ASSESSING MATURITY IN SWEET SORGHUM HYBRIDS AND ITS ROLE IN DAILY BIOMASS SUPPLY

A Thesis

by

PAYNE STEWART BURKS

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2012

Major Subject: Plant Breeding

Assessing Maturity in Sweet Sorghum Hybrids and its Role in Daily Biomass Supply

Copyright 2012 Payne Stewart Burks

ASSESSING MATURITY IN SWEET SORGHUM HYBRIDS AND ITS ROLE IN DAILY BIOMASS SUPPLY

A Thesis

by

PAYNE STEWART BURKS

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Approved by:

Chair of Committee,	William L. Rooney
Committee Members,	Seth C. Murray
	Gary N. Odvody
Head of Department,	David D. Baltensperger

May 2012

Major Subject: Plant Breeding

ABSTRACT

Assessing Maturity in Sweet Sorghum Hybrids and Its Role in Daily Biomass Supply.

(May 2012)

Payne Stewart Burks, B.S., Texas A&M University

Chair of Advisory Committee: Dr. William L. Rooney

Sweet sorghum is a highly versatile C_4 grass noted for its improved drought tolerance and water use efficiency relative to sugarcane. Sweet sorghum is well suited for ethanol production due to a rapid growth rate, high biomass production, and a wide range of adaptation. Unlike the 12-18 month growth cycle of sugarcane, sweet sorghum produces a harvestable crop in three to five months. Sweet sorghum and sugarcane crops are complementary and in combination can extend the sugar mill seasons in many regions of the world to an estimated 8 months. Seasonal growth and weather patterns both optimize and restrict production of each crop to specific times of the year, however these are different for the two crops. In addition to temporally spacing the date of harvest between crops, the genetic variability of maturity within the crops may also be used to extend the mill seasons; specific hybrids can be used and selected to maximize yield throughout the harvest season.

Under favorable growing environments, sweet sorghum hybrids of all maturity groups produced sugar yields ranging from 2.8 to 4.9 MT/ha. Early/medium, late, and very late maturity hybrids planted during April, May, and June planting dates are

necessary to maximize the mill season. In this study, early/medium maturity hybrids planted during April and May matured for harvest between late July and mid-August. June planting dates were unfavorable for early/medium maturity hybrids. In addition, late and very late maturity hybrids planted during April matured for harvest in late August; the additional growing season thus resulted in higher sugar yields. Timely planting of late and very late maturity hybrids in April, May, and June produce the maximum yields for harvests after mid August. Intermittent use of late and very late maturity hybrids can therefore extend sugar milling seasons into mid November if so desired.

ACKNOWLEDGEMENTS

I would like to thank my Lord and Savior for the opportunity, strength, and guidance throughout the course of this research.

I would like to thank my committee chair, Dr. Rooney, for his support, leadership, and direction during my tenure at Texas A&M University. I am also appreciative of my other committee members, Dr. Murray and Dr. Odvody for their participation and assistance. Furthermore, thanks to Dr. Viator at Louisiana State University for his hard work and dedication to this project.

I am extremely grateful to all my family and friends, most especially my wife, parents, and sister for their undying love, support, and patience. I cannot thank you guys enough. Also, I would like to recognize all my brothers at Texas A&M and ONE ARMY for their leadership and encouragement throughout my undergraduate and graduate years.

Finally, I would like to thank Texas A&M University for six amazing years as an Aggie. Gig'em.

TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

CHAPTER I

INTRODUCTION

The U.S. currently uses more petroleum than any other country and reducing petroleum use is important to reduce world energy demand and minimize the need for imported oil. In addition, concern over the environmental impact of burning fossil fuels has stimulated interest in alternative sources of energy. The US Energy Independence and Security Act of 2007 mandates that biofuels, and/or other renewable fuel sources supply up to 36 billion gallons of biofuels by the year 2022 (OPS, 2007).

In the U.S., corn is currently the primary biomass source used to produce ethanol. Corn is crucial to the ethanol industry because of the high concentration of starch present in the grain and the inexpensive price from the large amount of this commodity produced in the U.S. Starch is easily converted into simple sugars which yeast process to produce ethanol (Mosier and Ileleji, 2006). However, there is a finite limit to the amount of ethanol that can be produced from corn in the U.S because corn is more important as a feed and food grain. Based on gasoline consumption in 2006, the U.S. must produce 31.5 billion gallons of ethanol annually to replace 20% of our transportation fuel (Elobeid et al., 2006). Currently, the ethanol industry utilizes approximately 30% of the annual corn production to produce 14 billion gallons of ethanol. Additional corn use is limited by both policy (US Energy Independence and Security Act of 2007) and economics, as additional use is limited by demand for corn in

---

This thesis follows the style of Crop Science.

feed and food grain markets. Finally, perceived concerns over fuel versus food will continue to affect policy and production practices (Hoekman, 2009).

Because our biofuel needs cannot be met by starch-derived ethanol alone, ligno-cellulosic biomass sources will also be required (Heaton et al., 2008). There are many potential ligno-cellulosic biomass sources ranging from crop and wood residue to dedicated bioenergy crops grown specifically for energy production. These dedicated bioenergy crops are likely to be produced on land where other economic crop production options are limited (McKendry, 2002). As of now, a major limitation to cellulosic biofuels is the lack of economically feasible conversion methodologies – it is possible to produce biofuels from biomass, but further improvement in fermentation yield and cost efficiency are also necessary (Rooney et al., 2007).

Until economically feasible cellulosic conversion methods are deployed, sugar-producing crops provide the only feasible alternative to starch based grain. Sugar-based ethanol production is well established and is the predominant source of fermentable carbohydrates from sugarcane in Brazil (Gnansounou et al., 2005). In more temperate climates, production from sugar-based crops has been limited by both climate and crop characteristics. First, sugar in most crops is not stable for storage, it must be processed soon after harvest and the crop must still be actively growing. Due to this, a long harvest window is needed to make processing economical. Unfortunately, the harvest window of any single sugar crop is not long enough to (economically) justify production. Thus, the complementation of two sugar crops remains a potentially useful way to extend the harvest season and make biofuel production economically feasible. For sugarcane, sweet sorghum has specifically been proposed as a complementary crop for ethanol production (Reddy et al., 2005).

Sweet sorghum (*Sorghum bicolor* L Moench) is a highly versatile C_4 grass noted for its drought tolerance and water use efficiency when compared to corn (Prasad et al., 2007). Like other sorghums (grain, forage, biomass), sweet types have rapid growth rates, high biomass production potential, and wide adaptation (Reddy et al., 2007). Depending on the variety and/or hybrid, sweet sorghum produces a harvestable crop in 90-150 days and optimum yields occur from mid-summer through the fall season. This is complementary to sugarcane in many production environments when optimum sugar production and yields occur in the winter months.

For sweet sorghum, the primary interest is the sugars that accumulate in the stalk of the plant but sweet sorghum also produces significant quantities of grain (starch) and ligno-cellulosic biomass A combination of high brix values and sufficient biomass yields are vital for producing optimal amounts of sugar (Reddy et al., 2005). In addition to sugar from the stalk, current methods of starch to ethanol conversion that work for corn are applicable to grain sorghum (Wu et al., 2006). Sweet sorghum bagasse (fibrous residue after juice extraction) is well suited for cellulosic conversion to ethanol, especially from high biomass sweet sorghums, or direct combustion to generate electricity (Rooney et al., 2007). An additional method to further increase biomass (at the expense of grain) is to introduce photoperiod sensitive responses of late maturing varieties or hybrids. Photoperiod sensitive responses typically increase biomass production and accumulate higher amounts of dry matter within the plant and eliminate the production of grain.

Given the interest in sweet sorghum, several breeding programs are developing sweet sorghum hybrids. Because sugar yields are affected by maturity and optimal sugar yields are finite in the crop, hybrids of different maturity will be required to supply a processing plant with biomass that maximizes available sugar. It is also logical to expect that maturity will influence yield potential; it is long known in grain sorghum that earlier maturing hybrids have lower yields (Saeed et al., 1984). In addition to hybrid maturities, planting dates will influence harvest date. Thus, judicious management of planting dates and hybrid selection can be effective at both maximizing yield and managing harvest timing.

Given this background the objectives of this study were:

1. To evaluate the productivity of different sweet sorghum maturity genotypes when planted on different dates.
2. To utilize the information generated in objective 1 to make recommendations on optimum sweet sorghum hybrids and their respective planting dates to produce a consistent and stable harvest window from July to November.

CHAPTER II

LITERATURE REVIEW

Sweet Sorghum Germplasm and Genotypes

Sweet sorghums are a distinct class of sorghums that produce high concentrations and amounts of soluble sugar in the stalk of the plant (Smith et al., 1987). Historically (and currently), sweet sorghum is used for syrup production, but the renewed interest in the crop is based on its potential as a bioenergy crop (Rooney et al., 2007). Given its history, sweet sorghum improvement programs have focused primarily on syrup quality without considering the utilization of the crop for ethanol production. Thus, most existing sweet sorghums are varieties that are very good for small-farm syrup production, but they have limitations for use in industry. First, the feasibility of seed production on varieties, as opposed to hybrids, is very limited and second, these varieties are not widely adapted to target bioenergy production areas. For both problems, the use of hybrids provides a mechanism for the economic production of seed (Rooney et al., 2007).

The development of a hybrid sweet sorghum crop provides the opportunity to improve seed logistics and enhance yield components by capturing heterosis. In the past, true sweet sorghum hybrids were not produced due to the lack of sweet grain-type seed parents. Sweet sorghum seed-parent lines have been developed by the Texas AgriLife Research Sorghum Breeding Program in College Station, Texas (Rooney, personal communication). These seed parents produce acceptable seed yields that can be combine harvested and the hybrids have plant height, biomass and thus sugar yield equal to or better than traditional sweet sorghum varieties (Corn, 2009). Corn (2009) also discusses the importance of increased stem sugar concentration in seed parents because stem sugar concentration is a primarily additive trait. Hybrids also allow producers to capture heterosis for plant height, stem girth, total soluble solids, millable sweet-stalk yield, and extractable juice yield due to non-additive gene action (Reddy et al., 2005). Hybridization of sweet sorghum also provides a mechanism for better integrating non-recessive forms of disease and insect resistance into hybrids.

High-parent heterosis is defined as the increased performance of the hybrid relative to the highest producing parent (Lamkey and Edwards, 1999) and it is critical for adoption and use of hybrid crops. While high-parent heterosis is important for hybrid sweet sorghum production, seed production limitations that are associated with sweet sorghum varieties alone justify the development and adoption in the absence of heterosis (Corn, 2009). Several groups are currently investigating the performance of heterosis in sweet sorghum hybrids. Corn (2009) reported high levels of heterosis for stalk yield, grain yield, and juice yield. Research at ICRISAT has indicated that hybrids are more stress tolerant and higher yielding (Reddy et al., 2005). According to Reddy et al. (2009), sweet sorghum hybrids produced 11% and 5% more stalk and grain yield than varieties with similar maturity.

Sugar Accumulation of Sweet Sorghum

Total sugar accumulation in sweet sorghum is a product of sugar concentrations and extractable juice yield and it is influenced by an array of genetic and environmental factors. The highest sugar concentrations and yields are typically associated with the reproductive phase of growth; specifically, the hard dough stage of grain filling (Almodares et al., 2007). Hoffmann-Thoma et al., (1996) reported sugar accumulation in sweet sorghum followed patterns of sugarcane in which sugar accumulation occurs when plant internodal growth has ended. In sugarcane, sugar accumulation results from excess sugar being stored in the stalk when plant growth is reduced by cooler temperatures and shorter day lengths (Rozeff et al., 1998). Studies have consistently reported that soluble sugar concentrations in sweet sorghum were lowest during the boot stage of the plant growth and highest at the soft-dough stage of grain filling (Lingle, 1987). Thus, the optimal harvest time for sugar yield is generally thirty days post-anthesis (Naoyuki and Yusuke, 2004). Optimal sugar production may be related to specific genotype by environment interactions of an area (Corn, 2009). Tarpley and Vietor (2007) reported that the transport and storage mechanisms of sucrose within sweet sorghum are different than those observed in sugarcane.

Composition Profiles of Sweet Sorghum and Sugarcane

The composition of soluble sugars in sweet sorghum varies with genotype and environment. The predominant sugar in sweet sorghum is sucrose, but compared to sugarcane, sweet sorghum has a lower sucrose content and is slightly higher in fructose and glucose (Rooney et al., 2007). The greater concentrations of fructose and glucose reduced sugars in sweet sorghum makes sucrose crystallization more difficult than in sugarcane (Turhollow et al., 2010). Crystallization of sugar from sweet sorghum is further complicated by the presence of aconitic acid which inhibit the separation of sugar crystals from molasses (Ghaneker et al., 1992). Ghaneker et al., (1992) also reported crystallization interference from starch quantities found in juice extractions. Other crystallization difficulties might be presented by sweet sorghum's sizable, starch-enriched panicle of grain if this is not removed before milling. For these reasons crystallization of sugar from sweet sorghum has never been a commercially viable enterprise.

Sugarcane Production in the US

Due to climatic restrictions, sugarcane production in the US is limited to a very narrow area along the Gulf Coast and Hawaii. In Louisiana, 425,000 acres of sugarcane were harvested in 2004 and produced approximately 1.2 million tons of sugar (LSU, 2004). Commercial sugarcane production regions are also common to southern locations of Florida (Sinclair et al., 2004).

Sugarcane is a member of the same grass family as sorghum, (*Poaceae*) and it is adapted to tropical and subtropical climatic conditions (Rozeff et al., 1998). Sugarcane is a perennial crop with the average productive stand lasting approximately five years. Producers prefer persistence of the sugarcane crop due to high cost of planting sugarcane which is clonally propagated. Planting seasons for sugarcane vary with location. For example, optimum planting in Louisiana is between August and October (Sugarcane, 2001) and in Florida between late August and January (Baucum et al., 2006). Peak sugar yields for sugarcane occur in the winter months; hence the harvest window for the crop in the U.S. ranges from October to March, depending on exact location and temperature profiles (Turhollow et al., 2010).

Combined Sugarcane and Sweet Sorghum Cropping System

Based on traditional planting and harvest seasons for both sweet sorghum and sugarcane, combining production of both sweet sorghum and sugarcane has several benefits to biomass producers and ethanol processors. For the processor, the harvest season is extended, meaning that the mill season and sugar availability is extended. For example, the sugarcane harvest season in Louisiana is from October to December (USDA, 1997) and ethanol production could be extended into February. In the same environment, sweet sorghum harvest is projected to be feasible from mid July through mid November. Thus it should be possible to harvest sugar from July to December in Louisiana allowing a harvest window extension of up to 50% greater than monoculture of either crop. Bagasse from either crop can be used to generate electricity or in a cellulosic conversion process.

From an agronomic perspective, there are probable production benefits to such a system. Baucum et al., (2006) suggested that sweet sorghum should be planted on fallow sugarcane land, or land that is not replanted by January. This is feasible because the cropping season for sweet sorghum is relatively short (Swayze, 2009). In Arizona sweet sorghum can be successfully planted between the months of April and July (Teetor et al., 2010). Different maturity groups of sweet sorghum which are photoperiod and thermo-insensitive will allow for successful plantings at different dates (Reddy et al., 2005).

There is also the potential to extend the harvest season of sweet sorghum through ratoon cuttings. However, ratoon cropping is limited to environments with longer growing seasons, more moisture and furthermore, the ability to ratoon is often genotype specific (Rooney et al., 2007).

Milling Operations

The practicality of a combined sugarcane and sweet sorghum cropping system will rely heavily upon the success of milling operations. Sugar mills are very efficient, extracting at least 90% of soluble sugar with the efficiency of most mills well over 95% (Bennett and Anex, 2009). In these systems, it is assumed that sweet sorghum can be milled using sugarcane equipment but testing the efficiency of the process is important. To extend this mill season, a production plan to maximize the harvest window while optimizing yield and quality of both crops is important. The production systems for sugarcane are well established but new systems must be developed for sweet sorghum and it must complement existing sugarcane production. Sweet sorghum will have to be harvested where just-in-time harvesting can be accomplished due to the instability and perishable properties of the sugars. Other designs to stabilize sugars within the plant have been proven to be both time and cost inefficient (Rooney et al., 2007). Just-in-time harvesting will allow farmers to cut sweet sorghum at physiological maturity and transport to sugar mills quickly and easily, maximizing production and profitability.

CHAPTER III

INDIVIDUAL SWEET SORGHUM HYBRID ANALYSIS

Introduction

Due to differences in growth patterns and seasonal maturation, sweet sorghum and sugarcane are complementary crops and when combined, there is the potential to extend the sugar mill season in many sugarcane production regions. Not only do particular seasonal growth and weather patterns optimize production of each crop, they often restrict the production of the other crop. In addition to temporally spacing the date of harvest between crops, specific varieties and/or hybrids of different maturity can be identified that maximize yield over a longer harvest season. In either crop, extending the harvest season can specifically be accomplished by managing planting dates combined with specific hybrid maturity combinations. In sugarcane, regional specific varieties are currently already known and deployed to achieve maximum productivity throughout the harvest season, but these planting dates and hybrid choices for harvest optimization have not been determined in sweet sorghum. Given the recent development of sweet sorghum hybrids with different maturities, there is a need to identify optimum planting dates and hybrid choice to maximize yield.

Sugar yields and given input costs will ultimately determine the feasibility of sweet sorghum as a complementary crop in a sugarcane production system. Sugar yields are heavily influenced by both genetic and growing environmental factors. For this reason, other yield traits, i.e. fresh yield, dry yield, and brix percentage are important and must be determined. Furthermore, understanding the role of photoperiod sensitivity and responses under variable environments are crucial for sustainable sugar production.

Maturity influences sugar yield in sweet sorghum because peak sugar accumulation is strongly associated with physiological maturity (Almodares et al., 2007). Therefore, the photoperiod sensitivity genes (Ma1, Ma5, and Ma6) strongly influence the potential range of maturity available in sorghum (Rooney and Aydin, 1999; Murphy et al., 2011). In even moderately photoperiod sensitive (PS) sorghums, the days to anthesis for photoperiod maturity groups are long when they are planted in early spring; they will decrease for plantings made in late spring and early summer. Thus, PS hybrids planted in April and possibly May should produce the highest biomass yields, especially compared to the same hybrids planted in June and July even though these planting dates may be necessary to extend harvests into November. While largest yields should be expected from PS hybrids, photoperiod insensitive (PI) hybrids are also needed to enable earlier harvest dates. In PI hybrids maturity is independent of season so they can be planted early and late to produce a harvestable crop early and late, respectably.

Given these factors, the objective of this study was to evaluate the productivity of different sweet sorghum maturity genotypes when planted on different dates. From this research, recommendations on optimum sweet sorghum hybrids and their respective planting dates for production of a consistent and stable harvest window from July to November can be made.

Materials and Methods

Sweet Sorghum Germplasm

The maturity of the sweet sorghum hybrids in this study was based on production in a subtropical environment (Southeastern US) grown during the summer season. Maturity classes were roughly defined as early/medium, late, and very late. In general the early/medium hybrids are photoperiod insensitive and mature between 85-105 days. The late hybrids are moderately photoperiod sensitive and mature in summer between 120-150 days and the very late hybrids are photoperiod sensitive and mature in summer seasons between 130-160 days. Days to maturity between the late and very late groups overlap in some environments and across different planting dates (genotype by environmental interactions), presumably due to daylength and temperature variation in maturity response. The specific hybrids tested in each year were developed in the Texas Agrilife Sorghum Breeding program and seed was provided by Ceres, Inc. Individual hybrid entries varied due to the continual breeding, selection process, and seed availability (Table 1).

Table 1. Sweet sorghum hybrids used in field trials in the 2009 and 2010 evaluations in College Station, TX.

Genotype	Maturity class	2009	2010
TX09012	Early/Medium	X	
TX09014	Early/Medium	X	
TX09017	Early/Medium	X	
TX09021	Early/Medium	X	
TX09022	Early/Medium	X	
TX09023	Early/Medium	X	
TX09020	Late	X	
TX09056	Late	X	
TX09067	Late	X	
TX09068	Late	X	
TX09051	Early/Medium		X
TX09052	Early/Medium		X
TX09053	Early/Medium		X
TX09054	Early/Medium		X
TX09055	Late		X
TX09056	Late		X
TX09057	Late		X
TX09058	Late		X
TX09059	Very Late		X
TX09060	Very Late		X
TX09061	Very Late		X
TX09062	Very Late		X

Experimental Design

The hybrids in the trial were arranged in a split plot design with maturity class and month planted as main plot effects and specific hybrids as sub-plots. In 2009, hybrids of two maturity classes were included in the study; early/medium and late. In 2010, hybrids of three maturity classes were included in the study; early/medium, late and very late. In 2009, the trial was planted four times at monthly intervals from the 15th

of April through July in College Station at the Texas A&M Research Farm. In 2010, the trial was repeated in College Station, but only three plantings from 15 April through June were conducted. In most cases, each maturity group included 4 hybrids replicated 3 times for 12 total plots within each main plot, but there were exceptions. In 2009, hybrids were missing from some planting dates due to limited seed supply and in 2010, the very late maturity group only consisted of two hybrids. Maturity groups were also randomized within planting dates. Each subplot was 3 rows wide on 76 cm row spacing and 9.1 meters long. The middle row of each three-row sub-plot was used for data analysis to avoid border effects. Standard fertilization and irrigation practices were followed and these included a 10-34-0 pre-plant fertilizer applied at 330 kilograms per hectare (81 kilograms of nitrogen and 121 kilograms of phosphorus). An additional 22 kilograms of zinc was also incorporated into the soil prior to planting. During the early plant growth stages, rows were side dressed with 175 kilograms of 32-0-0. Each planting date was flood irrigated 2-4 times with application numbers varying due to rainfall during the season.

Agronomic Measurements

For each sub-plot, days to mid-anthesis were recorded from planting date to 50% flowering. Stalk lodging (2010 only) was measured on a scale (0-10) with 0 indicating 0% percent lodging and each subsequent number indicating a percentage of the plot lodged (10 indicates 100% lodging). Plant height was measured just prior to harvest as the distance from the ground to the top of the panicle of the primary stalk.

Composition samples were collected at harvested by randomly sampling 4-5 plants. These plants were cut just above the soil surface and weighed. Panicles were removed and vegetative plant samples were milled using a three-roller mill (Ampro Sugar Cane Crusher model Diamond) and juice was collected. A brix reading, or percentage of soluble concentration of juice extractions was taken promptly on the extracted juice using a digital refractometer (Atago Pocket Refractometer PAL-1 (made in Japan), range 0~53%). A bagasse sample was taken and fresh weights were recorded. Moisture content was determined by drying the bagasse sample in a forced air, convection dryer for three days at 48°C and measuring difference in fresh and dry weight. For total biomass yield, in College Station, plots were harvested using a self-propelled 5460 John Deere three-row forage harvester and plot biomass weights were recorded using a Peerless forage wagon with weigh cells. In a couple of harvest dates, severe lodging made machine harvest impossible. In these situations, a two meter length of plot was hand harvested to estimate biomass yield.

Total fermentable sugar yields were estimated using formula developed by Corn (2009) where fermentable sugar yield = ***.95 * juice yield * .97 * .873 * (brix/100).*** This formula approximates sugar values assuming commercial sugar extraction rates. Brix reading is the measurement on first juice expressed. Juice yield is reported in Mg ha^{-1} and estimated by subtracting total hybrid dry yield (Mg ha^{-1}) from fresh yield (Mg ha^{-1}). While not all moisture is extracted from the bagasse, it is assumed that 95% of all soluble sugars are extracted and this is standard for most sugarcane mills (Bennett and Anex, 2009). The second constant (.97) represents the reduction in sugar concentration in second juice extraction which is typically .97 of the original estimate (Engelke, 2005). Finally, the brix reading includes all solubles; not all are fermentable sugar and Corn (2009) indicated that fermentable sugars represented .873 of the soluble in solution in sorghum mill juice.

Statistical Analysis

Independent variables for individual 2009 and 2010 summers were examined for the maturity group effect and specific hybrids were analyzed during the 2010 summer. A GLM was utilized for maturity group analysis, but a mixed ANOVA was important for specific hybrid analysis in 2010. Hybrids were nested into respective early/medium, late, and very late maturity groups and reps were nested within month planted. Both hybrids and reps were considered random; all other variables were considered fixed. A combined analysis examining the maturity group effect was prevented by imbalanced data between 2009 and 2010 years. All data analysis was conducted using programs JMP 9.0. (SAS Institute Inc., Cary, North Carolina) and means were differentiated using student's t test. Given the differences in hybrids, maturity groups and production environments, the data were analyzed by environment and they were not combined.

Results

College Station 2009

Significant variation due to planting date and maturity group was detected for sugar yield, fresh biomass weight, dry biomass weight, brix%, height, and days to anthesis (Table 2). The maturity group x month planted interaction was significant for all measured traits except sugar yields implying that this interaction did not influence sugar yields (Table 2). However the relative productivity of sweet sorghum hybrids for fresh yield, dry yield, brix %, height, and days to anthesis were highly dependent upon genotype and environmental conditions. The absence of interaction for sugar yield is likely due to the fact that these hybrids were harvested specifically to optimize sugar yield.

Across all planting dates, the late maturity group hybrids produced significantly more fermentable sugar, fresh biomass and dry biomass than the early/medium maturity group hybrids (Table 3). As expected, the late maturity group produced the tallest and latest flowering hybrids across all planting dates (Table 3). At harvest, the early/medium maturity group did produce significantly higher brix percentage in the juice (Table 3). Among planting dates, the April planting produced the highest average brix concentrations (Table 4). The late maturity group produced more biomass (and sugar yield) than the early maturity group, likely because the late group was harvested approximately one month later

Sweet sorghum planted during May had the longest number of days to anthesis and produced the tallest plants among all planting dates (Table 4). Early growth of hybrids was slowed due to rainy conditions, but longer growing days are expected for a May planting date, which is favorable for full season growth, especially in the late maturity group (Table 5). The late maturity hybrids produced significantly higher sugar and fresh and dry biomass yields, but were lower for brix. The June planting date produced the highest sugar yield, fresh biomass yield, and dry biomass yield (Table 4), with the highest yields in the late maturity group. As observed in the previous planting dates, the late maturity groups were significantly lower for brix (Table 5).

The July planting date produced the lowest sugar yields, fresh biomass yields, dry biomass yields, and brix% of all planting dates (Table 4). Consistent with other planting dates, the late maturity hybrids outperformed the early group within the planting date, but both were very low compared to other planting dates (Table 5). This planting date was subjected to the warmest temperatures, and significant insect pressure. In addition, daylengths were decreasing which reduced the days to anthesis for the late maturity group. Interestingly, the average days to anthesis and harvest date were considerably prolonged in early/medium maturity hybrids from previous planting dates.

Comparison of the means of different maturity group by planting date interactions identified the most productive hybrids in each combination in reference to their relative optimal harvest data (Table 6). There was a clear separation for sugar, fresh, and dry biomass yields between late and early/medium maturity hybrids, but further research is needed to select optimal maturity groups and planting dates.

Table 2. Sugar, fresh yield, dry yield, brix %, height, and days to anthesis analysis of variance results for early/medium and late maturity groups in 2009 College Station, TX.

	Sugar yield (MT/ha)		Fresh yield (MT/ha)		Dry yield (MT/ha)		Brix %		Height cm		Days to anthesis	
Source of variance	Df	MS	Df	MS	Df	MS	df	MS	df	MS	df	MS
Maturity group	1	45.5**	1	19416.2**	1	3210.7**	1	67.3**	1	159345.2**	1	19999.1**
Month planted	3	27.3**	3	5539.2**	3	955.1**	3	77.3**	3	21690.0**	3	1020.3**
Maturity*Month	3	0.2	3	325.0**	3	146.0**	3	7.9*	3	2061.4**	3	1387.3**
Rep(Month)	8	0.5	8	169.4*	8	15.3	8	3.8	8	1543.0**	8	4.6
Error	88	0.4	90	63.2	88	12.3	89	2.9	91	356	91	11.7
R^2		0.78		0.87		0.85		0.58		0.88		0.96
CV		28.2		7.1		13.7		9.6		1.7		2.2

, * Significant at $p < .05$ and .01 respectively

Table 3. Late and early/medium maturity group average yields for traits sugar yield, fresh yield, dry yield, brix %, height, and days to anthesis across April, May, June, and July planting dates for 2009 Summer in College Station, TX.

Maturity Group	Sugar yield (MT/ha)	Fresh yield (MT/ha)	Dry yield (MT/ha)	Brix %	Height cm	Days to anthesis
Late	3.8a	58.6a	21.2a	12.5b	315.4a	101.0a
Early/Medium	2.4b	30.0b	9.5b	14.2a	233.7b	73.0b

Table 4. Average yields for combined early/medium and late maturity groups for traits sugar yield, fresh yield, dry yield, brix %, height, and days to anthesis for individual April, May, June, and July planting dates for College Station, TX 2009 summer.

Month planted	Sugar yield (MT/ha)	Fresh yield (MT/ha)	Dry yield (MT/ha)	Brix %	Height Cm	Days to anthesis
April	3.6b	46.9b	18.5b	15.6a	236.7d	79.7c
May	2.9c	43.6b	16.1c	13.4b	305.5a	95.5a
June	4.1a	61.8a	20.8a	13.1b	290.2b	86.0b
July	1.6d	24.7c	6.2d	11.2c	265.7c	86.7b

Table 5. Early/medium and late maturity group average yields for sugar yield, fresh yield, dry yield, brix %, height, and days to anthesis for April, May, June, and July planting dates in 2009 College Station, TX.

	Maturity Group	Sugar yield (MT/ha)	Fresh yield (MT/ha)	Dry yield (MT/ha)	Brix %	Height Cm	Days to anthesis	Harvest date
April	Late	4.3a	60.8a	26.2a	15.5a	263.9a	92.0a	21-Aug
	Early/medium	2.8b	33.0b	10.9b	15.8a	209.6b	67.0b	14-Jul
May	Late	3.6a	58.0a	23.3a	12.4b	348.6a	117.0a	23-Oct
	Early/medium	2.3b	29.2b	9.0b	14.5a	262.5b	73.0b	21-Aug
June	Late	4.9a	80.8a	27.2a	11.5b	337.3a	104.0a	23-Oct
	Early/medium	3.4b	42.9b	14.3b	14.6a	243.3b	68.0b	3-Sep
July	Late	2.2a	34.6a	8.3a	10.5b	311.9a	91.0a	17-Nov
	Early/medium	1.0b	14.8b	4.0b	11.9a	219.4b	82.0b	17-Nov

Table 6. Maturity group by month planting date interaction average yields for sugar yield, fresh yield, dry yield, brix %, height, and days to anthesis for 2009 College Station, TX.

Maturity*Month	Sugar yield (MT/ha)	Fresh yield (MT/ha)	Dry yield (MT/ha)	Brix %	Harvest Date
June,Late	4.9a	80.8a	27.2a	11.5cd	23-Oct
April,Late	4.3b	60.8b	26.2ab	15.5ab	21-Aug
May,Late	3.6c	58.0b	23.2b	12.4c	23-Oct
June,Early/Medium	3.4c	42.9c	14.3c	14.6b	3-Sep
April,Early/Medium	2.8d	33.0d	10.9d	15.8a	14-Jul
May,Early/Medium	2.3e	29.2d	9.0d	14.5b	21-Aug
July,Late	2.2e	34.6d	8.3d	10.5d	17-Nov
July,Early/Medium	1.0f	14.8e	4.0e	11.9cd	17-Nov

College Station 2010

Significant variation due to planting date, maturity group, and the interaction between the two was detected for all measured traits (Table 7). Across planting dates, the very late and late maturity groups (which are strongly and moderately PS respectively) produced higher sugar, fresh and dry biomass yields than the early/medium maturity group. In addition, these two groups were taller, later, and had more lodging problems (Table 8). Across hybrids, the yields in April and May planting dates were greater than June (Table 9). This was slightly different than trends in 2009, likely due to a more typical weather pattern in 2010.

Lodging was most severe in the April planting due to several severe storms that occurred post-anthesis (Table 9). The very late and late maturity hybrids were harvested approximately 1 month after the early/medium maturity group hybrids and produced significantly higher sugar and both fresh and dry biomass yields (Table 10). There were no significant differences for sugar yield and fresh and dry biomass yields between very late and late maturity group hybrids. The late maturity group had higher brix than the very late maturity group and the April planting date significantly ranked highest for overall brix percentage among all planting dates (Table 9).

Lodging issues were not as severe in the May planting (Table 9). In terms of productivity, the sugar yield, fresh yield and dry biomass yields were similar to the April planting date. Biomass yields were highest in the very late group and the late and early/medium groups were only different for fresh yield (Table 10). Sugar yields did not differ between maturity groups, due to higher brix concentrations in the early/medium maturity hybrids. The absence of a difference may be due to hot, dry weather that occurred in mid July; by this time the early/medium maturity group hybrids were near maturity and not as affected as the later maturing groups.

Yields (sugar, fresh biomass weight, and dry biomass weight) were lowest in the June planting date. In addition, this planting date was lowest for brix and plant height (Table 9). The same dry weather that affected the later maturity groups in the May planting now affected the early/medium maturity group planted in June; this group yielded lower than the late or very late groups (Table 10). Lodging was minimal in this planting date (Table 9). The very late and late maturity hybrids were substantially later maturing than the early/medium maturity group hybrids, presumably due to the photoperiod sensitive response (Table 10).

Performance of sweet sorghum based on planting date and maturity group interaction was more typical in 2010 than in 2009. The very late maturity hybrids were consistently the highest yielding and had the longest days to anthesis (Table 11). Thus they capitalized on the long growing season to produce the highest yields. The late maturity hybrids were next with the best yields occurring during the April planting date. Harvest dates for these trials ranged from July 28 through November 10 and this represents the widest possible window for just-in time harvesting of sweet sorghum for fermentable sugars.

Table 7. Sugar, fresh yield, dry yield, brix %, height, and days to anthesis analysis of variance results for early/medium, late, and very late maturity groups in 2010 College Station, TX.

	Sugar yield (MT/ha)		Fresh yield (MT/ha)		Dry yield (MT/ha)		Brix %		Height Cm		Days to anthesis		Lodging %	
Source of variance	Df	MS	Df	MS	Df	MS	df	MS	df	MS	df	MS	df	MS
Maturity group	2	11.3**	2	3972.0**	2	536.4**	2	7.3*	2	72886.5**	2	19096.1**	2	3982.8**
Month planted	2	3.6**	2	406.6**	2	116.6**	2	19.7**	2	74936.6**	2	1832.2**	2	19827.1**
Maturity*Month	4	4.0**	4	173.4*	4	45.8**	4	77.7**	4	5177.7**	4	1014.1**	4	882.8**
Rep(Month)	6	1.4*	6	203.7**	6	25.3*	6	2.2	6	259.8	6	6.7	6	826.7**
Error	61	0.63	73	60.6	63	10.5	73	2.3	75	170.5	75	15.9	75	130.3
R^2		.59		.7		.71		.71		.96		.97		.85
CV		25.4		5.9		11.5		9.1		1.1		2.2		14.4

, * Significant at $p < .05$ and .01 respectively

Table 8. Very late, late and early/medium maturity group average yields for traits sugar yield, fresh yield, dry yield, brix %, height, days to anthesis, and lodging % across April, May, and June planting dates for 2010 Summer in College Station, TX.

Maturity Group	Sugar yield (MT/ha)	Fresh yield (MT/ha)	Dry yield (MT/ha)	Brix %	Height Cm	Days to Anthesis	Lodging %
Very late	4.2a	59.7a	21.6a	13.4ab	353.5a	115.0a	36.1a
Late	3.8a	52.3b	17.3b	13.3b	358.1a	106.0b	28.1b
Early/medium	2.8b	36.1c	10.9c	14.1a	274.5b	67.0c	12.5c

Table 9. Combined average yields for traits sugar, fresh yield, dry yield, brix %, height, days to anthesis, and lodging % for all hybrids within early/medium, late, and very late maturity groups across April, May, and June planting dates in 2010 College Station, TX.

Month planted	Sugar yield (MT/ha)	Fresh yield (MT/ha)	Dry yield (MT/ha)	Brix %	Height Cm	Days to Anthesis	Lodging %
April	3.8a	49.8a	16.8a	14.7a	365.3a	91.0b	51.3a
May	3.5ab	48.6a	16.4a	13.7b	343.2b	84.0c	16.3b
June	3.0b	43.5b	13.3b	12.4c	262.6c	99.0a	2.7c

Table 10. Within month comparisons of very late, late, and early/medium maturity group yields for sugar, fresh yield, dry yield, brix %, height, days to anthesis, and lodging % for April, May, and June planting dates in 2010 College Station, TX.

	Maturity Group	Sugar (MT/ha)	Fresh yield (MT/ha)	Dry yield (MT/ha)	Brix %	Height Cm	Days to anthesis	Lodging %	Harvest date
April	Very late	4.8a	69.0a	25.0a	13.2b	397.9a	108.0a	75.0a	3-Sep
	Late	4.3a	54.0b	19.6b	15.3a	405.3a	101.0b	55.0b	25-Aug
	Early/medium	2.9b	35.9.c	10.1c	14.9ab	309.0b	73.0c	35.8c	28-Jul
May	Very late	3.8a	57.1a	22.4a	12.7b	357.8a	105.8a	33.3a	8-Oct
	Late	3.4a	52.3a	16.4b	10.9c	359.8a	93.7b	22.5b	8-Oct
	Early/medium	3.7a	40.6b	13.8b	17.1a	319.4b	63.9c	1.7c	25-Aug
June	Very late	4.1a	53.2a	17.5a	14.2a	305.0a	129.7a	0.0b	10-Nov
	Late	3.8a	50.6a	15.8a	13.5a	309.0a	120.0b	6.7a	10-Nov
	Early/medium	1.8b	31.8b	8.9b	10.4b	195.0b	62.7c	0.0b	22-Sep

Table 11. Maturity group by month planting date interaction average yields for sugar, fresh yield, dry yield, and brix % for 2010 College Station, TX.

Maturity*Month	Sugar yield (MT/ha)	Fresh yield (MT/ha)	Dry yield (MT/ha)	Brix %	Harvest Date
April,Very late	4.8a	69.0a	25.0a	13.2bc	3-Sep
April,Late	4.3ab	54.0b	19.6b	15.3b	25-Aug
June,Very late	4.1abc	53.2b	17.5bc	14.2bc	10-Nov
May,Very late	3.8abcd	57.1b	22.4ab	12.7d	8-Oct
June,Late	3.8bc	50.6b	15.8cd	13.5c	10-Nov
May,Early/medium	3.7bc	40.5c	13.8d	17.1a	25-Aug
May,Late	3.4cd	52.3b	16.4cd	10.9d	8-Oct
April,Early/medium	2.9d	35.9cd	10.1e	14.9b	28-Jul
June,Early/medium	1.8e	31.8d	8.9e	10.4d	22-Sep

Hybrid Performance in 2010

Significant variation existed among hybrids within maturity groups for all traits, except lodging. The maturity group by month planted interaction was also significant variation for all traits. Variation due to hybrids nested within maturity by month planted was not significant for yield traits which indicate that hybrid performance within maturity groups was consistent over month planted (Table 12).

The average yield of hybrids combined over planting dates indicates that the late maturity hybrids (TX09055 and TX09057) and very late maturity hybrids (TX09060 and TX09062) were the best performing hybrids for all yield traits (Table 13). There were differences between maturity groups for average days to anthesis, and the photoperiod sensitive maturity groups, characterized by delayed flowering were most susceptible to lodging. Yields between all early/medium maturity hybrids were fairly consistent for combined planting dates.

In the April planting date, there was major variation between photoperiod sensitive hybrids for most yield traits, especially sugar yield (Table 14). Some of the differences were due to agronomic differences that were accentuated by variation due to lodging. Of the late maturity hybrids, TX09055 was the best for sugar yield. Early/medium maturity hybrids were rather consistent for yields in the April planting date and were not as influenced by lodging. In the May planting date there was no consistent trend for yield amongst the different maturity group as individual hybrids from each entry group were distributed from high to low (Table 15). There was large variation for brix percentage between all maturity groups, but early/medium maturity hybrids ranked highest. Lodging was not as severe at this planting date, but very late maturity hybrids TX09060 and TX09062 were the most susceptible. In the June planting date, the late and very late groups were consistently higher in yield than the early/medium maturity hybrids (Table 16). The average days to anthesis for photoperiod sensitive groups continued to increase under growing conditions of the fall months and describable maturity differences were visible. Lodging was minimal for all hybrids.

Table 12. Sugar, fresh yield, dry yield, brix %, height, days to anthesis, and lodging percentage analysis of variance results for individual hybrid analysis of early/medium, late, and very late maturity groups in 2010 College Station, TX.

	Sugar (MT/ha)		Fresh yield (MT/ha)		Dry yield (MT/ha)		Brix %		Height Cm		Days to anthesis		Lodging %	
Source of variance	Df	MS	Df	MS	df	MS	df	MS	df	MS	df	MS	df	MS
Maturity group	2	9.9*	2	4161.9**	2	535.3**	2	10.8	2	72886.5**	2	19096.1**	2	3982.8**
Month planted	2	2.3	2	391.2	2	133.4	2	14.0*	2	74936.6**	2	1832.2**	2	19827.1**
Hybrid(Maturity group)	7	2.2**	7	235.5**	7	25.0*	7	6.3*	7	469.1**	7	103.2**	7	88.9
Rep(Month planted)	6	1.2*	6	238.5**	6	40.3**	6	2.1	6	259.8	6	6.7	6	826.7**
Maturity group*Month planted	4	5.0**	4	190.8**	4	48.3**	4	88.9**	4	5177.7**	4	1014.1**	4	882.8**
Hybrid(Maturity group)*Month planted	14	0.5	14	35.4	14	7.2	14	2.6	14	336.4**	14	20.5**	14	107.9
Error	45	0.5	53	44.7	45	9.6	54	2.3	54	88.8	54	3.3	54	141.5
R^2		0.77		0.85		0.83		0.81		0.99		0.99		0.88
CV		24.7		5.5		11.2		9.1		1		1.5		14.7

, * Significant at p < .05 and .01 respectively

Table 13. Individual hybrid average yields for sugar, fresh yield, dry yield, brix %, height, days to anthesis, and lodging % for all April, May, and June planting dates combined in 2010 College Station, TX.

Pedigree	Maturity group	Sugar (MT/ha)	Fresh yield (MT/ha)	Dry yield (MT/ha)	Brix %	Height cm	Days to anthesis	Lodging %
TX09055	Late	4.5a	60.9a	20.1ab	13.8abc	350.0b	106.c	23.bc
TX09062	Very late	4.3a	59.9a	22.1a	13.7abcd	355.6ab	115.0a	37.8a
TX09057	Late	4.1a	55.8a	18.3bc	13.8abcd	355.6ab	111.0b	27.8ab
TX09060	Very late	3.9ab	59.6a	21.0ab	12.4de	351.4b	114.0a	34.4a
TX09056	Late	3.5bc	48.4b	15.7cd	12.8cde	362.7a	101.0d	33.3ab
TX09052	Early/medium	3.0cd	39.1cd	12.5ef	14.5ab	263.3d	66.0e	11.1d
TX09051	Early/medium	2.9cd	36.1d	11.3f	15.1a	283.4c	67.0e	12.2d
TX09058	Late	2.8cd	44.3bc	15.1de	12.2e	364.1a	101.0d	27.8ab
TX09054	Early/medium	2.6d	33.7d	10.1f	13.6bcde	272.3cd	66.0e	11.1d
TX09053	Early/medium	2.5d	34.1d	10.2f	13.3bcde	278.8c	67.0e	15.6cd

Table 14. Individual hybrid yield for April planting date for sugar, fresh yield, dry yield, brix %, height, days to anthesis, and lodging % in 2010 College Station, TX.

Pedigree	Maturity group	Sugar (MT/ha)	Fresh yield (MT/ha)	Dry yield (MT/ha)	Brix %	Height cm	Days to anthesis	Lodging %	Harvest date
TX09055	Late	5.4a	66.2ab	23.6ab	15.7ab	406.4a	104.0b	43.3bc	25-Aug
TX09062	Very late	5.1ab	73.3a	27.0a	13.5abc	402.2a	108.0a	73.3ab	3-Sep
TX09056	Late	4.3abc	49.6cd	17.0bc	16.5a	406.4a	97.0c	63.3abc	25-Aug
TX09057	Late	4.2abc	56.7bc	22.2ab	15.1ab	406.4a	104.0b	60.0abc	25-Aug
TX09060	Very late	3.7bc	64.6ab	23.0ab	10.9c	393.7a	108.0a	76.7a	3-Sep
TX09058	Late	3.0c	43.7cde	17.2bc	14.0abc	402.2a	97.0c	53.3abc	25-Aug
TX09053	Early/medium	3.0c	36.1e	10.0cd	14.9ab	319.2bc	74.0d	40.0c	28-Jul
TX09052	Early/medium	3.0c	38.5de	11.7cd	15.2ab	281.9d	72.0e	33.3c	28-Jul
TX09051	Early/medium	2.7c	32.5de	12.0cd	16.7a	326.0b	73.0de	36.7c	28-Jul
TX09054	Early/medium	2.6c	32.8e	8.6d	12.8bc	309.0c	73.0de	33.3c	28-Jul

Table 15. Individual hybrid yields for May planting date for sugar, fresh yield, dry yield, brix %, height, days to anthesis, and lodging % in 2010 College Station, TX.

Pedigree	Maturity group	Sugar (MT/ha)	Fresh yield (MT/ha)	Dry yield (MT/ha)	Brix %	Height cm	Days to anthesis	Lodging %	Harvest date
TX09060	Very late	4.1ab	59.4a	26.3a	12.3b	355.6a	105.0a	26.7b	8-Oct
TX09051	Early/medium	4.1a	42.3bc	13.6c	17.5a	330.2b	64.0c	0.0d	25-Aug
TX09052	Early/medium	4.0a	43.4bc	14.9c	17.3a	306.5d	63.0c	0.0d	25-Aug
TX09057	Late	3.9ab	59.4a	16.9bc	11.4bc	359.8a	107.0a	23.3b	8-Oct
TX09055	Late	3.9ab	61.3a	19.6b	11.5bc	355.6a	92.0b	26.7b	8-Oct
TX09054	Early/medium	3.6ab	39.1bc	13.7c	17.7a	315.0cd	64.0c	0.0d	25-Aug
TX09062	Very late	3.4ab	54.8a	18.1bc	13.1b	359.8a	106.0a	40.0a	8-Oct
TX09053	Early/medium	3.1bc	37.4c	12.9c	15.7a	326.0bc	64.0c	6.7cd	25-Aug
TX09056	late	2.5c	45.6b	14.8c	9.8c	364.1a	87.0b	16.7bc	8-Oct
TX09058	late	2.3c	43.1bc	12.9c	9.9c	359.8a	89.0b	23.3b	8-Oct

Table 16. Individual hybrid yields for June planting date for sugar, fresh yield, dry yield, brix %, height, days to anthesis, and lodging % in 2010 College Station, TX.

Pedigree	Maturity group	Sugar (MT/ha)	Fresh yield (MT/ha)	Dry yield (MT/ha)	Brix %	Height cm	Days to anthesis	Lodging %	Harvest date
TX09055	Late	4.3a	55.1a	17.3a	14.4ab	287.9c	123.0b	0.0c	10-Nov
TX09057	Late	4.2a	51.2a	15.9a	14.9a	300.1bc	123.0b	0.0c	10-Nov
TX09060	Very late	4.2a	54.7a	16.7a	13.9abc	304.8bc	129.0a	0.0c	10-Nov
TX09062	Very late	3.9ab	51.6a	18.2a	14.6ab	304.8bc	130.0a	0.0c	10-Nov
TX09056	Late	3.4ab	49.9a	15.2a	12.2cd	317.5ab	118.0c	20.0a	10-Nov
TX09058	Late	3.2b	46.0ab	14.9a	12.7bcd	330.2a	117.0c	6.7b	10-Nov
TX09052	Early/medium	2.2c	35.3bc	10.9b	11.0de	201.5d	62.0e	0.0c	22-Sep
TX09051	Early/medium	1.8c	33.4bc	8.1b	11.1de	193.9d	64.0d	0.0c	22-Sep
TX09054	Early/medium	1.7c	28.9c	8.2b	10.1e	193.0d	63.0de	0.0c	22-Sep
TX09053	Early/medium	1.6c	28.8c	7.8b	9.4e	191.4d	63.0de	0.0c	22-Sep

Discussion

Planting Environments and Maturity Groups

Although all of these tests were grown in the same location, the monthly planting dates produced unique growing environments. Likewise, the different maturity groups and planting dates affected the relative maturity of the hybrids. For the late, and very late hybrids, maturity is influenced to some degree by photoperiod sensitivity. Given the daylengths in Central Texas, the late and very late hybrids were expected to have longer growing periods than the PI hybrids but these differences should be reduced in the June planting as the day lengths are then at their maximum and closer to the shorter days that will initiative reproductive growth. Evaluation of days to flowering and maturity and the differences between the groups revealed that this trend is not always consistent (Tables 17-18).

In both years of planting, the days to flower actually increased between April and June (Table 17-18). While not expected, this flowering for later planting dates was important to extend harvest dates into November (Tables 17-18). In 2009, flowering was delayed 12 days in late maturity hybrids between April and June planting dates (Table 17). During 2010, flowering was delayed 22 days and 19 days for respective very late and late maturity groups between April and June (Table 18). Based solely on summer day length hours, photoperiod sensitive sweet sorghum hybrids cannot be classified directly into a precise maturity day class. They are better classified into a maturity window, i.e. 120-150 days and 130-160 days for respective late maturity and very late maturity hybrids. Limited time and resources prevented separate harvest dates in 2010 for late and very late maturity hybrids for May and June planting dates, but very late maturity groups are approximately 10-15 days later maturing. For production purposes, a very late maturity group will be necessary to extend harvest dates 15 days past those of late maturity hybrids.

Table 17. Maturity class analysis examining the differences between planting date, harvest date, days to anthesis, and days to harvest during the 2009 summer in College Station, TX.

Maturity Class	Planting Date	Harvest date	Days to Anthesis	Days to harvest
Early/medium	13-Apr	14-Jul	67	92
Late	13-Apr	21-Aug	92	130
Early/medium	19-May	21-Aug	73	94
Late	19-May	23-Oct	117	157
Early/medium	12-Jun	3-Sep	68	83
Late	12-Jun	23-Oct	104	133
Early/medium	15-Jul	17-Nov	91	125
Late	15-Jul	17-Nov	82	125

Table 18. Maturity class analysis examining the differences between planting date, harvest date, days to anthesis, and days to harvest during the 2010 summer in College Station, TX.

Maturity class	Planting Date	Harvest Date	Days to anthesis	Days to harvest
Early/medium	13-Apr	28-Jul	73	106
Late	13-Apr	25-Aug	101	134
Very late	13-Apr	3-Sep	108	143
Early/medium	21-May	25-Aug	64	96
Late	21-May	8-Oct	94	140
Very late	21-May	8-Oct	106	140
Early/medium	17-Jun	22-Sep	63	97
Late	17-Jun	10-Nov	120	146
Very late	17-Jun	10-Nov	130	146

The results of this study clearly indicate that there is a limit to how late this crop can be planted. The July planting date in 2009 was the lowest yielding date (Table 5). In addition, it required substantially more effort and cost to establish in that additional irrigation and insecticide applications were required to maintain the crop. Thus, while a July planting date could possibly extend the sweet sorghum harvest further into November, the lower yields and increased establishment costs do not justify the investment and hybrids planted on earlier dates can be more effective. For example, plantings of the late and very late maturity groups in 2010 during June matured in that timeframe with reduced establishment requirements and higher yields. These results document the value of determining the optimum combination of maturity groups and planting date to meet production and harvest needs.

In addition to the interaction of maturity and planting date, environmental variation from year to year influences productivity and emphasize the importance of irrigation to maintain yield potential when dry conditions are encountered. Favorable growing conditions not only produced optimal hybrid yields for all maturity groups, but also allowed for timely harvest of material, extremely important for continually supplying sweet sorghum to milling facilities.

Sweet Sorghum Productivity and Hybrids

This study confirms the correlation between delayed maturity, increased plant height, and increased yield. In general, the early/medium maturity group flowered in a defined number of days (independent of daylength) and was the lowest yielding group. Larger R-Square values between maturity and sugar should be expected, but there were some inconsistencies in maturity between early/medium maturity group hybrids between the 2009 and 2010 summers (Table 19). While the yields of the photoperiod sensitive types (late and very late) were variable across years, they were consistently highest within a planting date. Like variation in maturity, the photoperiod sensitive groups were taller than the photoperiod insensitive group. Combined with the longer growing season, these hybrids were more prone to lodging, but breeding for lodging resistance should be expected to mitigate this problem.

Lodging was an issue in 2010 especially in the April planting date, when all hybrids root lodged following a major storm which produced high winds and 7 inches of rainfall in two days. Lodging was correlated with maturity group; the worst lodging was in the very late maturity group with less observed in the late and early groups respectively (Table 20). While some of this may be due to similar parentage of the hybrids within each group, the presence of lodging in all types clearly indicates that this is an issue with sweet sorghum. Severe lodging is important because lodging reduces harvestable biomass yield and a concurrent drop in quality (Hills et al., 1990). In the current study, brix percentages and fresh biomass yields remained productive under lodging environments, but these plots were hand-harvested. In mechanical harvest, quality is reduced due to the inclusion of more trash in the harvested material and the inability to collect the material during harvest (Egg et al., 1993). Thus, sweet sorghum breeding program should emphasize tolerance or resistance to lodging. Significant research in breeding lodging resistant sorghum has been completed; it is important to integrate these approaches into sweet sorghum breeding programs (Esechie et al., 1976; Sanchez et al., 2002). Agronomic management also affects lodging potential and further studies to optimize plant population, row spacing and fertilization must also address their effect on lodging (Turhollow et al., 2010).

Table 19. Correlation analysis for maturity, height, sugar yield, and fresh yield between maturity groups during the 2010 summer in College Station, TX.

	Maturity	Height	Sugar yield	Fresh yield
Maturity	1			
Height	0.65	1		
Sugar yield	0.5	0.48	1	
Fresh yield	0.66	0.57	0.86	1

All values significant at $p < .01$

Table 20. Correlation analysis examining the effects of lodging % to maturity, fresh yield, brix % between maturity groups for the April planting date during the 2010 summer in College Station, TX.

	Maturity	Fresh yield	Brix %
Lodging %	0.6**	0.12	-0.3

** Significant at $p < .01$

Specific Hybrid Performance

As with any crop, further improvement is absolutely essential to mitigate deficiencies in the currently available hybrids (i.e., lodging) and improve the yield potential and quality of the crop. The experimental hybrids tested in this study are essentially first generation hybrids; they represent the basic potential of the crop in hybrid combination. In addition, they also allow both breeding programs and producers to identify potential areas of weakness that should be the focus of future breeding efforts. Thus, this continued improvement of parental lines and accurate selection of hybrids based on dependable sugar yields and versatility under variable environments are crucial to sweet sorghum's success in the ethanol industry.

Because the experimental hybrids in this study changed between years, only the hybrids evaluated in 2010 were assessed to determine if variation amongst the hybrids exists. Within each maturity group, it was possible to identify superior hybrids for sugar yield (Table 13). For example, early/medium maturity hybrids TX09051 and TX09052 and late maturity hybrids TX09055 and TX09057 performed well for sugar yield (as well as biomass yield) at most all planting dates (Tables 14-16). Only two very late hybrids were tested and this limited the ability to detect differences. While the yields were good, lodging was a major problem in this group. Consequently, further research and breeding is needed to select optimal very late maturity hybrids

In the current study, the best hybrids were based on fermentable sugar yields estimated using the formula described by (Corn, 2009). Sugar yields are based on juice yield and brix. In sweet sorghums, juice yields are highly correlated with biomass yields and interestingly, total biomass yield was more correlated with sugar yield than was brix concentration (Figure 1). This implies that selection for biomass yield is useful for predicting sugar yields. While this is not consistently true, this observation in the current dataset was due to a couple of factors. First, the genetic variability for sugar concentration is rather limited in these hybrids and thus the variation in brix concentration is relatively low compared to a study that included both sweet and non-sweet sorghums (Murray et al., 2009). Second, brix concentration is highly variable on a daily and even hourly basis due to evapotranspiration, temperature, and soil water availability (Corn, 2009). Thus, machine-combined, biomass yields are more reliable for predicting sugar yields in a group of sweet sorghum. These results are similar to those observed in elite sugarcane as well (Singels et al., 2005). It does not mean that brix is unimportant, but it is does confirm that once brix is sufficiently high, biomass yield becomes the primary influence in sugar yield.

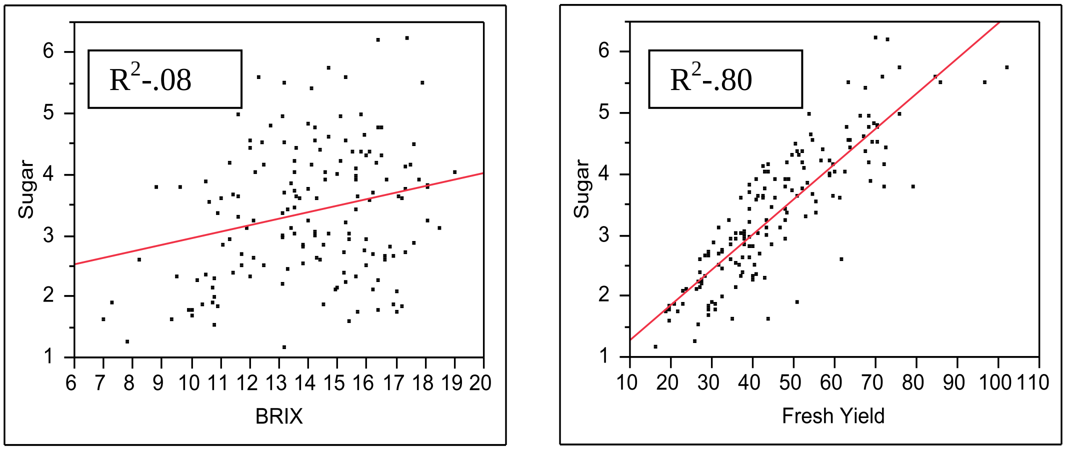

Figure 1. Correlations for determining the accuracy of brix% or fresh yield as a predictor for sugar yields.

Importance of Maturity Groups in Sweet Sorghum

Hybrids from the late and very late maturity groups produce higher yields (Table 8), and required a longer growing season. In 2010, the earliest date that the late hybrids matured was August 25th (Table 10). Conversely, early hybrids were ready for harvest by July 28th. From a processing perspective, an additional month of processing is critical for economical viability. Therefore, early or photoperiod insensitive hybrids are essential to maximizing the processing window. The early/medium group averaged 2.8 MT/ha across all planting dates in 2010 (Table 8), but the early/medium group is most important in the April planting date, because this is the only type of hybrid that is ready to harvest within 100 days. Over two years, yield at this date averaged 2.8 and 2.9 MT/ha in 2009 and 2010 years respectively. Thus, processors and economists must determine if current yields in early/medium hybrids justify production. Since these are first generation hybrids, it is logical to expect improvements in these hybrids with consistent breeding efforts.

Because of their higher yield potential, it is important to fully utilize both the late (moderately photoperiod sensitive) and very late (strongly photoperiod sensitive) maturity hybrids for as much as the harvest season as possible. These hybrids reach harvest maturity in late August and with timely plantings produce optimal yields through late October. Because the crop is in the field longer, production does involve somewhat greater risk. For example, drought lowered sugar yields for late and very late maturity hybrids planted in May 2010 (Table 10). Finally, some fluctuations in flowering time were observed and a further characterization of the germplasm is needed to determine the exact cause of this variation.

Production Plan for Industrial Processing

Data from the 2010 trial was used to produce a best-case scenario production plan to maximize yield over a harvest season from July to November (Table 11). Planting dates were assumed to fall on or near the 15th of April, May and June. Harvest windows were based on ½ month intervals (i.e., July 16-July 31 through November 1-15) (Table 21). For each interval, the yield of the best hybrid from the highest yielding maturity group was chosen to supply biomass during that harvest interval.

Table 21. Harvest date examination of maturity group and planting date combinations and corresponding sugar, fresh, and dry yields.

Harvest Date	Planting date	Maturity Group	Sugar yield MT/ha	Fresh yield MT/ha	Dry yield MT/ha
July 16-July 31	4/15	Early/medium	2.9	35.9	10.1
Aug. 1-Aug. 15	5/15	Early/medium	3.7	40.5	13.8
Aug. 16-Aug. 31	4/15	Late	4.3	54.0	19.6
Sep. 1-Sep 15	4/15	Very late	4.8	69.0	25
Sep. 16-Sep. 30	5/15	Late	3.4	52.3	16.4
Oct. 1-Oct. 15	5/15	Very late	3.8	57.1	22.4
Oct. 16-Oct. 31	6/15	Late	3.8	50.6	15.8
Nov. 1- Nov. 15	6/15	Very late	4.1	53.2	17.5

For the first two harvest intervals, only early/medium maturity hybrids were physiologically mature and these were planted in the April and May planting dates, respectively (Table 21). Late hybrids planted in April are the only group of hybrids ready in the late August planting. In early September, the very late hybrids planted in April and the early hybrids planted in June were both harvested, but yields were higher in the very late hybrid so they are included in the production plan. In late September and early October, the May plantings of late and very late hybrids produced the highest yields. Finally, if late October and early November harvests are necessary, a duplication of the late and very late hybrids planted in June are the highest yielding option (Table 21). If this production is used to complement sugarcane, it is unlikely that sweet sorghum harvest is needed in November as sugarcane will be ready to harvest at that time.

This information can then be adjusted to develop a planting plan and area requirement for each harvest window. Based on the yields obtained herein, a total of 2573 hectares would be required to provide biomass to an industrial plant that processes

1,000 MT/day (Table 22). The majority of the crop would be planted in April, with reduced hectarage in May and June, depending on when the transition to sugarcane would take place.

Table 22. Projected planting plan to meet the need of a 1000 tons biomass/day mill.

Month planted	Maturity Group	Estimated fresh weight MT/ha	Area planted Ha	Harvest date
April	Early/medium	35.9	445	July 16-July 31
	Late	54.0	296	Aug. 16-Aug. 31
	Very late	69.0	232	Sep. 1-Sep 15
May	Early/medium	40.5	395	Aug. 1-Aug. 15
	Late	52.3	306	Sep. 16-Sep. 30
	Very late	57.1	281	Oct. 1-Oct. 15
June	Late	50.6	317	Oct. 16-Oct. 31
	Very late	53.2	301	Nov. 1- Nov. 15
		Total	2573	

By utilizing a combination of varying maturity classes accurately placed into specific planting date environments, sugar milling seasons will extend and compliment sugarcane harvest seasons by approximately 3 to 4 months for 8 continual months of sugar availability (Table 23).

The information presented herein is only directly applicable to the College Station, TX location only. The same hybrids planted at different latitudes and environments will likely change in productivity and possibly in relative maturity. Therefore, it is essential to test these hybrids in different environments for determining overall adaptability and yield stability.

Table 23. Planting and harvesting scheme of sweet sorghum and sugarcane to accomplish an eight month continual harvest of sugar.

<table>
<tr><th></th><th>Apr.</th><th>May</th><th>June</th><th>July</th><th>Aug.</th><th>Sep.</th><th>Oct.</th><th>Nov.</th><th>Dec.</th><th>Jan.</th><th>Feb.</th><th>Mar.</th></tr>
<tr><td rowspan="2">Sweet Sorghum</td><td colspan="3">Planting Season</td><td colspan="9"></td></tr>
<tr><td colspan="3"></td><td colspan="5">5 Month Harvest</td><td colspan="4"></td></tr>
<tr><td rowspan="2">Sugarcane</td><td colspan="4"></td><td colspan="3">Planting Season</td><td colspan="5"></td></tr>
<tr><td colspan="6"></td><td colspan="5">5 Month Harvest</td><td></td></tr>
<tr><td>Combined</td><td colspan="3"></td><td colspan="8">Eight Month Continual Harvest</td><td></td></tr>
</table>

CHAPTER IV

CONCLUSIONS

Sweet sorghum is a highly versatile annual row crop that produces sufficient sugar yields to be considered for use in ethanol production either as a stand-alone crop or as a complement to sugarcane production. Currently available sweet sorghum hybrids can be separated into three maturity classes: early/medium (non-photoperiod sensitive), late (moderately photoperiod sensitive), and very late (strongly photoperiod sensitive). Each of these groups are important to maximize productivity over a harvest window in temperate climates of the Southeastern US that are favorable for sweet sorghum and sugarcane production.

Under favorable growing environments, sweet sorghum hybrids of all maturity groups produced sugar yields ranging from 2.8 to 4.9 MT/ha. Excessively wet and/or dry periods affected productivity of sweet sorghum in various ways ranging from maturity delays, yield reductions, and lodging. Dry weather was common to late season plantings and reduced sugar yields for all maturity class hybrids, but had stronger effect on early/medium maturity hybrids.

Early/medium, late, and very late maturity hybrids planted during April, May, and June planting dates are necessary to maximize productive efficiency of the mill season. Early/medium maturity hybrids planted during April and May were ready for harvest between late July and mid-August. June planting dates were not needed for early/medium maturity hybrids. In addition, late and very late maturity hybrids planted during April are ready to harvest in late August and produce significantly higher sugar yields. Timely planting of late and very late maturity hybrids are important in April, May, and June planting dates, and these hybrids deliver the maximum yields for harvests after mid August. Intermittent use of late and very late maturity hybrids can extend sugar milling seasons into mid November if so desired.

The results indicate that sweet sorghum can be produced and harvested over a range of time, provided that the climate allows such a window. Accomplishing this goal requires a thorough understanding of the maturity of the hybrids in the specific environment and their relative yield potential in those environments. If this information is available, it is possible to predict planting times and productivity for a harvest season that maximizes yield through judicious deployment of each type of hybrid.

REFERENCES

Almodares, A., R. Taheri, and S. Adeli. 2007. Inter-relationship between growth analysis and carbohydrate contents of sweet sorghum cultivars and lines. Journal of Environmental Biology 28:527-531.

Baucum, L.E., R.W. Rice, and T.J. Schueneman. 2006. An overview of Florida sugarcane. Agronomy Department document SS-AGR-232. University of Florida/IFAS, Gainesville, FL.

Bennett, A.S., and R.P. Anex. 2009. Production, transportation and milling costs of sweet sorghum as a feedstock for centralized bioethanol production in the upper Midwest. Bioresource Technology 100:1595-1607.

Corn, R.J. 2009. Heterosis and compositon of sweet sorghum. PhD Dissertation, Soil and Crop Sciences, Texas A&M University, College Station, TX.

Egg, R.P., C.G. Coble, C.R. Engler, and D.H. Lewis. 1993. Feedstock storage, handling and processing. Biomass and Bioenergy 5:71-94.

Elobeid, A., S. Tokgoz, D.J. Hayes, B.A. Babcock, and C.E. Hart. 2006. The long-run impact of corn-based ethanol on the grain, oilseed, and livestock sectors: a preliminary assessment, Center for Agricultural and Rural Development (CARD), Ames, IA.

Engelke, J. 2005. Sugarcane: measuring commercial quality. Department of Agriculture Farmnote (Ed.), Government of Western Australia. Kununurra, Western Australia. No. 23/2002.

Esechie, H.A., J.W. Maranville, and W.M. Ross. 1976. Relationship of stalk morphology and chemical composition to lodging resistance in sorghum. Crop Science 17:609-612.

Ghaneker, A.R., C.D. Basarkar, and N. Nimbker. 1992. Potential and practive relation to sorghum as a source of sugar in parts of India. Int. Crops Res. Institute Semiarid Tropics 1:139-142.

Gnansounou, E., A. Dauriat, and C.E. Wyman. 2005. Refining sweet sorghum to ethanol and sugar: economic trade-offs in the context of North China. Bioresource Technology 96:985-1002.

Heaton, E.A., F.G. Dohleman, and S.P. Long. 2008. Meeting US biofuel goals with less land: the potential of Miscanthus. Global Change Biology 14:2000-2014.

Hills, F., R. Lewellen, and I. Skoyen. 1990. Sweet sorghum cuItivars for alcohol production. Cal Ag 44:14-16.

Hoekman, S.K. 2009. Biofuels in the U.S. - Challenges and opportunities. Renewable Energy 34:14-22.

Hoffmann-Thoma G., Hinkel K., Nicolay P., Willenbrink J. 1996. Sucrose accumulation in sweet sorghum stem internodes in relation to growth. Physiologia Plantarum 97:277-284.

Lamkey, K.R., and J.W. Edwards. 1999. The quantitiative genetics of heterosis. In Coors JG and Pandley S (eds) The Genetics and Exploitation of Heterosis in Crops, CCSA, ASA, and SSA: Madison, WI, USA. p. 31-48.

Lingle, S.E. 1987. Sucrose metabolism in the primary culm of sweet sorghum during development. Crop Sci. 27:1214-1219.

LSU Ag Center. 2004. Sugarcane Summary for Crop Year 2004.

Mckendry, P. 2002. Energy production from biomass (part 1): overview of biomass. Bioresource Technology 83:37-46.

Mosier, N.S., and K. Ileleji. 2006. How fuel ethanol is made from corn. Purdue University Cooperative Extension. West Lafayette, IN.

Murphy, R.L., R.R. Klein, D.T. Morishige, J.A. Brady, W.L. Rooney, F.R. Miller, D.V. Dugas, P.E. Klein, and J.E. Mullet. 2011. Coincident light and clock regulation of pseudoresponse regulator protein 37 (PRR37) controls photoperiodic flowering in sorghum. Proceedings of the National Academy of Sciences 108:16469-16474.

Murray, S.C., W.L. Rooney, M.T. Hamblin, S.E. Mitchell, and S. Kresovich. 2009. Sweet sorghum diversity and association mapping for brix and height. The Plant Genome. 2:48-62.

Naoyuki, T., and G. Yusuke. 2004. Cultivation of sweet sorghum (*Sorghum bicolor* (L.) Moench) and determination of its harvest time to make use as the raw material for fermentation, practiced during rainy season in dry land of Indonesia. Plant Production Science 7:442-448.

OPS. 2007. Fact Sheet: Energy Independence and Security Act of 2007. In Office of the Press Secretary (Ed.).

Prasad, S., A. Singh, N. Jain, and H.C. Joshi. 2007. Ethanol production from sweet sorghum syrup for utilization as automotive fuel in India. Energy & Fuels 21:2415-2420.

Reddy, B.V.S., A.K. Ashok, and S. Ramesh. 2007. Sweet sorghum: A water saving bio-energy crop. In International conference on Linkages between Energy and Water Management for Agriculture in Developing Countries, January 2007. ICRISTAT. Patancheru, India.

Reddy, B.V.S., P.S. Rao, A.A. Kumar, P.S. Reddy, P.P. Rao, K.K. Sharma, M. Blummel, and C.R. Reddy. 2009. Sweet sorghum as a biofuel crop: Where are we now? In proceedings of the Sixth Int. Biofuels Conference, 4-5 March 2009, New Delhi, India. p. 191-202.

Reddy, B.V.S., S. Ramesh, P.S. Reddy, B. Ramaiah, P.M. Salimath, and K. Rajashekar. 2005. Sweet Sorghum- A potential alternate raw material for bio-ethanol and bio-energy. International Sorghum and Millets News Letter 2005. 46:79-86.

Rooney, W.L., and S. Aydin. 1999. Genetic Control of a Photoperiod-Sensitive Response in Sorghum bicolor (L.) Moench. Crop Sci. 39:397-400.

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

Rozeff, N., J.M. Amador, and J.E. Irvine. 1998. South Texas Sugarcane Handbook. Texas A&M University Agricultural Research and Extension Center at Weslaco and Rio Grande Sugar Growers, Inc. Santa Rosa, Tx.

Saeed, M., C.A. Francis, and J.F. Rajewski. 1984. Maturity Effects on Genotype × Environment Interactions in Grain Sorghum. Agronomy Journal. 76:55-58.

Sanchez, A.C., P.K. Subudhi, D.T. Rosenow, and H.T. Nguyen. 2002. Mapping QTLs associated with drought resistance in sorghum (Sorghum bicolor L. Moench). Plant Molecular Biology 48:713-726.

Sinclair, T.R., R.A. Gilbert, R.E. Perdomo, J.M. Shine, G. Powell, and G. Montes. 2004. Sugarcane leaf area development under field conditions in Florida, USA. Field Crops Research 88:171-178.

Singels, A., R.A. Donaldson, and M.A. Smit. 2005. Improving biomass production and partitioning in sugarcane: theory and practice. Field Crops Research 92:291-303.

Smith, G.A., M.O. Bagby, L. R.T., D.L. Doney, P.H. Moore, F.J. Hills, L.G. Campbell, G.J. Hogaboam, G.E. Coe, and K. Freeman. 1987. Evaluation of sweet sorghum for fermentable sugar production potential. Crop Science 27:788-793.

Sugarcane Production Handbook. 2001. Louisiana State University Agricultural Center, Baton Rouge, LA, Publication # 2859.

Swayze, S. 2009. The sweet sorghum opportunity: A complementary source of low-cost fermentable sugars for biofuel. International Sugar Journal 111: 691-695.

Tarpley, L., and D.M. Vietor. 2007. Compartmentation of sucrose during radial transfer in mature sorghum culm. BMC Plant Biology 7:33.

Teetor, V.H., D.V. Duclos, E.T. Wittenberg, K.M. Young, J. Chawhuaymak, M.R. Riley, and D.T. Ray. 2010. Effects of planting date on sugar and ethanol yield of sweet sorghum grown in Arizona. Industrial Crops and Products 34:1293-1300.

Turhollow, A.F., E.G. Webb, and M.E. Downing. 2010. Review of sorghum production practices: Applications for bioenergy, Oak Ridge National Laboratory. Department of Energy. Oak Ridge, TN.

USDA. 1997. Usual Planting and Harvesting Dates for U.S. Field Crops. National Agricultural Statistics Service (NASS). United States Department of Agriculture. Washington, DC.

Wu, X., R. Zhao, S.R. Bean, P.A. Seib, J.S. Mclaren, R.L. Madl, M. Tuinstra, M.C. Lenz, and D. Wang. 2006. Factors impacting ethanol production from grain sorghum in the dry-grind process. Cereal Chemistry 84:130-136.

VITA

Payne Stewart Burks received his Bachelor of Science degree in Agronomy from Texas A&M University in May 2009. He entered the Crop Science Department at Texas A&M University during the summer of 2009 and pursued a Master of Science degree in Plant Breeding. His research interests include sweet sorghum genetics and the biofuel industry. He plans to publish a manuscript on these topics with a focus on developing sweet sorghum as a sustainable biofeedstock in the biofuel industry.

Mr. Burks may be reached at the University of Illinois-Institute for Genomic Biology, 1206 W. Gregory Drive, Urbana, Illinois 61801 or at 2404 Fields South Drive, Champaign, Illinois 61822. His email address is pburks2@illinois.edu.