulated soil water depletion at Stillwater (RMSE < 34 mm) and canopy cover at Chickasha and Woodward (RMSE < 11%) for both crops. This calibrated model was then used to predict ethanol yields as a simulation study at Goodwell, Oklahoma. The corn, forage sorghum and switchgrass were simulated using AquaCrop five water levels: rainfed with initial soil moisture conditions of 60% available water capacity, 80% available water capacity, 100% available water capacity, and irrigation treatments at 70% allowable depletion, and at 50% allowable depletion. The simulation study was done over a period of ten years 2002-2011 to assess the long term performance. County average yields were consistent with simulated grain yields for corn under irrigated and rainfed conditions. Forage sorghum produced 30 % higher theoretical ethanol yields than corn under irrigated environments but not under rainfed environments. Switchgrass did not produce significantly higher theoretical ethanol yields than corn at any water level. Based on this modeling study, forage sorghum may have potential as an alternative to corn in the Oklahoma Panhandle given the advent of cellulosic ethanol production but forage sorghum is unlikely to help meet the challenge of groundwater depletion.

ADVISER’S APPROVAL: Dr. Tyson Ochsner