MANAGEMENT OF BIOFUEL SORGHUMS IN KANSAS

by

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Abstract

Current demand for ethanol production is stressing feedstock production. Previous research has shown sweet sorghum and photoperiod sensitive sorghum [*Sorghum bicolor* (L.) Moench] as viable feedstocks which may supplement or replace current feedstocks. Studies were conducted at two dryland locations in north central and northeast Kansas in 2008 and 2009 to determine the effects of cultivar, nitrogen fertilizer rate, plant density, and harvest date on sweet sorghum juice and biomass yields. The cultivar study indicated the cultivar 'M81E' generally had the greatest yield. Other cultivars were not well suited for this region. No significant results were found in the nitrogen rate trial, indicating sweet sorghum may be insensitive to nitrogen fertilizer applications. The plant density trial results indicated that sweet sorghum possess a great ability to compensate for plant spacing. No differences were found in juice yields across densities, and the only difference found in total dry biomass was at the highest plant density. Results from the harvest date study indicate that sweet sorghum harvest should be delayed until at least the grain soft dough stage and can be continued for at least 10 days after a killing freeze without a yield penalty. Delaying harvest allowed for an increase in total dry matter and fermentable carbohydrates without a decrease in juice yield. Two studies were conducted at two dryland locations in northcentral and northeast Kansas in 2008 and 2009 to determine the effects of plant density on photoperiod sensitive sorghum yields, with an additional study to determine the effects of winter weathering. Photoperiod sensitive sorghum was found to be similarly insensitive to plant density, with few differences found in total dry biomass yield. Yields were found to decrease significantly due to winter weathering. A final study was conducted to examine a variety of sorghums as biofuel feedstocks. Photoperiod sensitive sorghum yielded the greatest in 2008 while sweet sorghum yielded less. In 2009, sweet and photoperiod sensitive sorghum yielded less than the cultivar TAMUXH08001. Sweet sorghum yields are generally the greatest with 'M81E' and when harvested after soft dough. Yields of both sorghums are occasionally influenced by plant density.

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CHAPTER 1 - Sweet Sorghum

Abstract

Research has shown sweet sorghum [*Sorghum bicolor* (L.) Moench] as a viable biofuel feedstock. Studies were conducted at two dryland locations in northcentral and northeast Kansas in 2008 and 2009 to determine cultivar, nitrogen fertilizer rate, and plant density effects on sweet sorghum total dry matter, juice yield, fermentable carbohydrates, and grain yield. A separate study was conducted in northeast Kansas in 2009 to examine the effect of harvest date on yield. After plot weights were collected, a sub-sample of stalks was pressed to extract juice. Results of the cultivar study indicated the cultivar 'M81E' generally had the greatest yield. Other cultivars were not well suited in this region. No significant results were found in the nitrogen rate trial, indicating sweet sorghum may be insensitive to nitrogen fertilizer applications. The plant density trial results indicate that sweet sorghum possess a great ability to compensate for variations in plant spacing. No differences were found in juice yields across densities, and the only difference found in total dry matter was at the highest plant density. Results from the harvest date study indicate that the harvest of sweet sorghum should be delayed until at least the grain soft dough stage and can be continued for at least 10 days after a killing freeze without a yield penalty. Delaying harvest allows for an increase in total dry matter and fermentable carbohydrates without a decrease in juice yield.

Introduction

There is a distinct need for new sources of ethanol feedstocks with demand for ethanol on the rise and governmental regulations calling for increased output. Currently, the United States utilizes maize (*Zea mays)* and sorghum [*Sorghum bicolor* (L.) Moench] grain for ethanol production. Brazil has seen much success in ethanol production by utilizing sugarcane (*Saccharum officinarum)*. Unfortunately, sugar cane grows only in a very limited area of the United States. Sweet sorghum, which was originally used in syrup production, may be a viable alternative to sugar cane in the United States, as well as a replacement for grain based ethanol. As with all sorghums, sweet sorghum is suitable for a wide range of environments (Smith et al., 1987) with the implication that it could effectively be grown outside of historical sugar cane production areas. Almodares et al. (2009) reported that sweet sorghum is an excellent choice under hot and dry climatic conditions which are not favorable to maize or sugarcane. Estimated sweet sorghum ethanol yields can meet or exceed those of maize (Putnam et al., 1991) in wetter climates, let alone climates less favorable for maize. Miller and Ottman (2010) suggested that sweet sorghum can be effectively water stressed to a soil water depletion of 65 % and still produce biomass and ethanol yields similar to that of a well watered crop.

Sweet sorghum is an excellent candidate for biofuel production due to its high biomass production and accompanying fermentable carbohydrates (FC). Refractometric brix values are a common method of measuring FC (Tsuchihashi and Goto, 2004). These FC are composed of approximately: 70% sucrose, 20% glucose, and 10% fructose (Wu et al., 2008) and are easily converted into ethanol (Almodares et al., 2009). Typical grain based ethanol production requires the conversion of grain starches to FC. Utilization of high FC sweet sorghum juice allows this process to be avoided, decreasing energy inputs into the ethanol production process. After the juice is extracted, the remaining crushed stems, known as bagasse, have several uses. Bagasse is suitable for animal feed, energy production through burning, or cellulosic ethanol production (Prasad et al, 2007). An alternative use for bagasse is to leave it in the production field as residue cover if extraction methods and economics allows.

Sweet sorghum has proven to be somewhat management insensitive in regards to nitrogen application rates and plant density. Several studies (Almodares et al., 2007; Wortmann et al., 2010) have found little or no response to N fertilization in sweet sorghum. Only a small application of fertilizer may be needed on relatively fertile soil (Freeman et al., 1986). Freeman et al. (1986) suggested that for syrup production, a N rate of only 45 kg N ha^{-1} provided maximum economic yields. Wortmann et al. (2010) found that N had no effect on sweet sorghum in four of seven site-years. This lack of response to N may be due to lower N uptake, a more gradual rate of nutrient uptake, and N uptake later in the season compared with other grain crops (Wortmann et al., 2010). However, other studies have found responses to N fertilization. Kumar et al. (2008) found that wet biomass and juice yields increased with increasing N application rates, however, N rates had no effect on brix values. Juice, wet biomass, and grain yields increased with N applications, and the highest yields were at 150 kg N ha^{-1} (Poornima et al., 2008) but no differences were found in brix values. Sanjana Reddy et al., (2008) also stated that brix values were not effected by N application, but wet biomass and juice yields were increased as N application rate increased, with an optimum rate of 64 kg N ha^{-1}. Lueschen et al. (1991) found that N fertilizer applications did not impact overall ethanol yield, and went on to suggest this makes sweet sorghum an attractive ethanol feedstock alternative compared with maize. The lower N requirement of sweet sorghum may lead to lower ethanol production costs (Putnam et al., 1991) especially when coupled with the lack of prefermentation processing.

The effects of plant density on sweet sorghum production have not been thoroughly studied. In experiments with hill planting where sweet sorghum was planted in widely spaced clusters, yield components were not influenced by plant arrangement (Broadhead and Freeman, 1980). The same study also found increases in biomass yield and brix values by reducing drilled row spacing from 105 cm to 52.5 cm. Changes in plant density had no effect on biomass yield, juice yield, or brix values, but did have a slight effect on plant height (Lueschen et al., 1991), and the authors attributed this mainly to the plant space compensating characteristic of sorghums. Wortmann et al. (2010) reported no significant effect of plant density on sweet sorghum biomass and juice yield or brix values, except for plant height. In contrast, Broadhead et al. (1963) found that biomass and juice yields decreased with increasing plant spacing. Sweet sorghum planted in hills produced numerous tillers which, at least partially, compensated for wide plant spacing, while closely spaced plants competed intensely for soil moisture resulting in small plants (Broadhead et al., 1963).

Harvest timing is an important management factor as it influences, among other factors: biomass production, juice yields, and FC content. Even though sweet sorghum grows rapidly, it needs adequate time to produce biomass, juice, and FC; but it must be harvested before yield is lost. Delaying harvest is beneficial as biomass yield and FC content increase with time after anthesis (Zhao et al., 2009; Almodares et al, 2007; Tsuchihashi and Goto, 2004). According to Freeman et al. (1986) after the stalks reach their full size, maturity of the plant advances at approximately the same rate as the maturity of the seed head. Usually, FC concentration increases from the milk stage to the soft dough stage of the seed, then declines as the seed head matures (Hills et al., 1990). Lueschen et al. (1991) found that harvest timing influenced brix values and plant moisture. The results indicated that FC reached a maximum concentration near late September and plant moisture was the lowest in mid October, after a killing frost in early October. Broadhead (1969) reported no significant effect due to harvest date on biomass or juice yield, but FC concentration decreased with time after anthesis. Biomass yields continue to increase through nodal branching after grain maturity if soil moisture is not limiting (Webster, 1963). Optimum harvest time is before plants are mature (Prasad et al., 2007) as FC decreases after that point. Tsuchihashi and Goto (2004) suggest the optimum harvest date is 32 days after anthesis in dryland production in Indonesia during the rainy season. Sweet sorghum harvest should be delayed after anthesis to allow for yields to increase, but must be harvested before a killing freeze.

Little previous research has investigated management practices for sweet sorghum in Kansas. Therefore, the objectives of this research were to evaluate sweet sorghum cultivars, nitrogen fertilizer rates, and plant densities at four site-years in northeast and northcentral Kansas. Harvest dates were studied during one site-year in northeast Kansas. All treatments were evaluated based on dry biomass, grain, and juice yields; in addition brix values, above-ground node number, and plant heights were also measured. Emphasis was placed on biomass and juice yields, as well as the brix values as ethanol production processes will require a high amount of biomass and high FC juice for optimal ethanol output.

Materials and Methods

Research was conducted in 2008 and 2009 at one dryland location in northcentral Kansas, the Kansas State University (KSU) North Central Kansas Experiment Field near Belleville, KS (39°49’N, 97°40’W) and one dryland location in northeast Kansas, the KSU Agronomy Research Field near Manhattan, KS (39°8’N, 96°38’W). The soil series at Belleville was a Crete silt loam (fine, smectitic, mesic Pachic Argiustolls), and a Rossville silt loam (fine-silty, mixed, superactive, mesic Cumulic Hapludolls) at Manhattan. Soil samples were taken to a depth of 0-15 cm and 15-30 cm after planting at Manhattan in June 2008, and 0-15 cm at both locations before planting in 2009. Samples were composed of 20 individual cores taken across the entire plot area and thoroughly mixed and analyzed for: pH, Mehlich 3 P, K, N [ammonia (NH_4^+) and nitrate (NO_3^-)], and organic matter (OM) (Table 1.1). Cumulative in-season growing degree units (GDUs), precipitation amounts, and 30 year normals for all site years were calculated from nearby weather station data (High Plains Regional Climate Center, 2010). Growing degree units were calculated using a maximum temperature of 38°C and a minimum temperature of 5.6°C (Table 1.2.)

Cultivar Trial

Experimental design was a randomized complete block design. Individual plot size was 3.1 m wide by 9.2 m long. Sweet sorghum cultivars planted in 2008 were experimental cultivars: ‘XH001’, ‘XH007’, ‘XH011’, ‘XH012’, and ’XH019’ (Texas A&M Univ., College Station, TX), and ‘M81E’ (Mississippi State Univ., Starkville, MS). In 2009, cultivars planted were experimental cultivars: ‘TX09017’, ‘TX09020’, ‘TX09021’, ‘TX09023’ (Texas A&M University, College Station, TX), and ‘M81E’ (Mississippi State Univ., Starkville, MS). Cultivars were no-till planted 20 May 2008 and 21 May 2009 at Manhattan with soybean as the previous crop both years. The Belleville location was planted into conventionally tilled soil 11 June 2008 and no-till planted into burned sorghum residue 19 June 2009 (Table 1.3). Planting was delayed at Belleville in 2009 due to wet soil conditions. All crops were planted using a no-till row crop planter on 76 cm row spacing. Seeding rates were reduced in 2009 in an attempt to reduce lodging.

Weed control at both locations was through pre-emergence herbicides applied at labeled rates in combination with recommended carrier volume and adjuvant rates (Table 1.4). Hand weeding was used as necessary through the growing season to minimize weed pressure. Herbicides were applied with an all-terrain vehicle mounted boom sprayer at Manhattan and a tractor mounted boom sprayer at Belleville.

Nitrogen fertilizer was broadcast applied after planting both years at Manhattan, and at Belleville N was pre-plant knife applied in 2008 and surface dribble applied after planting in 2009 (Table 1.3). Dry urea (46-0-0) was used both years at Manhattan, and liquid urea ammonium nitrate solution (28-0-0) was used both years at Belleville. Fertilization rates were reduced in 2009 to limit rapid and excessive early growth in an attempt to decrease lodging.

Plots were harvested after physiological maturity but before a killing freeze (Table 1.3). Plots were rated to determine lodging severity in 2009; plots were all uniformly lodged in 2008 so severity was not noted on an individual plot basis. A 4.6 m length of the center two rows was hand harvested from the four row plots to avoid border effects. The sample was weighed to obtain total biomass wet weight. A 10 plant sub-sample was randomly selected from each sample and weighed for sub-sample wet weight. Grain heads from all plants in both the sample and sub-sample were counted, removed, and weighed for head wet weight. Four random plants were selected from the sub-sample to be measured for plant height and above-ground node number. Leaves were removed from plants in the sub-sample, leaving only stalks that were pressed once in a triple-roll sorghum mill. Bagasse (stalk after pressing) was collected and combined with removed leaves for the bagasse wet weight. Juice was weighed and a sub-sample was collected and stored in a cooler at approximately 5°C within five minutes of extraction for transport to the laboratory. Brix values were obtained in the laboratory utilizing a pocket refractometer (Model PAL-1, ATAGO, Tokyo, Japan). Bagasse and grain heads were dried in a forced air dryer at 65°C for 72 hours, then weighed to obtain head dry weight and bagasse dry weight. Grain heads were threshed utilizing a stationary thresher (Model LDB, ALAMACO, Nevada, IA), saving the grain for grain weight. A grain sub-sample was processed (GAC 2000, DICKEY-john Corp., Springfield, IL) for moisture content and test weight. A 200 seed sub-sample was then counted, dried at 105°C for two days, and weighed to obtain seed dry weight.

Biomass moisture content at harvest was calculated on a wet mass basis. Dry biomass and grain yield were corrected using the respective plant and grain moisture content. Total dry biomass yield included all above-ground harvested biomass and was corrected to oven dry moisture content. Grain yield was calculated from threshed grain weight and adjusted to 13 % moisture using measured moisture content at threshing. Final biomass, grain, and juice yields were calculated from individual plot weights. Equality of population variances for plant moisture content, total dry biomass, grain yield, juice yield, brix value, node number, and plant height were tested using Hartley's test for homogeneity (Ott, 1988). Variances for Hartley's test were obtained through PROC MEANS (SAS Institute, 2005). Analysis of variance was performed using PROC ANOVA (SAS Institute, 2005). Mean separations were performed for the treatment effects (cultivar) if the pairwise t-tests were significant ($p = 0.05$).

Nitrogen Rate Trial

A randomized complete block design was used for this study. Individual plot size was 3.1 m wide by 9.2 m long. All plots were planted to 'M81E' (Mississippi State Univ., Starkville, MS) sweet sorghum. Plots were no-till planted 20 May 2008 and 21 May 2009 at Manhattan with soybean as the previous crop both years. The Belleville location was no-till planted into burned sorghum residue 19 June 2009 (Table 1.3). The plot was not established in 2008 at Belleville due to a pre-plant application of nitrogen on the plot area. Planting was delayed at Belleville in 2009 due to wet soil conditions. All crops were planted using a no-till row crop planter on 76 cm row spacing. Seeding rates were reduced in 2009 in an attempt to reduce lodging. Nitrogen fertilizer treatment rates were broadcast applied by hand after planting as dry urea (46-0-0) in all site-years (Table 1.3). Application rates in all site-years were: 0, 45, 90, 135, and 180 kg N ha^{-1}.

Weed control at both locations was through pre-emergence herbicides applied at labeled rates in combination with recommended carrier volume and adjuvant rates (Table 1.4). Hand weeding was used as necessary through the growing season to minimize weed pressure. Herbicides were applied with an all-terrain vehicle mounted boom sprayer at Manhattan and a tractor mounted boom sprayer at Belleville.

Plots were harvested after physiological maturity but before a killing freeze (Table 1.3). A 4.6 m length of the center two rows was hand harvested from the four row plots to avoid border effects. The sample was weighed to obtain total biomass wet weight. A 10 plant sub-sample was randomly selected from each sample and weighed for sub-sample wet weight. Grain heads from all plants in both the sample and sub-sample were counted, removed, and weighed for head wet weight. Four random plants were selected from the sub-sample to be measured for plant height and above-ground node number. Leaves were removed from plants in the sub-sample, leaving only stalks that were pressed once in a triple-roll sorghum mill. Bagasse (stalk after pressing) was collected and combined with removed leaves for the bagasse wet weight. Juice was weighed and a sub-sample was collected and stored in a cooler at approximately 5°C within five minutes of extraction for transport to the laboratory. Brix values were obtained in the laboratory utilizing a pocket refractometer (Model PAL-1, ATAGO, Tokyo, Japan). Bagasse and grain heads were dried in a forced air dryer at 65°C for 72 hours, then weighed to obtain head dry weight and bagasse dry weight. Grain heads were threshed in a stationary thresher (Model LDB, ALAMACO, Nevada, IA), saving the grain for grain weight. A grain sub-sample was processed (GAC 2000, DICKEY-john Corp., Springfield, IL) for moisture content and test weight. A 200 seed sub-sample was then counted, dried at 105°C for two days, and weighed to obtain seed dry weight.

Biomass moisture content at harvest was calculated on a wet mass basis. Dry biomass and grain yield were corrected using the respective plant and grain moisture content. Total dry biomass yield included all above-ground harvested biomass and was corrected to oven dry moisture content. Grain yield was calculated from threshed grain weight and adjusted to 13 %

moisture using measured moisture content at threshing. Final biomass, grain, and juice yields were calculated from individual plot weights. Equality of population variances for plant moisture content, total dry biomass, grain yield, juice yield, brix value, node number, and plant height were tested using Hartley's test for homogeneity (Ott, 1988). Variances for Hartley's test were obtained through PROC MEANS (SAS Institute, 2005). Analysis of variance was performed using PROC ANOVA (SAS Institute, 2005). Mean separations were performed for the treatment effects (N application rate) if the pairwise t-tests were significant ($p = 0.05$).

Plant Density Trial

A randomized complete block design was used for this study. Individual plot size was 3.1 m wide by 9.2 m long. All plots were planted to 'M81E' (Mississippi State Univ., Starkville, MS) sweet sorghum. Plots were no-till planted 20 May 2008 and 21 May 2009 at Manhattan with soybean as the previous crop both years. The Belleville location was planted into conventionally tilled soil 11 June 2008 and no-till planted into burned sorghum residue 19 June 2009 (Table 1.3). Planting was delayed at Belleville in 2009 due to wet soil conditions. All crops were planted using a no-till row crop planter on 76 cm row spacing.

Nitrogen fertilizer was broadcast applied after planting both years at Manhattan, and at Belleville N was pre-plant knife applied in 2008 and surface dribble applied after planting in 2009 (Table 1.3). Dry urea (46-0-0) was used both years at Manhattan, and liquid urea ammonium nitrate solution (28-0-0) was used both years at Belleville. Fertilization rates were reduced in 2009 to limit rapid and excessive early growth in an attempt to decrease lodging.

Plots were planted using the highest seeding rate possible. At approximately the three leaf stage, plant density was measured in all plots. The plant density was averaged in the highest treatment plots and those plots were hand thinned to that value. Remaining plots were hand thinned to the desired treatment plant densities. Plant density treatments in 2008 were: 87 000, 173 000, 260 000, and 309 000 plants ha^{-1}. In 2009, treatments were: 43 000, 87 000, 130 000, 173 000, and 260 000 plants ha^{-1}. The highest treatment rate was slightly lower in 2009 due to poor seed germination.

Weed control at both locations was through pre-emergence herbicides applied at labeled rates in combination with recommended carrier volume and adjuvant rates (Table 1.4). Hand weeding was used as necessary through the growing season to minimize weed pressure.

Herbicides were applied with an all-terrain vehicle mounted boom sprayer at Manhattan and a tractor mounted boom sprayer at Belleville.

Plots were harvested after physiological maturity but before a killing freeze (Table 1.3). A 4.6 m length of the center two rows was hand harvested from the four row plots to avoid border effects. The sample was weighed to obtain total biomass wet weight. A 10 plant sub-sample was randomly selected from each sample and weighed for sub-sample wet weight. Grain heads from all plants in both the sample and sub-sample were counted, removed, and weighed for head wet weight. Four random plants were selected from the sub-sample to be measured for plant height and above-ground node number. Leaves were removed from plants in the sub-sample, leaving only stalks that were pressed once in a triple-roll sorghum mill. Bagasse (stalk after pressing) was collected and combined with removed leaves for the bagasse wet weight. Juice was weighed and a sub-sample was collected and stored in a cooler at approximately 5°C within five minutes of extraction for transport to the laboratory. Brix values were obtained in the laboratory utilizing a pocket refractometer (Model PAL-1, ATAGO, Tokyo, Japan). Bagasse and grain heads were dried in a forced air dryer at 65°C for 72 hours, then weighed to obtain head dry weight and bagasse dry weight. Grain heads were threshed in a stationary thresher (Model LDB, ALAMACO, Nevada, IA), saving the grain for grain weight. A grain sub-sample was processed (GAC 2000, DICKEY-john Corp., Springfield, IL) for moisture content and test weight. A 200 seed sub-sample was then counted, dried at 105°C for two days, and weighed to obtain seed dry weight.

Biomass moisture content at harvest was calculated on a wet mass basis. Dry biomass and grain yield were corrected using the respective plant and grain moisture content. Total dry biomass yield included all above-ground harvested biomass and was corrected to oven dry moisture content. Grain yield was calculated from threshed grain weight and adjusted to 13 % moisture using measured moisture content at threshing. Final biomass, grain, and juice yields were calculated from individual plot weights. Equality of population variances for plant moisture content, total dry biomass, grain yield, juice yield, brix value, node number, and plant height were tested using Hartley’s test for homogeneity (Ott, 1988). Variances for Hartley’s test were obtained through PROC MEANS (SAS Institute, 2005). Analysis of variance was performed using PROC ANOVA (SAS Institute, 2005). Mean separations were performed for the treatment effects (plant density) if the pairwise t-tests were significant ($p = 0.05$). Regression analysis was performed using PROC REG (SAS Institute, 2005) on significant linear or quadratic responses. When appropriate, the line of best fit equations for plateau models were determined using PROC NLIN (SAS Institute, 2005).

Harvest Date Trial

A randomized complete block design was used for this study. Individual plot size was 3.1 m wide by 9.2 m long. All plots were planted to ‘M81E’ (Mississippi State Univ., Starkville, MS) sweet sorghum. Plots were no-till planted 26 May 2009 at Manhattan with soybean as the previous crop (Table 1.3). Crops were planted using a no-till row crop planter on 76 cm row spacing. Nitrogen fertilizer was top dress applied after planting using dry urea (46-0-0).

Weed control was through pre-emergence herbicides applied at labeled rates in combination with recommended carrier volume and adjuvant rates (Table 1.4). Hand weeding was used as necessary through the growing season to minimize weed pressure. Herbicides were applied with an all-terrain vehicle mounted boom sprayer.

Plots were harvested according to treatment. Harvest date treatments were largely based on plant growth stages: grain milk stage, grain soft dough stage, grain hard dough stage, and after a killing freeze. These growth stages corresponded to: 87, 126, 136, and 155 days after planting (DAP) or 21 August, 29 September, 9 October, and 28 October 2009, respectively. Weather played a large role in determining harvest dates. The regrowth from the first harvest date (grain milk stage) was harvested a second time before the killing freeze, only observing total biomass, moisture content, number of leaves present, and plant height.

A 4.6 m length of the center two rows was hand harvested from the four row plots to avoid border effects. The sample was weighed to obtain total biomass wet weight. A 10 plant sub-sample was randomly selected from each sample and weighed for sub-sample wet weight. Grain heads from all plants in both the sample and sub-sample were counted, removed, and weighed for head wet weight. Four random plants were selected from the sub-sample to be measured for plant height and above-ground node number. Leaves were removed from plants in the sub-sample, leaving only stalks that were pressed once in a triple-roll sorghum mill. Bagasse (stalk after pressing) was collected and combined with removed leaves for the bagasse wet weight. Juice was weighed and a sub-sample was collected and stored in a cooler at approximately 5°C within five minutes of extraction for transport to the laboratory. Brix values were obtained in the laboratory by utilizing a pocket refractometer (Model PAL-1, ATAGO, Tokyo, Japan). Bagasse and grain heads were dried in a forced air dryer at 65°C for 72 hours, then weighed to obtain head dry weight and bagasse dry weight. Grain heads were threshed in a stationary thresher (Model LDB, ALAMACO, Nevada, IA), saving the grain for grain weight. A grain sub-sample was processed (GAC 2000, DICKEY-john Corp., Springfield, IL) for moisture content and test weight. A 200 seed sub-sample was then counted, dried at 105°C for two days, and weighed to obtain seed dry weight.

Biomass moisture content at harvest was calculated on a wet mass basis. Dry biomass and grain yield were corrected using the respective plant and grain moisture content. Total dry biomass yield included all above-ground harvested biomass and was corrected to oven dry moisture content. Grain yield was calculated from threshed grain weight and adjusted to 13 % moisture using measured moisture content at threshing. Final biomass, grain, and juice yields were calculated from individual plot weights. Analysis of variance was performed using PROC ANOVA (SAS Institute, 2005). Mean separations were performed for the treatment effects (harvest date) if the pairwise t-tests were significant ($p = 0.05$). Regression analysis was performed using PROC REG (SAS Institute, 2005) on significant linear or quadratic responses. When appropriate, the line of best fit equations for plateau models were determined using PROC NLIN (SAS Institute, 2005).

Results and Discussion

In-season (1 May – 31 October) cumulative precipitation was above normal at both locations in both years (Table 1.2). Manhattan normally receives 613 mm of precipitation and Belleville receives 551 mm. Cumulative in-season GDUs in 2008 were below normal at Manhattan and approximately normal at Belleville (Table 1.2), but both locations accumulated nearly the same amount of GDUs. In 2009, GDUs were below normal at both locations, with Belleville receiving fewer GDUs than Manhattan. Wet soil conditions delayed planting by approximately one week at Belleville in 2009. Severe lodging was observed at both locations in 2008, leading to a reduction in seeding rates and standard nitrogen fertilization rates in 2009.

Cultivar Trial

Different cultivars were grown in 2008 and 2009 and testing of population variances revealed large differences between locations, so results are presented for each separate site year in this study. In 2008 at both locations, all cultivars experienced severe lodging. However, at Manhattan, the experimental cultivars lodged much earlier in the season than ‘M81E’. In 2009 at Manhattan, ‘M81E’ did not lodge while all other cultivars lodged with varying degrees of severity. Only slight lodging was observed at Belleville in 2009.

Total Dry Matter

A significant treatment effect was found for total dry matter yield at Manhattan in 2008 and 2009 and at Belleville in 2009 (Tables 1.5, 1.7, and 1.8). The cultivar ‘M81E’ produced more biomass than the other cultivars at Manhattan in 2008, and the experimental cultivars ‘XH001’ and ‘XH012’ produced the least biomass. At Belleville in 2008, no significant treatment effect was found. In 2009, ‘M81E’ produced more biomass at both Manhattan and Belleville, and ‘TX09021’ produced the least at both Manhattan and Belleville. At Manhattan, the biomass production of ‘TX09017’ was similar to ‘TX09021’.

The lodging experienced in this study may have increased variability in total dry matter yields, making it difficult to observe interactions in some site-years. The resistance of ‘M81E’ to lodging at Manhattan in 2009 may have caused less dry matter loss compared with other cultivars. However, differences were observed at Belleville in 2009 where only slight lodging occurred. At Manhattan in 2008, ‘M81E’ matured towards the end of the growing season, while the other cultivars matured much earlier. This early maturation reduced the time available for dry matter accumulation in the stalks. The cultivar ‘M81E’ had more time to increase plant height and therefore, produce more dry matter. At Belleville in 2008, the plots were harvested before ‘M81E’ had reached full maturity, thereby decreasing the time available for it to accumulate dry matter. In 2009, some cultivars progressed more closely with ‘M81E’, but others still matured sooner, thereby limiting the time available to accumulate dry matter. Also, the plots in 2009 at Belleville were planted later and received fewer GDUs, shortening the available time for dry matter production relative to Manhattan.

Plant Moisture

A significant treatment effect was found for plant moisture at Manhattan in 2008 and at Belleville in 2008 and 2009 (Tables 1.5, 1.6, and 1.8). The highest moisture content was found with ‘M81E’ at Manhattan in 2008 and at Belleville in 2008 and 2009. At Manhattan in 2008, ‘XH019’ had the lowest moisture content. In 2008 at Belleville all cultivars except ‘M81E’ had similar moisture contents, and in 2009 the lowest moisture content was observed with 'TX09023'.

The differences in plant moisture may be due to factors similar to those for total dry matter. All cultivars except 'M81E' lodged earlier than 'M81E' at Manhattan in 2008. The early lodging of the experimental cultivars allowed more time for the plants to air dry in the field compared with 'M81E'. Also, those same cultivars matured more quickly than 'M81E'. Because 'M81E' was still actively growing at harvest time, it may have inherently had a higher plant moisture content, as moisture content decreases with maturity. The plots were harvested at Belleville in 2008 and 2009 before 'M81E' reached physiological maturity. This early harvest occurred while 'M81E' still had a high moisture content due to active growth. In 2009, the cultivar 'TX09020' matured at a rate similar to 'M81E' and had a similar moisture content. The differences in moisture content were expected to cause a difference in juice yields.

Above-ground Node Number

A significant treatment effect was found for the number of above-ground nodes at both locations in 2008 (Tables 1.5 and 1.6). The cultivar 'M81E' had an average of three to four more above-ground nodes than the experimental cultivars in the trial. These results indicate that 'M81E' had a longer period before anthesis during which additional nodes were created, in theory leading to an increase in plant height and total dry matter.

Plant Height

A significant treatment effect was found for plant height at Manhattan in 2008 and at Belleville in 2008 and 2009 (Table 1.5, 1.6, and 1.8). The cultivar 'M81E' was the tallest cultivar in the trial averaging up to 4.0 m in height, with the remaining cultivars averaging 3.0 m or less. The cultivar 'M81E' had a longer maturity than the other cultivars in this study. The additional time before anthesis compared with other cultivars allowed 'M81E' to continue vegetative growth and increase plant height. Other cultivars did not have sufficient time to reach an equivalent height before anthesis as they matured more quickly. The above-ground node data indicate that 'M81E' increased plant height mainly through the additional nodes, not node elongation as 'M81E' had an average of three to four additional above-ground nodes plant^{-1} compared with other cultivars in 2008. The lack of additional nodes in 2009 may have accounted for the lack of height differences at Manhattan and the relatively small differences at

Belleville. Additional plant height should be beneficial to commercial sweet sorghum production, as it leads to an increase in total dry biomass yield (Figures 1.1 and 1.2).

Juice Yield

A significant treatment effect was found for juice yield in all site years (Tables 1.5, 1.6, 1.7, and 1.8). Juice yield was greatest with cultivar 'M81E' and not different for all other cultivars at Manhattan in 2008 and the range was similar at Belleville in 2008. In 2009 at Manhattan, juice yields were observed from the lowest yield with cultivar 'TX09021' to the highest with cultivar 'M81E' and yields followed a similar pattern at Belleville. Yields were lowest with cultivar 'TX09021' and 'TX09017', and the highest yield was observed with cultivar 'M81E'.

The cultivar 'M81E' was specifically bred for superior sirup production (Broadhead et al., 1981). Therefore, it may have been predisposed to yield more juice than other cultivars. In addition, in 2008 at both locations 'M81E' also had the highest plant moisture which correlates with juice yield (Figure 1.3). The higher plant moisture in 'M81E' was likely due to early season lodging in other cultivars allowing those stalks to dry in the field, potentially decreasing juice yield. Additionally, it is possible that the longer growing season of 'M81E' caused it to be actively growing at harvest time, potentially increasing the juice yield compared with the other cultivars, which had senesced before plot harvest occurred. In 2009 at Manhattan, other cultivars such as 'TX09020' matured at a rate similar to that of 'M81E' and had similar moisture contents at harvest. Plots were harvested at Belleville before physiological maturity was reached with 'M81E', resulting in decreased juice yield. Shorter season cultivars did not senesced, leading to higher moisture content and a corresponding greater juice yield than at Manhattan.

Brix

A significant treatment effect was found for brix values at Belleville in 2009 (Table 1.8). The lowest brix value was observed with cultivar 'M81E' and the highest with cultivar 'TX09017'. No differences were found in brix values at other site years.

These results are in contradiction to Broadhead et al., (1981) who stated that 'M81E' was bred for high fermentable sugar production. Brix values are an estimation of fermentable sugar (fermentable carbohydrates, or FC) that correlates well (Tsuchihashi and Goto, 2004), implying that 'M81E' should have had high brix values in all site-years. Broadhead et al., (1981) reported brix values ranging from 12.2 to 17.7 % which is higher than what was found for 'M81E' in this study. It is possible that the longer growing season of 'M81E' and the below normal amount of GDUs lead to the harvest of plots before appropriate FC accumulation. Other cultivars in the study matured more quickly and may have had the opportunity for full FC production prior to harvest.

Grain Heads and Yield

No significant treatment effect was found for the grain head number in any site year, but a significant treatment effect was found for grain yield in all site years (Tables 1.5, 1.6, 1.7, and 1.8). The lowest grain yields were found with the cultivar 'M81E' in all site years. At Belleville in 2008, the grain yield for was not different for the experimental cultivars. In 2009, grain yield was lowest with 'M81E' at both Manhattan and Belleville. In 2009 at Manhattan, the highest grain yield was measured with 'TX09021' and at Belleville, the highest yields were measured with 'TX09021' and 'TX09023'.

The cultivar 'M81E' had the longest growing season in the study and did not have an adequate amount of GDUs to fully mature, leading to low grain yields. Other cultivars matured more quickly, allowing adequate time to mature and produce grain. Lodging issues caused slight grain losses in some cultivars increasing variation. The GDUs received were far below normal at both locations in 2009, further leading to lower overall grain production with all cultivars.

Nitrogen Rate Trial

No significant treatment effects were found for any yield components in this study (Table 1.9) in any site year. Data was analyzed separately for each site year as testing revealed large population variances. Soil test results (Table 1.1) indicated a large amount of N was present in plots before planting. At Manhattan, approximately 82 and 65 kg N ha^{-1} was available at the 0 – 15 cm depth in 2008 and 2009, respectively. At Belleville in 2009, approximately 79 kg N ha^{-1} was available at the 0 – 15 cm depth.

At these soil test levels, sweet sorghum may be insensitive to N fertilizer applications. The lack of response is in line with previous research (Almodares et al., 2007; Lueschen et al., 1991; Wortmann et al., 2010). Wortmann et al., (2010) suggested that the lack of response to N fertilizer may be due to lower N uptake, a more gradual nutrient uptake rate, and N uptake later in the season compared with other grain crops. The organic matter present in the soils of this study would certainly provide mineralized N throughout the growing season, perhaps enough to sustain sweet sorghum's gradual uptake. Additionally, the available N level in these soils may have been great enough to provide for sweet sorghum's requirements. Freeman et al. (1986) suggested that only a small N fertilizer application, such as 45 kg N ha^{-1} may be necessary for optimal production. Additionally, the cooler temperatures in both growing seasons were less than normal, perhaps impeding sweet sorghum's rate of growth and N uptake. In contrast, other research (Kumar et al., 2008; Poornima et al., 2008; Reddy et al., 2008) has found a response to the addition of N fertilizers. Even though a response was not found in this study, it may be beneficial to continue this research on sites specifically selected for low soil test N to determine if sweet sorghum requires additional N in Kansas.

Plant Density Trial

Testing of population variances revealed large differences between locations, so results are presented for each separate site-year. In addition, plant density treatments were modified in 2009. In 2008 at Manhattan, plots lodged severely shortly before harvest and only slight lodging was observed at Belleville. In 2009, no lodging was observed at either location. At Belleville in 2009, planting was delayed by one week due to wet weather.

Total Dry Matter

A significant treatment effect was found for total dry biomass at Belleville in 2009 (Table 1.10). Dry biomass increased linearly from approximately 11.0 Mg ha^{-1} to 16.0 Mg ha^{-1} with increasing plant density (Figure 1.4). It was observed that at lower plant densities sweet sorghum produced numerous tillers. This tiller production appears to have almost completely compensated for the lower plant densities, resulting in a lack of differences below 263 000 plants ha^{-1}. Similar trends were seen in other site years, but the treatments were not different. Precipitation was nearly normal and the GDUs received were well below normal at Belleville in 2009. These conditions may not have been as favorable for sweet sorghum, possibly limiting the amount of tillering and the dry matter production $tiller^{-1}$. In this situation, a high planting rate would be necessary for maximum yield as the tillers would not be able to compensate for limited plant densities due to unfavorable weather conditions.

Plant Moisture

No significant treatment effect was found for plant moisture content in any site year (Table 1.10). Because juice yield is correlated with plant moisture, these results indicate that plant density had no effect on the juice production in sweet sorghum plants. Additionally, plant density did not affect the rate of maturity, which would have allowed some plants to dry and decrease in moisture content before other treatments.

The highest plant densities were expected to create stress through plant competition, which should have increased the plant maturity rate. This change in the rate of maturity would have caused the highest plant density treatment to dry more quickly and to have a lower plant moisture content than other treatments. It was also anticipated that changes in plant density would cause a change in plant stem diameter, which was observed in the plots. These results indicate that plant stem diameter also had no affect on plant moisture.

Above-ground Node Number

A significant treatment effect was found for the above-ground node number at Belleville in 2008 (Table 1.10). The above-ground node number decreased linearly from approximately 15.0 to 13.7 nodes plant^{-1} with increasing plant density (Figure 1.5). No significance was found in other site years, although similar trends were observed.

Precipitation was well above normal and the GDUs received at Belleville in 2008 were slightly above normal. These conditions may have been favorable for increased plants growth at lower densities through the addition of above-ground nodes. Higher plant density treatments may have experienced adequate plant competition to slightly suppress growth, decreasing the above-ground node number.

Plant Height

A significant treatment effect was found for plant height at Belleville in 2008 and at Manhattan in 2009 (Table 1.10). At both locations plant height decreased with increasing plant density (Figure 1.6). No significance was found in other site years. At Belleville in 2008, plant height decreased linearly with increasing plant density from 3.6 to 3.3 m. At Manhattan in 2009 the treatments ranging from 43 000 to 173 000 plants ha^{-1} were not different with an average height of 4.0 m, and plant height decreased linearly to 3.8 m at the treatment of 260 000 plants ha^{-1}. A similar trend was observed in 2008 at Manhattan, but the treatments were not different.

The results indicate that under certain conditions, the highest plant densities may have created enough plant competition to suppress plant height. Alternatively, competition between tillers produced at lower plant densities may have increased plant height reducing the variability between treatments. At Belleville in 2008, a similar linear decrease with increasing plant density was observed in above-ground nodes plant^{-1}, implying that node length likely did not change as plant density changed. Results from all site-years found the above-ground node number and plant height to be well correlated (Figure 1.7), further indicating that node length likely did not change across plant densities. However, the above-ground node number plant^{-1} did not decrease with increasing plant density at Manhattan in 2009, indicating node length likely decreased with increasing plant density to account for the decrease in plant height.

At Belleville in 2008, precipitation was well above normal and the GDUs received were slightly above normal and in 2009, precipitation was approximately normal and GDUs received were well below normal. The conditions at Belleville in 2008 may have been beneficial for additional sweet sorghum growth and somewhat detrimental in 2009. At Manhattan in 2008, a similar amount of GDUs were received and higher precipitation occurred, and in 2009 the GDUs and precipitation received was higher than in Belleville. The conditions in 2009 at Manhattan may have been more conducive to sorghum growth than in Belleville, allowing differences to be found at Manhattan, and not in Belleville.

Juice Yield

No significant treatment effect was found for juice yield in any site year (Table 1.10). The results indicate that changes in plant density had no effect on sweet sorghum juice yield in Kansas. These results also support research by Broadhead and Freeman (1980), Lueschen et al. (1991), and Wortmann et al. (2010) that reported no juice yield response to plant density. However, Broadhead et al. (1963) observed that juice yield decreased in closely planted sweet sorghum when compared with sweet sorghum planted in widely spaced hills.

In this study, similar results were found with plant moisture, indicating that the two components are related. It is possible that at the lower plant densities sweet sorghum produced enough tillers to compensate for the lack of nearby plants. It was anticipated that an increase in plant density would cause a decrease in plant stem diameter, which was observed in all site years. The change in stem diameter did not cause a change in juice yield, implying that the juice yield from fewer large stalks was not different from a greater number of small stalks.

Brix

A significant treatment effect was found for brix values at Manhattan in 2009 (Table 1.10). A plateau model was fit to brix values as reading increased linearly from 11.4 to 12.4 %, corresponding with an increase in plant density from 43 000 to 130 000 plants ha^{-1} (Figure 1.8).

Brix values were not different across treatments of 130 000 to 260 000 plants ha^{-1}. No significant response was found in other site years. Research by Broadhead and Freeman (1980) also observed that brix values increased as plant density increased. In contrast, Lueschen et al. (1991) and Wortmann et al. (2010) reported that plant density did not affect brix values.

Grain Heads

A significant treatment effect was found for the grain head number ha^{-1} in all site years (Table 1.10). In all site years, the grain head number tended to increase linearly with increasing plant density (Figure 1.9). At the lowest plant density treatments, the head number averaged roughly 100 000 heads ha^{-1} and increased to roughly 190 000 heads ha^{-1} at the highest plant densities.

These data show that the grain head number plant^{-1} increased with plant density. However, the head number ha^{-1} did not always match the plant density (plants ha^{-1}). At Manhattan in 2008 sweet sorghum produced roughly one head plant^{-1} at a plant density of 87 000 plants ha^{-1}. At the higher plant densities, less than one head plant^{-1} was observed. These results may indicate that numerous plants either did not survive from the time of plant thinning until harvest, or increased plant competition at higher plant densities prevented several plants from forming a grain head. In 2008 at Belleville, an average of more than one head plant^{-1} was observed at the lowest plant density (87 000 plants ha^{-1}). At the higher plant density treatments, the head number plant^{-1} observed was higher than at Manhattan in 2008, but was still less than one head plant ha^{-1}.

In 2009, the average head number plant^{-1} was approximately the same or greater than one head plant ha^{-1} for plant densities from 43 000 to 130 000 plants ha^{-1} and less than one head plant ha^{-1} with plant densities at 173 000 and 260 000 plants ha^{-1}. These results indicate considerable axillary heading or tiller production at the lower plant densities. In 2009 at 43 000 plants ha^{-1}, the head number ha^{-1} was approximately three times the plant density at Manhattan, and twice the plant density at Belleville. The results in 2009 indicate that sweet sorghum positively compensates for plant spacing at plant densities below 130 000 plants ha^{-1}, and responds negatively at plant densities above 130 plants ha^{-1}. In 2008, the only positive plant spacing compensation was observed at Belleville at the plant density of 87 000 plants ha^{-1}.

Grain Yield

A significant treatment effect was found for grain yield at Manhattan in 2008 (Table 1.10). Grain yield increased from approximately 1900 to 2800 kg ha^{-1} as plant density increased (Figure 1.10). Similar trends were observed in other site years, but no differences were found. These results indicate that at one site year, as plant density increased, grain yield also increased. At the same site year, the grain head number ha^{-1} also increased with increasing plant density. Therefore, it is possible that the additional grain yield is due to additional grain heads ha^{-1} at higher plant densities, not additional grain head^{-1}.

A short growing season in 2009 prevented grain production at Belleville and likely reduced yield at Manhattan. An impending killing freeze in 2009 caused plots at Belleville to be harvested well before physiological maturity so grain yield data were not collected. Precipitation was higher in 2008 than in 2009 and the amount of GDUs received was higher. These conditions helped increase grain yields over 2009, but at Belleville in 2008 plots were harvested before physiological maturity due to an impending killing freeze. This early harvest reduced grain weight and increased variability.

Harvest Date Trial

Plots were harvested beginning at 87 days after planting (21 August 2009), at the approximate growth stages: grain milk stage, grain soft dough stage, grain hard dough stage, and after killing freeze. A killing freeze (-1°C) was observed 18 October, remaining plots were then allowed 10 days before harvest. All sweet sorghums plants were removed from plots during harvest, allowing regrowth. Regrowth in the first harvest date plots was harvested again during the third harvest.

Total Dry Matter

Harvest date affected total dry matter yield (Table 1.11). A linear plateau model fit the increase in total dry matter with time, as dry matter increased between the milk and soft dough stages, then remained constant (Figure 1.11). Regrowth from the first harvest date yielded 0.4 Mg ha^{-1} of dry biomass.

The results indicate that dry biomass production increased linearly from the grain milk stage to the soft dough stage, then remained constant through the remaining harvest dates. These findings are in line with research by Almodares et al. (2007), Tsuchihashi and Goto (2004), and Zhao et al. (2009) who reported that biomass yields increase with time after anthesis. It was observed in this study that a killing freeze did not immediately impact total dry matter yield. Maximum dry biomass harvest is possible at any point after sweet sorghum reaches the soft dough stage. Regrowth dry biomass yields likely did not reach a level where harvest removal would be economically feasible.

Plant Moisture

Harvest date affected plant moisture (Table 1.11). Plant moisture was highest at the grain milk stage and decreased linearly with time to the after killing freeze harvest date. The regrowth plant moisture content was observed to be 86.5 % when harvested.

These results indicate that as growth stage progressed, sweet sorghum plant moisture decreased. Since moisture content is correlated with juice yield, this should indicate a similar decrease in juice yield with maturity. The decrease in moisture content is likely due to grain filling as the plant begins to mature. The killing freeze also decreased plant moisture content. Before the killing freeze, moisture content was not different for 10 days. Ten days after the killing freeze, moisture content had significantly decreased. Lueschen (1991) also reported a decrease in plant moisture content after a killing frost.

Juice Yield

Juice yield was not different between harvest dates (Table 1.11). Regrowth was not pressed as it had not reached adequate size. Although no differences were found, a downward trend was observed in the results. This trend is similar to the changes observed in plant moisture content. The most important result is that, against expectations, the killing freeze did not impact juice yield as it did plant moisture. Juice yield was expected to decrease with harvest date as observed with moisture content due to the correlation between moisture content and juice yield (Figures 1.12 and 1.13). Research by Broadhead (1969) also reported that harvest date did not have a significant effect on juice yield. With the observed trends, it is possible that differences could be found in a study repeated over several site years.

Brix

A significant harvest date effect was found for brix values (Table 1.11). Brix values increased with time, reaching a maximum of 13.2 % observed after the killing freeze. Initial brix value was observed to be 5.6 % at milk stage. Regrowth brix values were not measured as no juice was extracted from the regrowth.

These results indicate that brix values increased as sweet sorghum matured. Also, brix values continued to increase after a killing freeze. This may be due to the plants drying and juice loss after the freeze. Fermentable carbohydrates, measured by brix values, would remain in the stalks at a higher concentration as the plant juice yield decreased. This increase in brix values may partially compensate for any potential juice loss as sweet sorghum matures. The brix value nearly doubles between the grain milk stage and grain soft dough stage. This increase in brix suggests that harvest should be delayed until at least the soft dough stage. These findings are in agreement with research by Hills et al. (1990) that observed an increase in FC from milk stage to soft dough stage, in addition, it was observed that FC decreased as the seed head matured. Broadhead (1969) also reported a decrease in FC with time after anthesis.

Grain Heads and Yield

Neither the grain head number ha^{-1} nor grain yield was affected by harvest date (Table 1.11). Grain head number and yield data were not measured during milk and soft dough stage harvests as the grain was immature. The only changes in grain yield that may have been observed in this study would have been due to differences in grain moisture and bulk density that occurred as grain matured between harvest dates.

Summary and Conclusions

Several general characteristics of sweet sorghum development were observed in these studies. Juice yield was found to increase linearly with total dry matter yield (Figures 1.12 and 1.13). Juice yield was also found to increase as plant moisture content increased (Figure 1.3). This relationship was expected as plant moisture content is a measurement of the juice level in plant stalks. Therefore, a higher plant moisture content should lead to a higher juice yield. Finally, total dry matter was found to increase as plant height increased (Figures 1.1 and 1.2). This relationship was also expected as plant height is increased by adding more material (biomass) to the plant. These results support statements that moisture content and juice variability is similar, and that any factor that changes plant height impacts total dry matter production.

Results from the cultivar trial in 2008 indicate that ‘M81E’ outperformed all other cultivars in the trial in total dry biomass and juice yield. In 2009, however, ‘TX09020’ and ‘TX09023’ performed nearly as well as ‘M81E’. Some differences between the experimental cultivars and ‘M81E’ may be due to differences in the required growing period of the cultivars. The experimental cultivars in 2008 matured much earlier in the season than ‘M81E’ and in 2009, the cultivars that yielded similar to ‘M81E’ also had similar maturities as ‘M81E’. In 2008, the early maturing experimental cultivars did not appear to be well adapted to northeast and northcentral Kansas. These cultivars would be better utilized in more northern climates, and possibly in Kansas for late season plantings. Certain cultivars in 2009 were better acclimated to geographical areas in this study. The cultivar ‘M81E’ is a full season cultivar, requiring more GDUs than other cultivars, and will not always reach physiological maturity before a killing freeze in this region. In both locations in 2009, ‘M81E’ had the lowest brix value, but in 2008 brix values did not vary across cultivars. Fewer GDUs were received in 2009, which slowed development of sweet sorghum, thereby preventing full FC production in longer maturity cultivars before harvest. Brix values indicate the FC present in sweet sorghum juice, therefore, it is desirable for juice to have a high brix value. A greater brix value can also compensate for a lower juice yielding cultivar, as that cultivar will still produce a usable FC amount. In addition, it was observed in the field that ‘M81E’ either did not lodge, or lodged later in the season than other cultivars. This resistance to lodging is a desired harvest trait.

The results from the N rate trial showed no response to N for any yield component. This lack of differences demonstrated that sweet sorghum did not need additional fertilization under conditions in this study. It is possible that N levels present in the soil may be adequate to support sweet sorghum growth in certain conditions. Sweet sorghum appears to have a small overall N requirement and a gradual N uptake rate. In comparison with maize, sweet sorghum is more desirable for its comparable ethanol yield, and as this and other research suggests, sweet sorghum will not require high fertilization to attain maximum yields.

Few differences in yield components were found in the plant density trial. This demonstrates that sweet sorghum may be insensitive to plant density, due in part to its ability to compensate for plant spacing. A considerable degree of tillering was observed in plots with low plant densities, indicating that sweet sorghum can compensate for variable plant spacing. At one site year, the only difference in total dry matter was found by increasing the plant density to 260 000 plants ha^{-1} and similar trends were observed in other site years. It is not known if the additional yield gained at these high plant densities will be economically feasible. No differences in juice yield were found across plant densities, implying that if sweet sorghum is grown solely for juice extraction, plant densities ranging from 43 000 to 309 000 plants ha^{-1} will return similar juice yields.

Results for the harvest date trial found differences in total dry matter, plant moisture, above-ground node number, plant height, and brix values. Total dry biomass increased only from the milk stage to the soft dough stage and juice yield was not different across all harvest dates, even after a killing freeze. Brix values increased across all harvest dates. The ideal harvest date for sweet sorghum, indicated by data from one site year, is at soft dough stage or later, as dry biomass increased to the maximum and the brix value was nearly twice its value at milk stage. After soft dough stage, dry biomass did not decrease, and the brix values continued to increase. A downward trend was observed in juice yield with increasing harvest date, but no differences were found. The increase in FC, as indicated by brix values, may compensate for any loss of juice yield. Most importantly, no biomass or juice yield loss was observed 10 days after a killing freeze. These results indicate that the potential harvest season for sweet sorghum is 10 days longer than previously expected. Regrowth from the first harvest date did not produce an appreciable amount of dry biomass; however, it may have grown enough to create sufficient winter cover. In a production system requiring high biomass removal, this winter cover may be necessary to maintain soil productivity.

Results from these studies indicate there are certain management practices which can increase biomass and juice yields in sweet sorghum. However, it was also found that other practices did not impact yields. Implications from these findings are that sweet sorghum should be managed for greater plant heights, which will increase total dry matter yields, in turn creating an increase in juice yields. This study also found the most effective way to increase biomass and juice yields was through cultivar selection and proper harvest date. Under certain conditions, plant density increased yields. Nitrogen fertilization rates had no effect on yields in this study.

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Chapter 1 – Tables

Table 1.1. Soil test results for two locations in Kansas in 2008 and 2009.

Year	Location	Depth	pH	P	K	NH_4^+N	NO_3^-N	OM
		cm		- - - - - - - - - - -	ppm - - - - -	- - - - - -		%
2008	Manhattan	0-15	6.2	34	451	6.1	11.3	2.1
		15-30	6.2	13	311	5.2	8.1	1.9
2009	Manhattan	0-15	6.6	26	401	4.4	11.1	1.5
2009	Belleville	0-15	5.2	48	449	5.5	22.4	-

Table 1.2. In season cumulative growing degree units and precipitation for two locations in Kansas.

	Growing Degree Units[†‡]			Precipitation[†]		
Location	2008	2009	Normal	2008	2009	Normal
	- - - - - - - -	GDUs	- - - - - - - - -	- - - - - - - - - -	m	- - - - - - - - - -
Manhattan	4860	4534	5251	879	674	613
Belleville	4963	4241	4904	748	560	551

[†] Growing season set as 1 May – 31 October of each year. Data from High Plains Regional Climate Center.

[‡] Base temperature set as 5.6°C for GDU calculation.

Table 1.3. Planting, nitrogen fertilization, and harvest dates and seeding and fertilization rates in 2008 and 2009 at Manhattan and Belleville, KS.

Year	Location	Study	Planting Date	Target Seeding Rate	Nitrogen Rate†	Nitrogen Application Date	Harvest Date
2008				seeds ha^{-1}	kg N ha^{-1}		
	Manhattan	Cultivar	20 May	279 000	180	04-Jun.	23 Sep.
		Nitrogen	20 May	358 000	By Treatment	04-Jun.	30 Sep.
		Density	20 May	358 000	180	04-Jun.	01 Oct.
	Belleville	Cultivar	11 Jun.	200 000	112	Pre-plant	25 Sep.
		Density	11 Jun.	346 000	112	Pre-plant	24 Oct.
2009							
	Manhattan	Cultivar	21 May	131 000	120	25-May	9 & 10 Oct.
		Nitrogen	20 May	87 000	By Treatment	21-May	7 & 8 Oct.
		Density	20 May	321 000	120	25-May	7 & 8 Oct.
		Harvest Date	26 May	158 000	120	26-May	By Treatment
	Belleville	Cultivar	19 Jun.	111 000	112	13-Jul.	06 Oct.
		Nitrogen	19 Jun.	131 000	By Treatment	10-Jul.	06 Oct.
		Density	19 Jun.	321 000	112	13-Jul.	06 Oct.

† Nitrogen fertilizer applied as 46-0-0 at Manhattan and 28-0-0 at Belleville.

Table 1.4. PRE-emergence herbicide application information for 2008 and 2009 at Manhattan and Belleville, KS.

Year	Location	Herbicide and rate	Date
2008		kg a.i. ha^{-1}	
	Manhattan	1.7 atrazine[†] + 1.1 glyphosate[‡]	21 May
2009			
	Manhattan	1.4 atrazine + 1.1 S-Metolachlor[§] + 1.1 glyphosate	22 May
	Belleville	1.1 glyphosate	19 Jun.

[†] Atrazine [2-chloro-4(ethylamino-6-(isopropylamino)-s-triazine]

[‡] Glyphosate [N-(phosphonomethyl)glycine]

[§] S-Metolachlor [2-chloro-N-(2-ethyl-6-Methylphenyl)-N-[(1S)-2-methoxy-1-methylethyl]acetamide]

Table 1.5. Results and analysis of variance results for total dry biomass, plant moisture, above-ground nodes, plant height, juice yield, brix, grain heads, and grain yield of different sweet sorghum cultivars at Manhattan, KS in 2008.

		Total Dry Biomass	Plant Moisture	Above-ground Nodes	Plant Height	Juice Yield	Brix	Grain Heads	Grain Yield
		Mg ha^{-1}	%	# plant^{-1}	m	L ha^{-1}	%	# ha^{-1}	kg ha^{-1}
Cultivar									
	M81E	24.9	77.2	14.0	4.0	33 554	12.0	119 022	2580
	XH001	15.2	75.6	10.0	2.9	14 945	9.9	138 044	4349
	XH007	16.4	73.6	10.3	2.9	13 210	12.2	156 522	4699
	XH011	16.2	74.5	10.3	2.9	15 514	11.7	153 804	4114
	XH012	15.3	75.1	10.7	3.0	14 520	11.3	120 652	3373
	XH019	18.9	71.6	10.5	2.9	15 391	13.5	135 870	4210
	LSD	2.7	2.3	1.2	0.2	3 439	NS	NS	973
Source		- - - - - - - - - - - - - - - - - - Pr > F - - - - - - - - - - - - - - - - - -							
	Rep	0.0666	0.0110	0.7910	0.9997	0.0881	0.1666	0.0326	0.1593
	Cultivar	<0.0001*	0.0029*	<0.0001*	<0.0001*	<0.0001*	0.0625	0.2143	0.0037*
	C.V.	9.99	2.06	7.04	4.07	12.78	12.27	18.12	16.61

*Results are significant at the *p*=0.05 level.

Table 1.6. Results and analysis of variance results for total dry biomass, plant moisture, above-ground nodes, plant height, juice yield, brix, grain heads, and grain yield of different sweet sorghum cultivars at Belleville, KS in 2008.

		Total Dry Biomass	Plant Moisture	Above-ground Nodes	Plant Height	Juice Yield	Brix	Grain Heads	Grain Yield
		Mg ha^{-1}	%	# plant^{-1}	m	L ha^{-1}	%	# ha^{-1}	kg ha^{-1}
Cultivar									
	M81E	16.8	82.1	14.9	3.5	31 991	9.0	141 304	710
	XH001	17.5	74.0	11.7	2.8	15 877	7.0	139 131	3112
	XH007	16.9	73.2	11.3	2.7	16 094	9.8	134 783	2367
	XH011	17.8	73.6	11.5	2.9	16 489	8.5	131 884	2371
	XH012	15.8	74.3	11.3	2.8	14 408	8.9	134 783	2306
	XH019	15.0	74.4	11.3	2.8	15 251	8.6	137 681	2121
	LSD	NS	2.5	0.7	0.1	3 408	NS	NS	1077
Source		- Pr > F -							
	Rep	0.3386	0.2398	0.0083	0.0278	0.0546	0.6369	0.1084	0.0685
	Cultivar	0.3526	<0.0001*	<0.0001*	<0.0001*	<0.0001*	0.8997	0.9891	0.0120*
	C.V.	9.75	1.79	3.04	2.56	10.21	33.74	13.51	27.36

*Results are significant at the *p*=0.05 level.

Table 1.7. Results and analysis of variance results for total dry biomass, plant moisture, above-ground nodes, plant height, juice yield, brix, and grain yield of different sweet sorghum cultivars at Manhattan, KS in 2009.

		Total Dry Biomass	Plant Moisture	Above-ground Nodes	Plant Height	Juice Yield	Brix	Grain Yield
		Mg ha^{-1}	%	# plant^{-1}	m	L ha^{-1}	%	kg ha^{-1}
Cultivar								
	M81E	17.0	81.3	12.2	3.7	33 133	14.1	19
	TX09017	10.6	77.3	9.6	3.1	12 758	15.1	184
	TX09020	14.9	78.0	10.1	3.7	19 539	15.8	30
	TX09021	8.8	75.0	10.4	3.4	7 471	15.5	362
	TX09023	12.3	74.7	10.4	3.3	11 184	16.3	291
	LSD	4.2	NS	NS	NS	9 112	NS	143
Source		- Pr > F -						
	Rep	0.3300	0.4437	0.8386	0.8072	0.0399	0.5533	0.8188
	Cultivar	0.0115*	0.0743	0.1805	0.0604	0.0014*	0.7206	0.0018*
	C.V.	17.47	3.36	11.25	7.94	28.78	12.35	42.83

*Results are significant at the *p*=0.05 level.

Table 1.8. Results and analysis of variance results for total dry biomass, plant moisture, above-ground nodes, plant height, juice yield, brix, grain heads, and grain yield of different sweet sorghum cultivars at Belleville, KS in 2009.

		Total Dry Biomass	Plant Moisture	Above-ground Nodes	Plant Height	Juice Yield	Brix	Grain Heads	Grain Yield
		Mg ha^{-1}	%	# plant^{-1}	m	L ha^{-1}	%	# ha^{-1}	kg ha^{-1}
Cultivar									
	M81E	14.0	81.3	10.4	3.1	21 951	13.6	135 807	488
	TX09017	12.8	78.0	8.2	2.6	13 148	17.4	150 152	2827
	TX09020	13.1	80.7	9.7	3.0	20 112	14.5	100 420	619
	TX09021	11.1	79.0	9.8	2.9	12 777	14.5	119 070	2783
	TX09023	13.8	76.0	8.9	2.7	13 085	16.0	122 895	3076
	LSD	1.7	2.3	NS	0.3	5 154	2.2	NS	642
Source		- Pr > F -							
	Rep	0.2829	0.3429	0.1916	0.4652	0.5595	0.4272	0.3316	0.6519
	Cultivar	0.0270*	0.0042*	0.0650	0.0329*	0.0069*	0.0251*	0.0664	<0.0001*
	C.V.	7.05	1.53	8.48	6.31	16.89	7.60	13.95	17.42

*Results are significant at the *p*=0.05 level.

Table 1.9. Analysis of variance results for total dry biomass, plant moisture, above-ground nodes, plant height, juice yield, brix, grain heads, and grain yield of sweet sorghum under different nitrogen fertilizer rates at Manhattan and Belleville in 2008 and 2009.

	Source	Total Dry Biomass	Plant Moisture	Above-ground Nodes	Plant Height	Juice Yield	Brix	Grain Heads	Grain Yield
2008	Manhattan	- -			Pr > F				
	Rep	0.0546	0.1894	0.8880	0.2577	0.7224	0.5501	0.1835	0.8746
	Treatment	0.1548	0.8597	0.9328	0.5599	0.0755	0.9595	0.5730	0.1507
	C.V.	11.41	2.25	7.45	4.14	0.51	12.17	17.87	34.94
2009	Manhattan								
	Rep	0.0594	0.3140	0.2329	0.3161	0.8094	0.1987	0.4413	0.6138
	Treatment	0.7813	0.5367	0.4911	0.6114	0.6965	0.4094	0.3536	0.3447
	C.V.	7.77	1.81	4.92	3.65	10.36	4.02	9.67	18.46
2009	Belleville								
	Rep	0.9356	0.0003	0.0218	0.0014	0.0083	0.0016	0.7650	-
	Treatment	0.2192	0.1625	0.5828	0.6206	0.7039	0.6076	0.2094	-
	C.V.	7.11	0.76	5.55	4.11	10.62	3.68	7.86	-

Table 1.10. Analysis of variance results for total dry biomass, plant moisture, above-ground nodes, plant height, juice yield, brix, grain heads, and grain yield of sweet sorghum under different plant densities at Manhattan and Belleville in 2008 and 2009.

	Source	Total Dry Biomass	Plant Moisture	Above-ground Nodes	Plant Height	Juice Yield	Brix	Grain Heads	Grain Yield
2008	Manhattan	Pr > F							
	Rep	0.0506	0.0862	0.5577	0.6857	0.2471	0.9511	0.6722	0.3063
	Treatment	0.0971	0.9906	0.2558	0.1966	0.3555	0.2421	0.0031*	0.0395*
	C.V.	9.46	1.14	6.51	4.28	9.97	13.86	18.12	16.37
2008	Belleville								
	Rep	0.6994	0.8132	0.6385	0.0599	0.4948	0.8179	0.4049	0.5005
	Treatment	0.1229	0.3778	0.0398*	0.0037*	0.3052	0.1681	0.0339*	0.2292
	C.V.	12.74	1.77	3.60	1.81	9.05	17.15	17.48	22.24
2009	Manhattan								
	Rep	0.4388	0.7198	0.0020	0.6878	0.8744	0.0503	0.8761	0.7419
	Treatment	0.4262	0.1408	0.1281	0.0379*	0.4827	0.0357*	<0.0001*	0.0653
	C.V.	12.76	0.83	6.35	3.12	11.36	4.18	11.96	18.61
2009	Belleville								
	Rep	0.4358	0.0229	0.0781	0.0002	0.0299	0.0066	0.0980	-
	Treatment	0.0164*	0.0802	0.1267	0.0772	0.6150	0.3411	0.0021*	-
	C.V.	10.07	1.09	6.75	2.61	9.98	7.51	16.75	-

*Results are significant at the *p*=0.05 level.

Table 1.11. Results and analysis of variance results for total dry biomass, plant moisture, above-ground nodes, plant height, juice yield, brix, grain heads, and grain yield of sweet sorghum at different harvest dates at Manhattan, KS in 2009.

		Total Dry Biomass	Plant Moisture	Above-ground Nodes	Plant Height	Juice Yield	Brix	Grain Heads	Grain Yield
		Mg ha^{-1}	%	# plant^{-1}	m	L ha^{-1}	%	# ha^{-1}	kg ha^{-1}
Treatment									
	Milk	14.7	87.3	13.0	3.5	42 828	5.6	-	-
	Soft Dough	21.0	82.0	16.0	4.2	42 630	11.9	-	-
	Hard Dough	19.0	82.5	15.6	4.1	38 982	12.6	116 559	1302
	After Freeze	19.1	79.8	14.1	4.1	36 019	13.2	110 821	900
	Regrowth	0.4	86.5	3.3[†]	0.5	-	-	-	-
	LSD	2.3	0.2	1.4	0.1	NS	0.9	NS	NS
		- Pr > F -							
Source					- -				
	Rep	0.3414	0.3810	0.8662	0.3813	0.6161	0.2264	0.4617	0.7399
	Treatment	<0.0001*	<0.0001*	<0.0001*	<0.0001*	0.1139	<0.0001*	0.5373	0.2622
	C.V.	9.87	0.72	7.55	2.13	10.01	5.10	10.28	23.50

*Results are significant at the *p*=0.05 level.

[†] Indicates all leaves present above-ground.

Chapter 1 – Figures

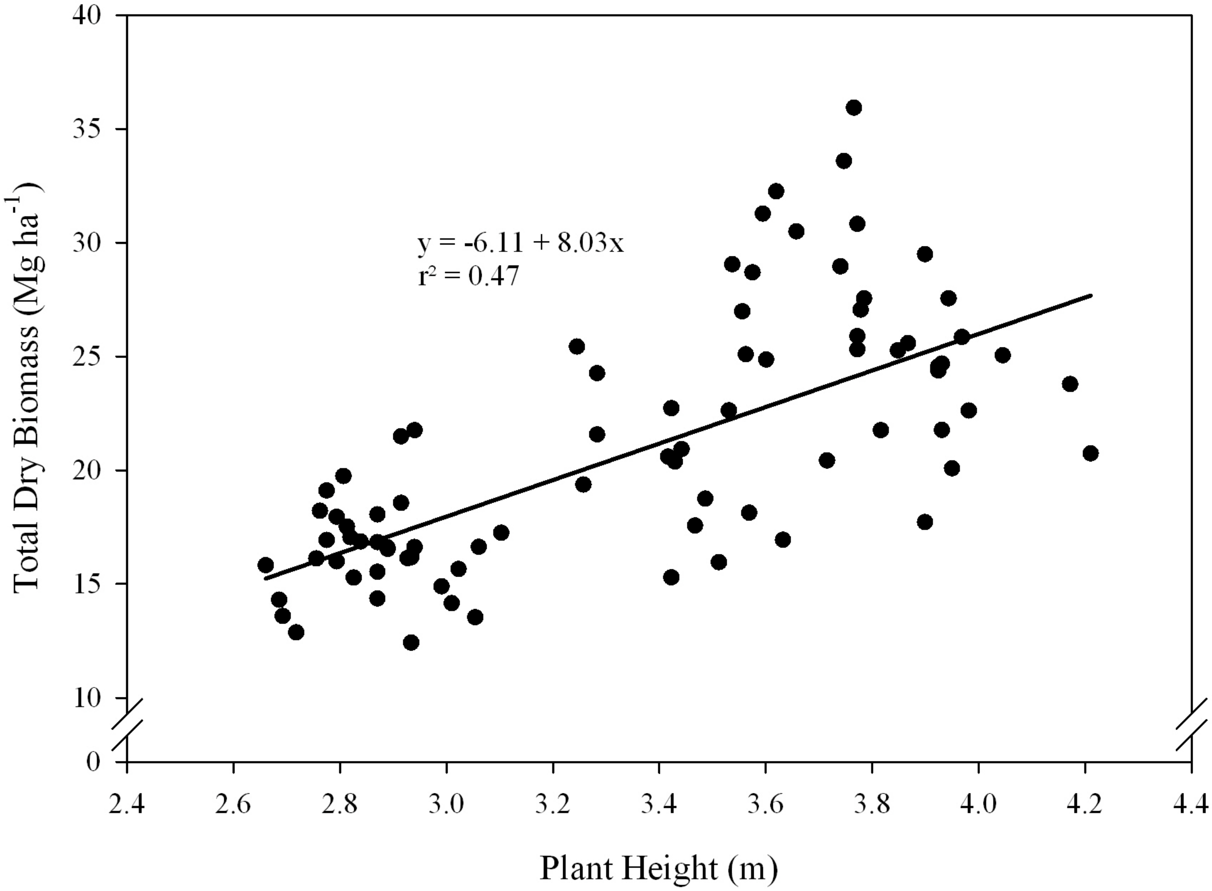


Figure 1.1. Relation of total dry biomass to plant height of sweet sorghum at two locations in Kansas in 2008.

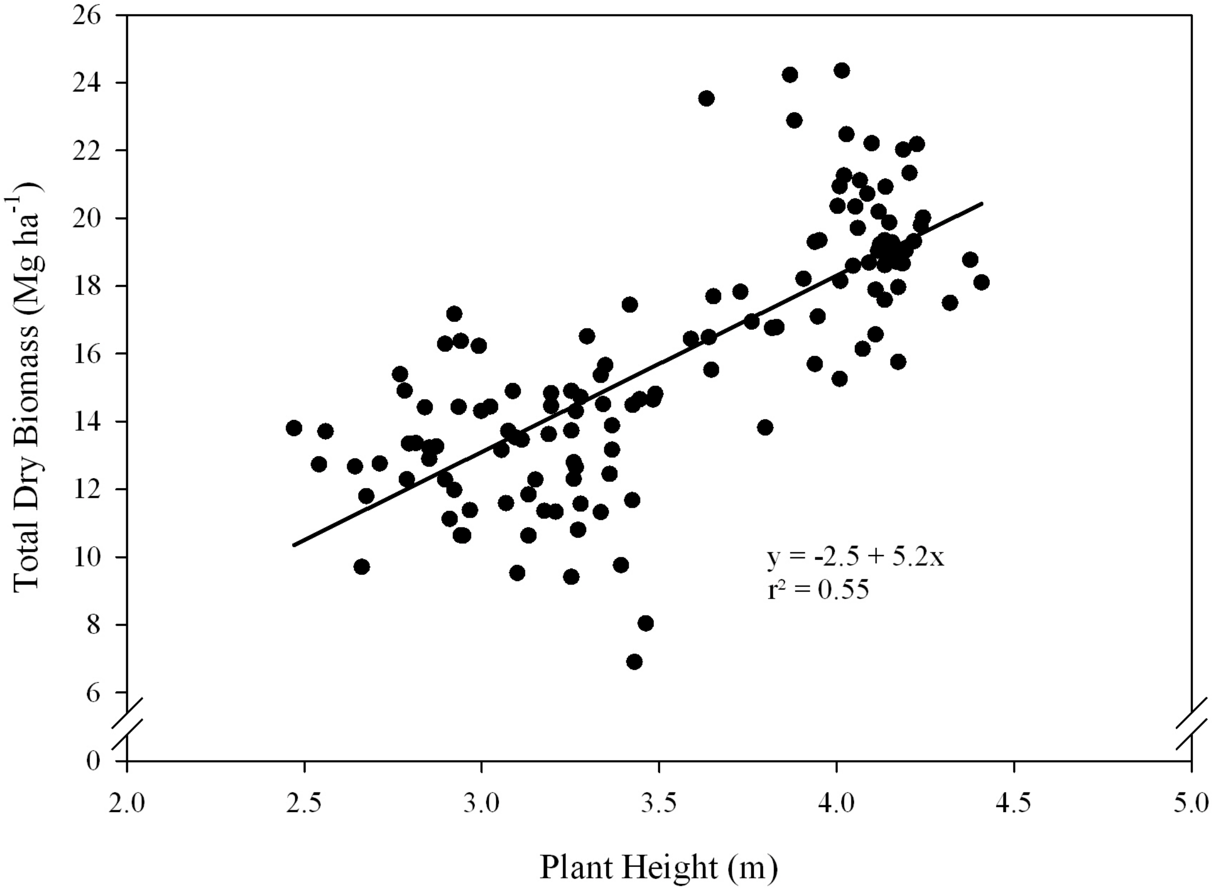


Figure 1.2. Relation of total dry biomass to plant height of sweet sorghum at two locations in Kansas in 2009.

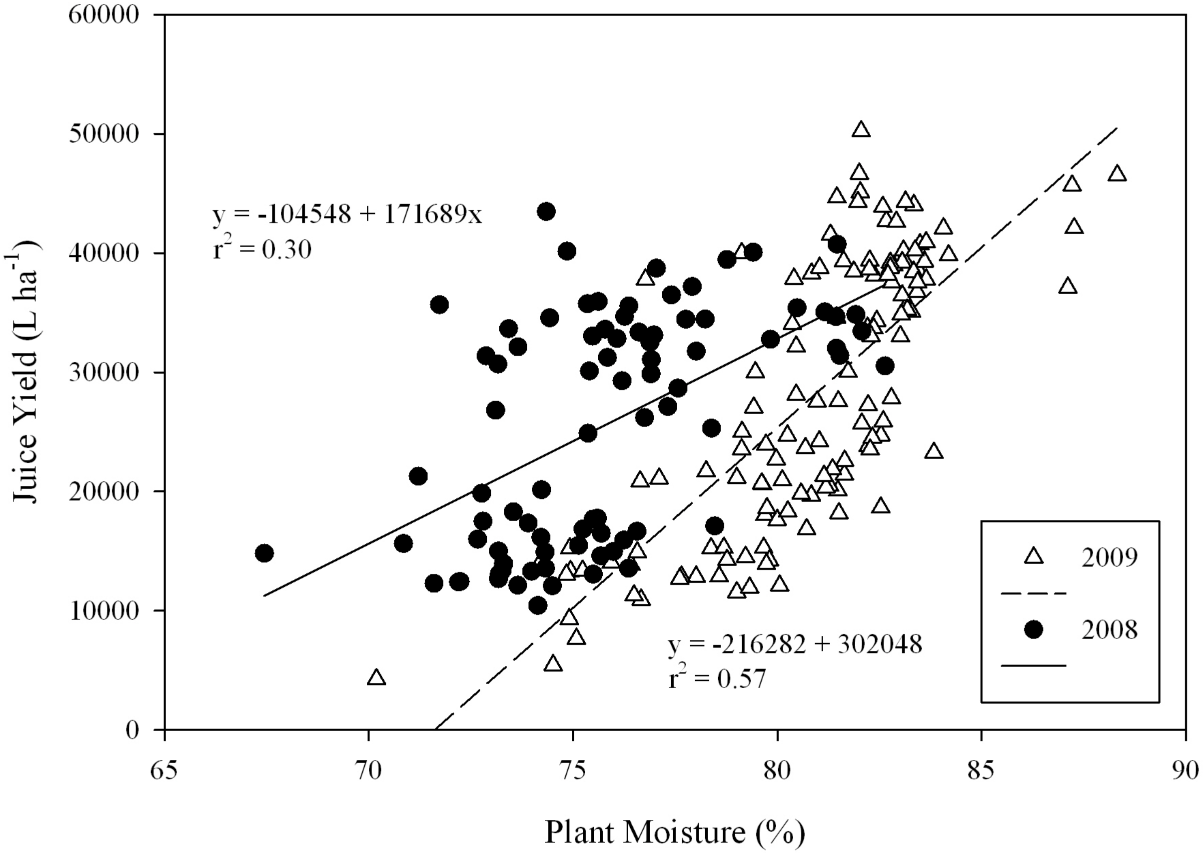


Figure 1.3. Relation of juice yield to plant moisture of sweet sorghum at two locations in Kansas in 2008 and 2009.

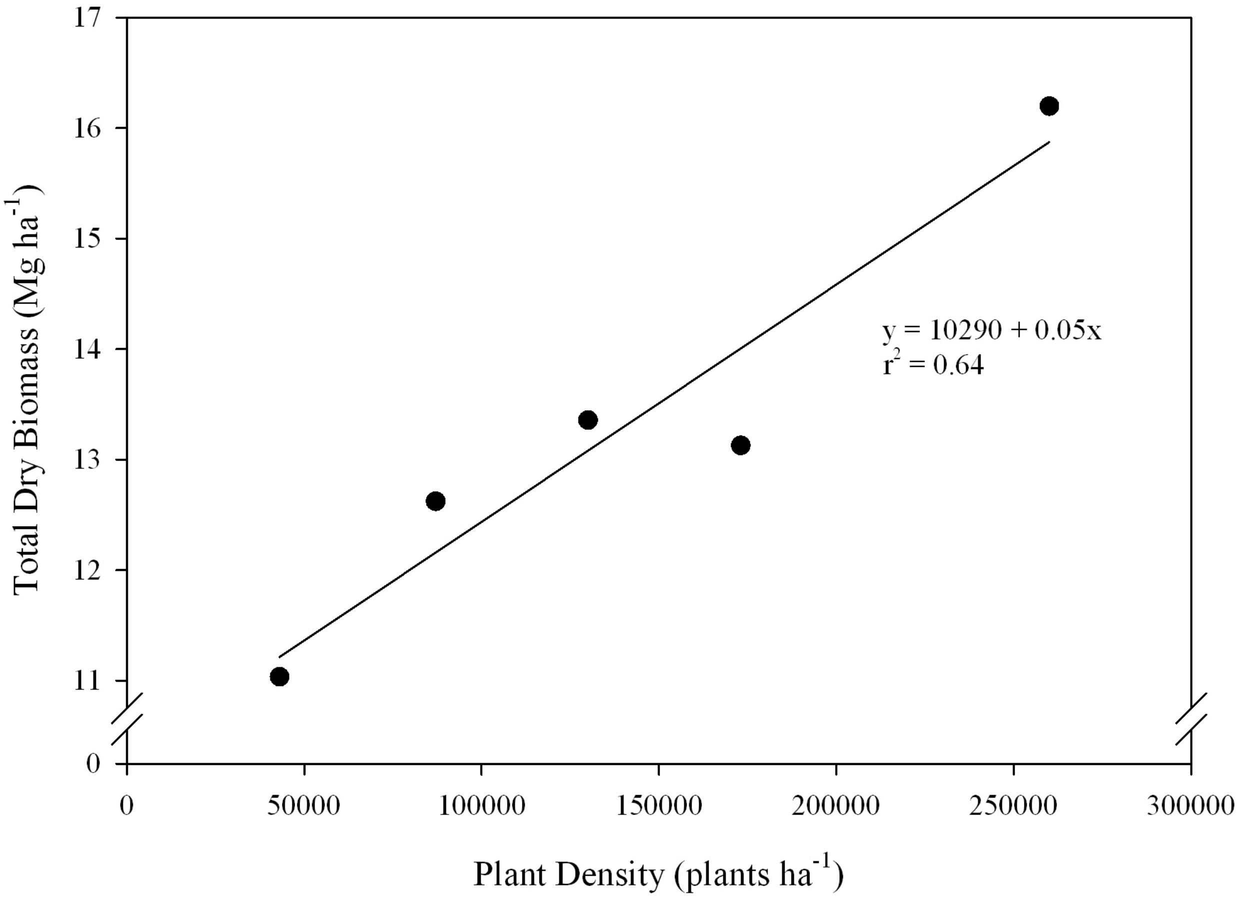


Figure 1.4. Relation of total dry biomass to sweet sorghum plant density at Belleville in 2009.

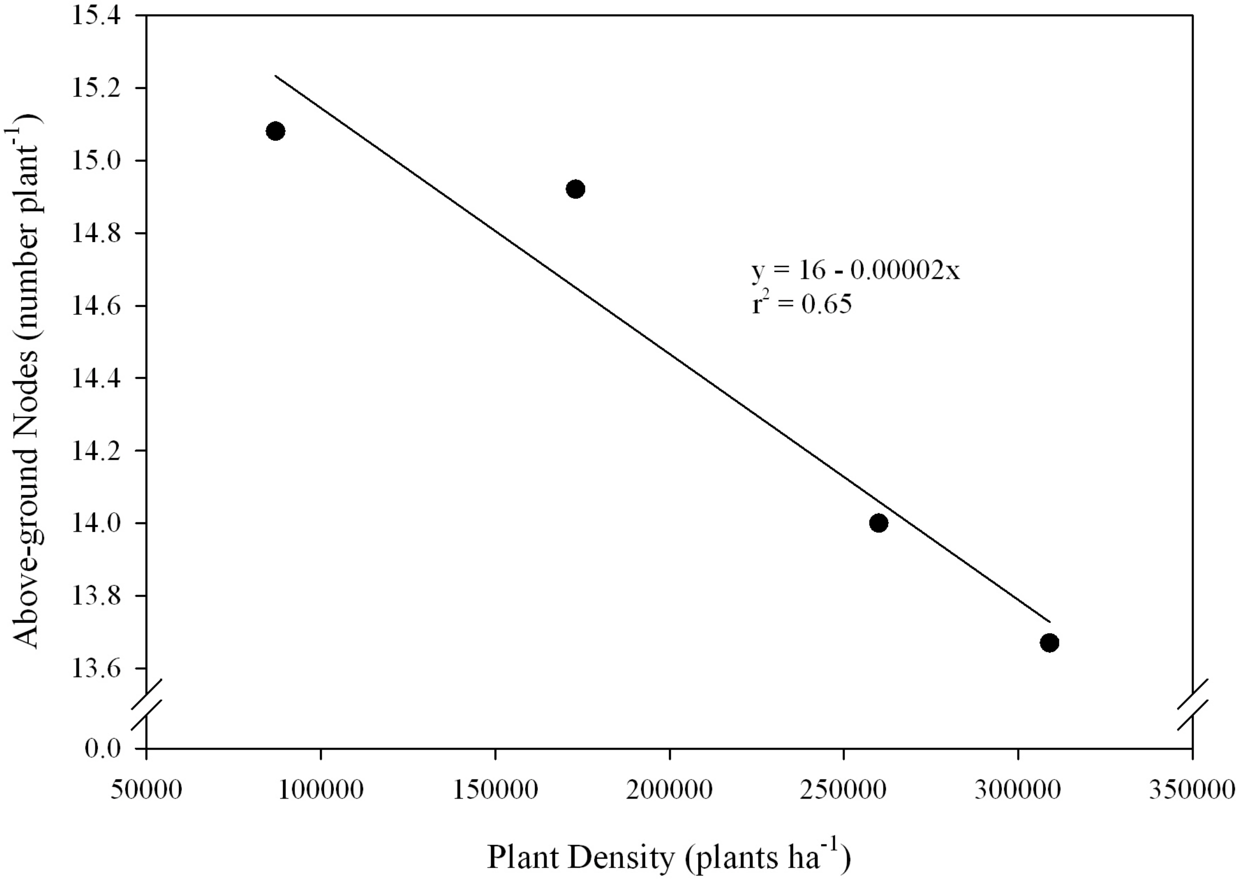


Figure 1.5. Relation of above-ground node number to sweet sorghum plant density at Belleville in 2008.

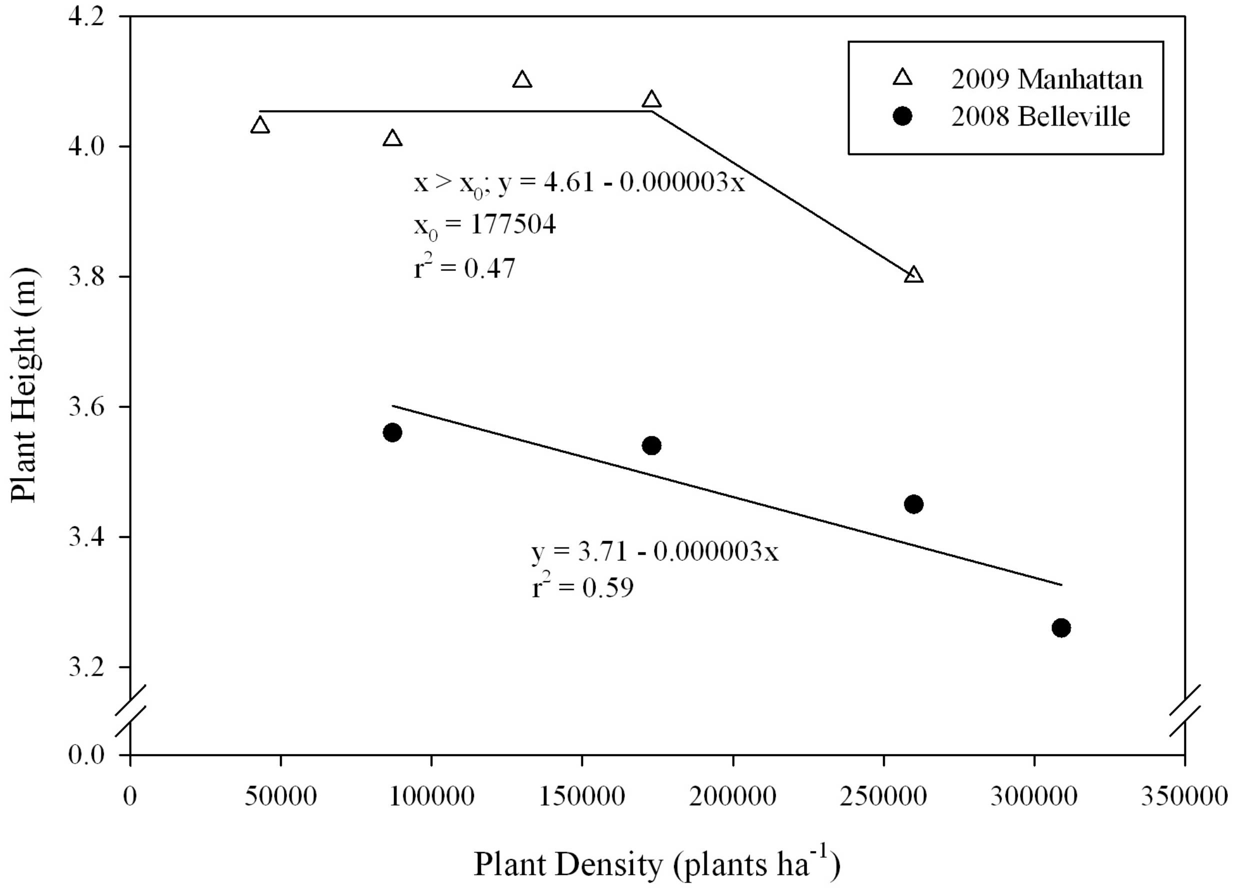


Figure 1.6. Relation of plant height to sweet sorghum plant density at Belleville in 2008 and at Manhattan in 2009.

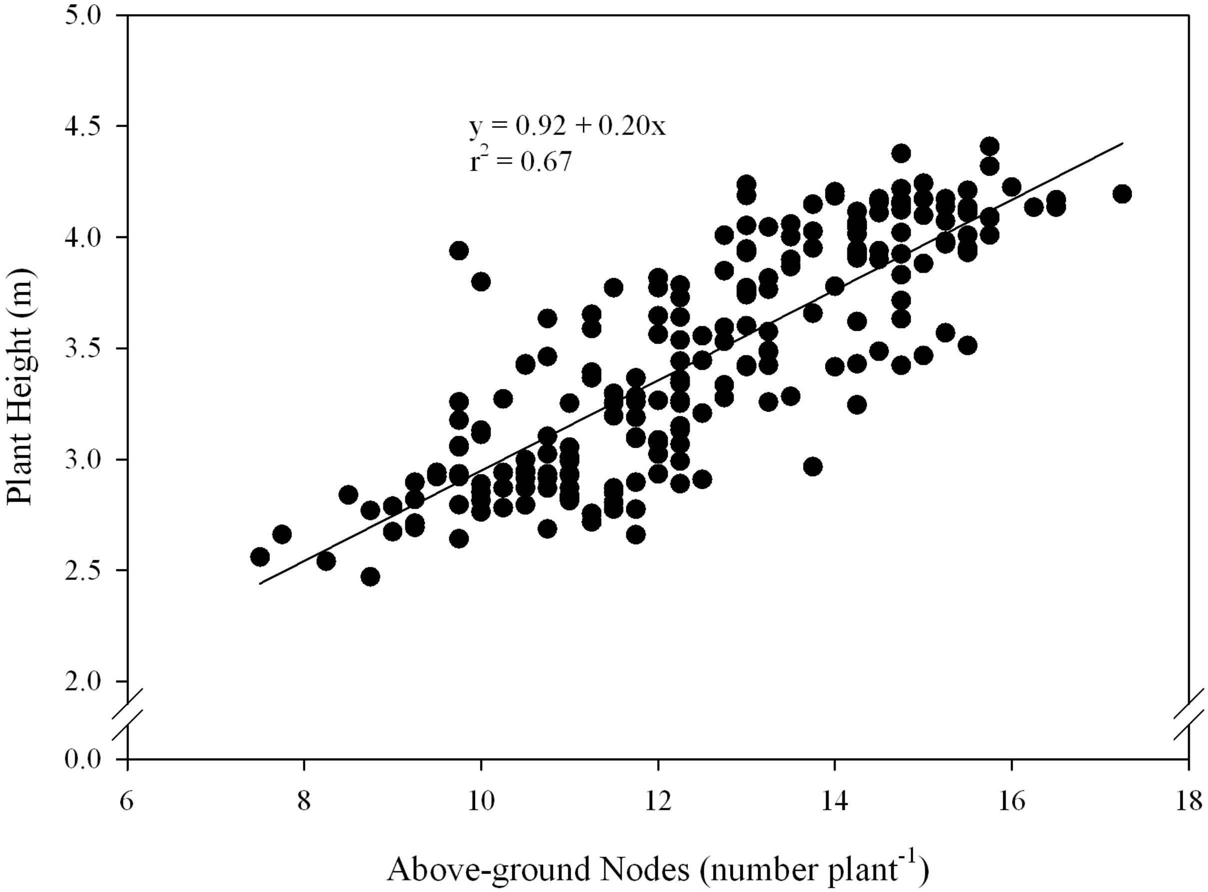


Figure 1.7. Relation of sweet sorghum plant height to above-ground node number at Manhattan and Belleville in 2008 and 2009.

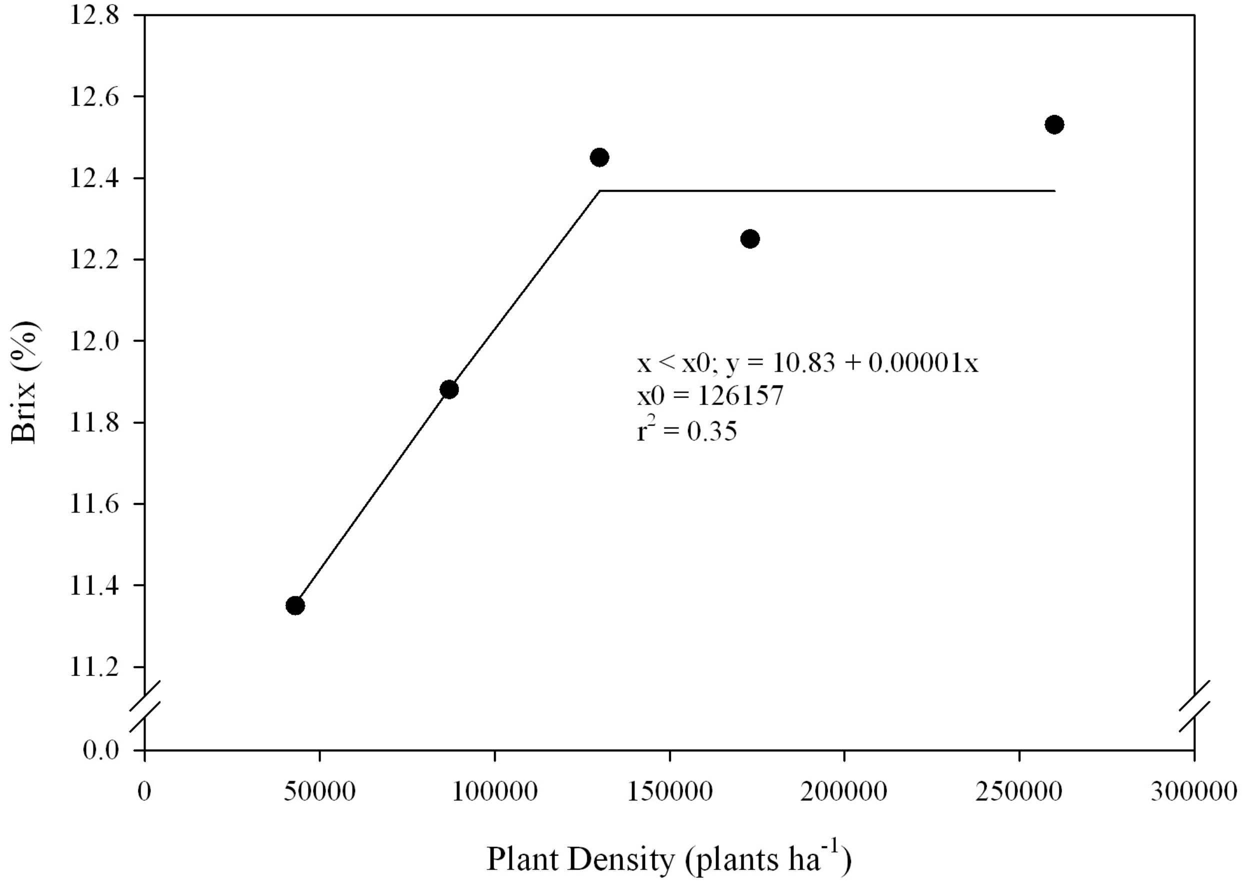
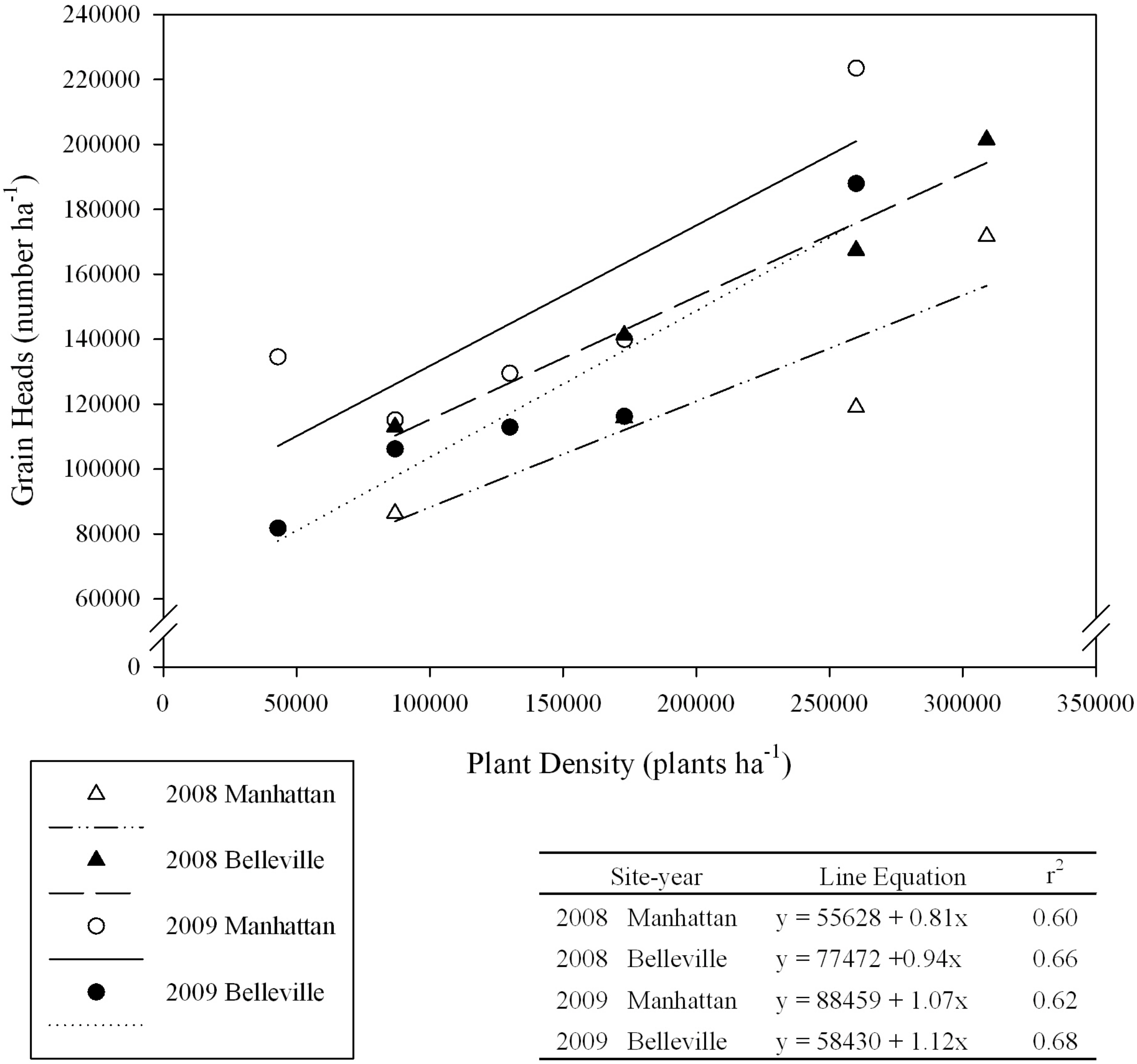


Figure 1.8. Relation of brix to sweet sorghum plant density at Manhattan in 2009.



Site-year		Line Equation	r^2
2008	Manhattan	y = 55628 + 0.81x	0.60
2008	Belleville	y = 77472 +0.94x	0.66
2009	Manhattan	y = 88459 + 1.07x	0.62
2009	Belleville	y = 58430 + 1.12x	0.68

Figure 1.9. Relation of number of grain heads to sweet sorghum plant density at Manhattan and Belleville in 2008 and 2009.

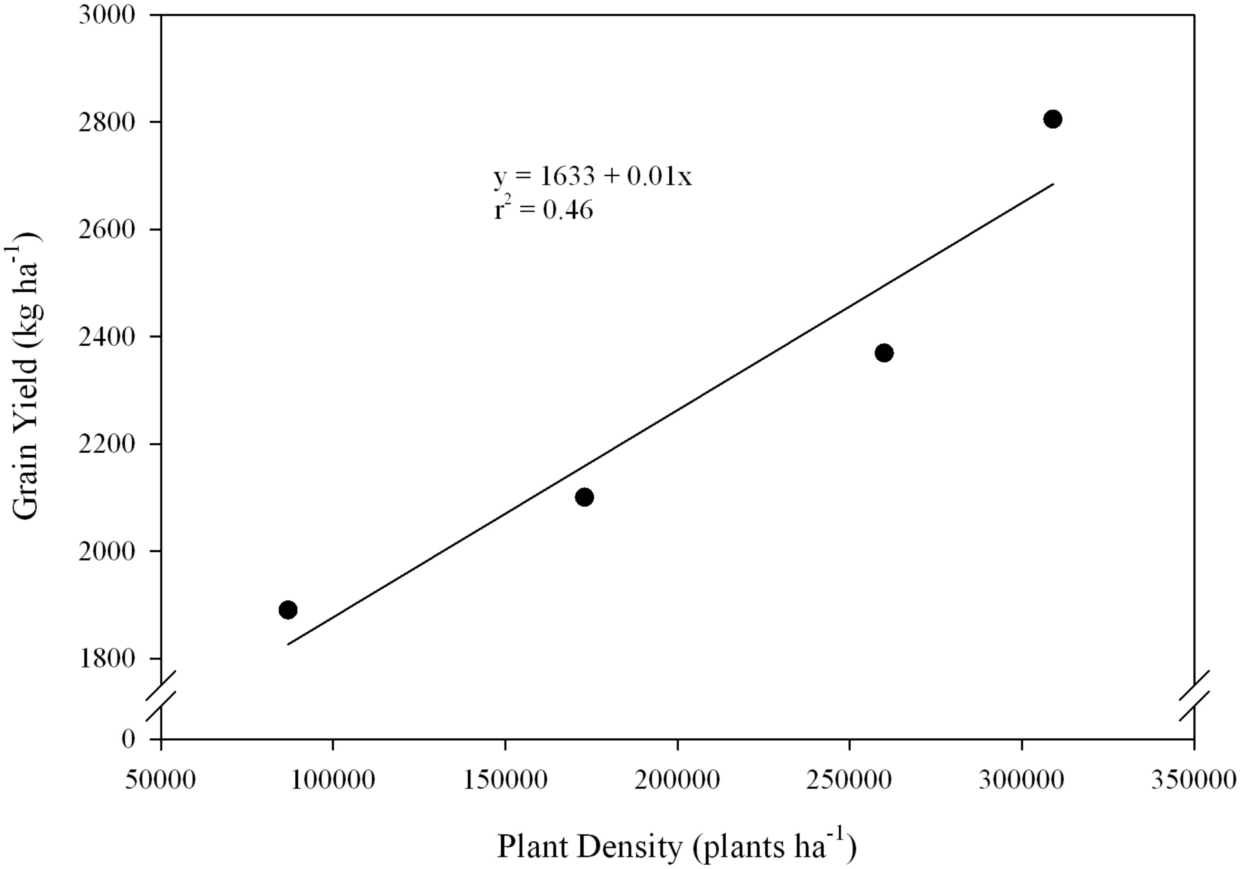


Figure 1.10. Relation of sweet sorghum grain yield to plant density at Manhattan in 2008.

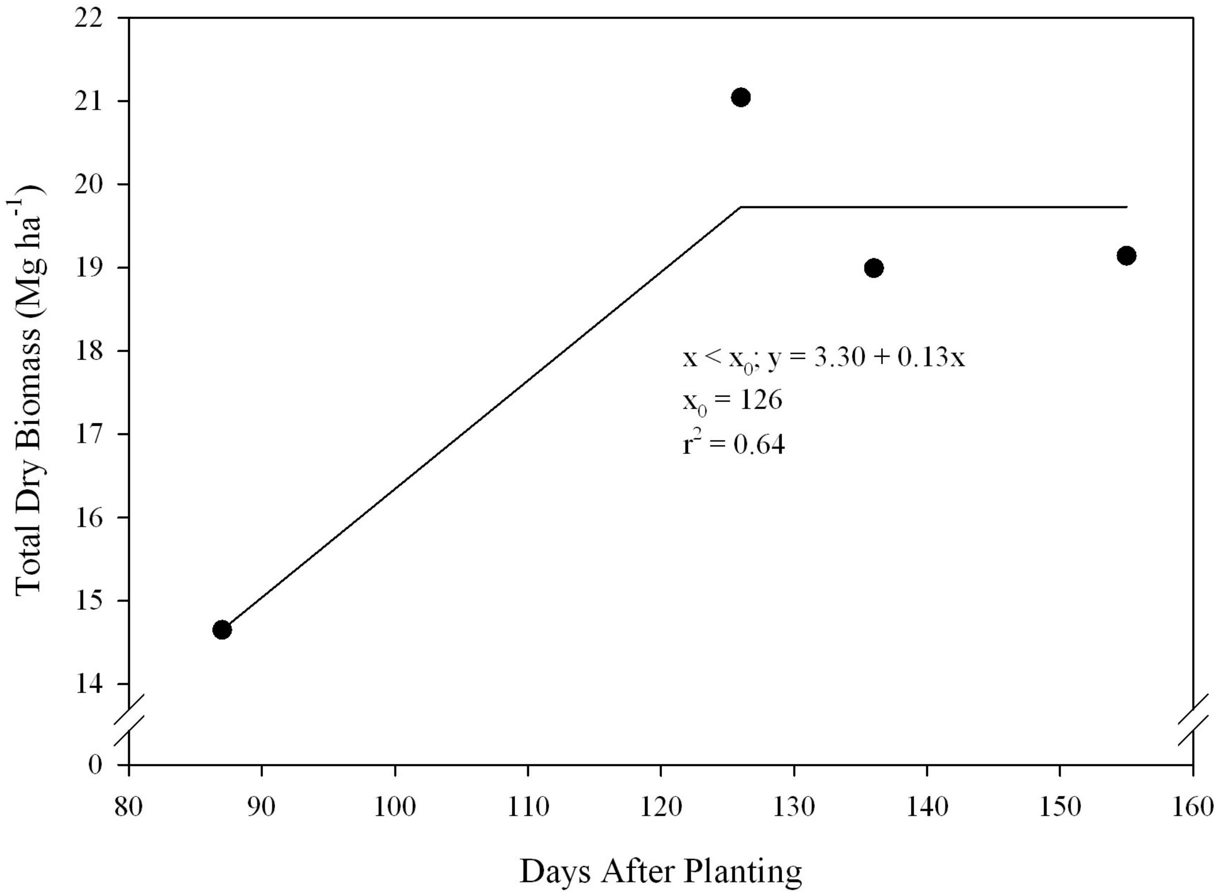


Figure 1.11. Relation of total dry biomass yield of sweet sorghum to days after planting at Manhattan in 2009.

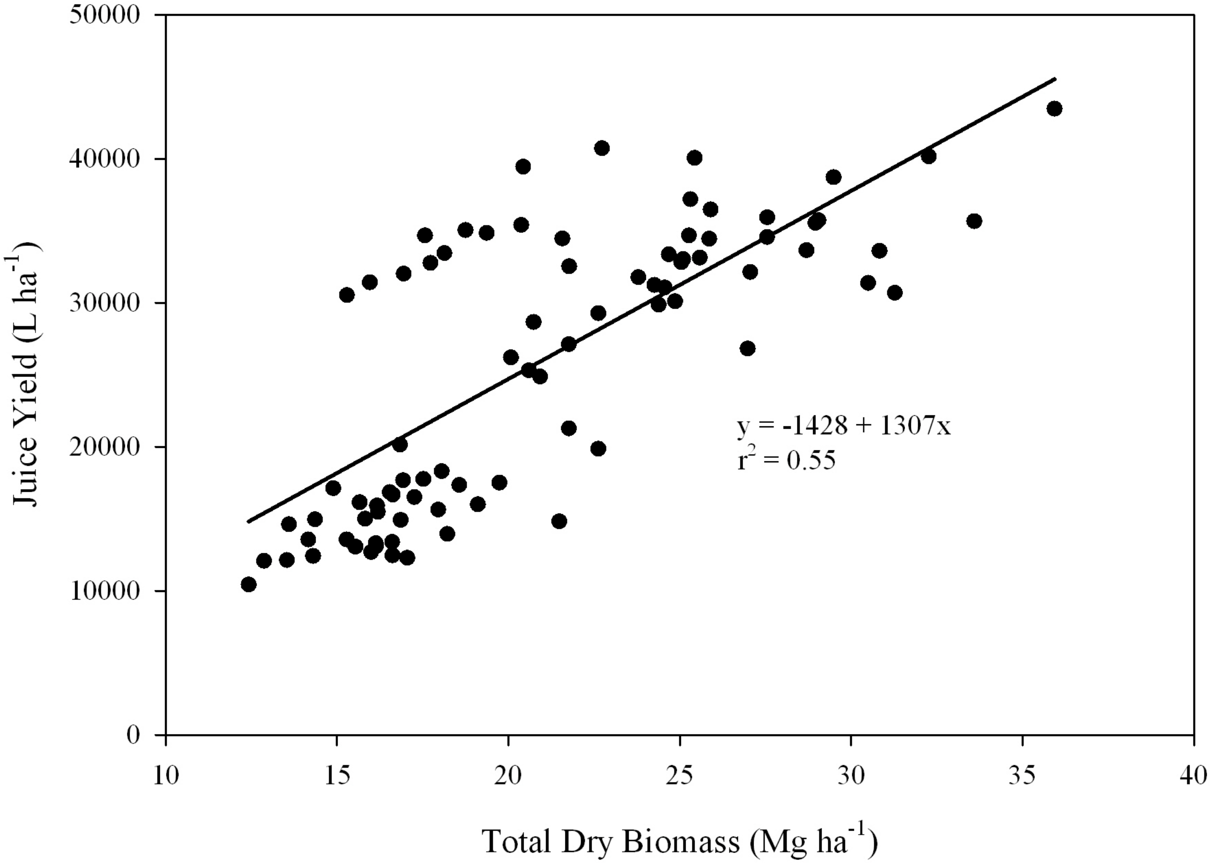


Figure 1.12. Relation of juice yield to total dry biomass of sweet sorghum at two locations in Kansas in 2008.

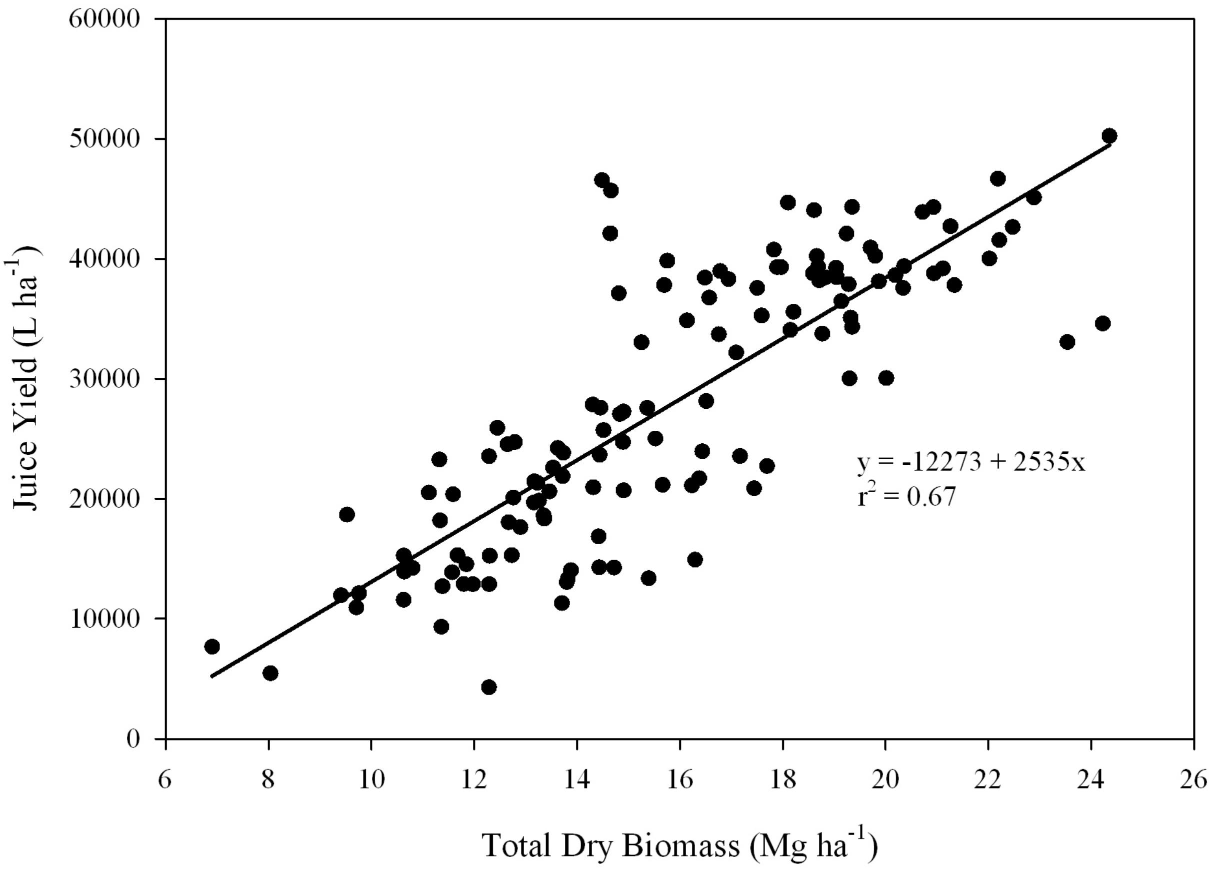


Figure 1.13. Relation of juice yield to total dry biomass of sweet sorghum at two locations in Kansas in 2009.

CHAPTER 2 - Photoperiod Sorghum and Biofuel Feedstocks

Abstract

Increased demand for ethanol is stressing current production methods. New, innovative production methods and biofuel feedstocks will be required. Certain sorghum types [*Sorghum bicolor* (L.) Moench] have shown promise as feedstocks for cellulosic ethanol production, which will require large quantities of plant biomass. Photoperiod sensitive (PS), brown midrib, and sweet sorghum types have been shown to produce high amounts of biomass. Production for biofuel feedstocks may also require that sorghum remain in fields during the winter months. With these requirements, studies were conducted at two dryland locations in northcentral and northeast Kansas in 2008 and 2009 to evaluate feedstocks types, PS sorghum plant density, and winter weathering. Plots were generally harvested after a killing freeze, and total dry biomass, moisture content, and plant height were observed. Sweet sorghum juice yields were also recorded. The feedstock study found photoperiod sorghum had the greatest biomass yields, likely due to full season heat unit accumulation. The plant density study found that PS sorghum can compensate for large variations in plant density, but higher densities may have an advantage in years with exceptional growing conditions. It was also observed that smaller stemmed plants dried faster than larger stemmed plants. Results from the harvest date trial indicate that biomass yields and moisture content decreased during the winter months. High PS sorghum seeding rates may yield more biomass in certain years, and will dry faster, limiting the time between cutting and baling for storage.

Introduction

Government regulations and consumer demand are leading to an increased need for ethanol. Currently, ethanol producers in the United States utilize grain from maize (*Zea mays*) and sorghum [*Sorghum bicolor* (L.) Moench] for ethanol production. However, these crops have typically been grown for food, leading to food shortage concerns if ethanol production is increased. Research has shown that ethanol can be effectively produced from cellulosic materials such as wood, grass, and wastes (Lynd et al., 1991). Agricultural feedstocks, such as annual crop plant material, offer an advantage over wood feedstocks in that the time from planting to harvest is less than one year and the feedstocks could be grown in rotation with conventional food crops (Lynd et al., 1991). An additional benefit from cellulosic ethanol production is that the fermentation residue can be burned for additional energy output (Lynd et al., 1991).

Agricultural feedstocks include plant residues remaining after grain harvest such as stalks and maize cobs, or whole crop plants. Forage crops such as grass, maize, and sorghum historically have been developed for high biomass production and increased digestibility in animals. Perennial warm season grasses offer the benefit of perennial growth, but biomass yields are low. However, sorghum is an annual crop that is well suited to this region and has the potential for high biomass yields (Butler and Bean, 2002). In addition, production costs of sorghum are generally lower than those of other feedstock types (Rooney et al., 2007). Sorghum biomass yields are often higher than maize, and those yields can be attained at lower water use rates than maize (McCollum et al., 2005). Marsalis et al. (2010) also found greater stability in forage sorghum dry matter yields with fluctuating precipitation than forage maize. Several sorghum types have been developed for forage production, including photoperiod sensitive (PS), brown midrib (*bmr*), and sweet sorghum. General characteristics of PS sorghum include tall growth and large dry matter yields (Marsalis, 2006). This sorghum type requires long nights before it will initiate the reproductive growth. These conditions occur late enough in the season that PS sorghum will not flower in this region. Because PS sorghum stays in the vegetative stages for most of the growing season, it will accumulate a large amount of GDUs, therefore creating large biomass yields (Rooney et al., 2007). The *bmr* sorghum types contain a gene that results in lower lignin concentrations. Lower lignin leads to increased digestibility in animals, and therefore should result in higher conversion rates in a cellulosic ethanol system. However, there is about a 10 % yield reduction with many *bmr* sorghums (Butler and Bean, 2002). Sweet sorghum is another high biomass producing sorghum that also contains a high fermentable carbohydrate level in the plant juice (Freeman et al., 1986; Putnam et al., 1991). This allows for ethanol production through the fermentation of the extracted juice in addition to dry matter conversion to ethanol.

Photoperiod sensitive sorghum has been found to produce high biomass amounts. Trials in 2003 and 2004 in Kansas reported that ‘1990CA’, a PS sorghum cultivar, had greater than or equal dry matter yields as other entries (Roozeboom et al, 2004; Roozeboom et al., 2005).

Observed dry matter yields were 10.0 Mg ha^{-1} in 2003 and 15.8 Mg ha^{-1} in 2004. Other cultivars in the trials ranged from 7.6 to 8.2 Mg ha^{-1} in 2003 and 11.0 to 13.5 Mg ha^{-1} in 2004, with Sorghum Partners 'FS-5' yielding similar to '1990CA' both years. Photoperiod sensitive sorghum fertility management is similar to conventional forage sorghums managment. Plant density management studies have found that PS sorghum is somewhat insensitive to density. Marsalis (2006) found that increasing forage sorghum seeding rates did not consistently result in higher yields. No differences in total dry matter yield was found between plant densities from 61 750 to 123 500 plants ha^{-1} in a forage sorghum study (Stickler and Laude, 1960). A planting rate study by Marsalis et al. (2010) found that high plant densities did not necessarily contribute to increased dry matter yields. However, Olson (1971) reported that biomass yield increased as plant density increased from 175 000 to 350 000 plants ha^{-1}. If plant density is low, however, it has been observed that plants will tiller to compensate for excessive plant spacing (Marsalis, 2006). Stickler and Laude (1960) reported less tillering and finer plant stems at the highest plant density in their study. Research has found that stem diameter and tillering increased with decreased plant density (Caravetta et al., 1990a) while plant height and dry matter yields decreased with decreased plant density (Caravetta et al., 1990b). Also, it has been reported that seeding rates should be high in order to decrease stem size, which will facilitate faster plant drying (Marsalis, 2006).

Once suitable feedstocks have been identified for cellulosic ethanol production, proper harvesting methods will need to be developed. Ethanol plants will require a steady input supply throughout the year to sustain production, as it would not be economical to operate the plant only during the typical fall harvest season. This year-round supply could be provided through storage of feedstocks at the plant, or as-needed harvesting (Rooney et al., 2007). Material storage will be land and resource intensive. This favors as-needed harvesting, or leaving the feedstocks in the field where they will be harvested on an as-needed basis. If possible, fields could be harvested early enough in the year to allow for regrowth and a second harvest, which will supply material through the late summer and into early winter months. Leaving material in the field to be harvested as needed can supply material through the winter months, so that only enough feedstocks will need to be stored at the ethanol plant to last until new material can be harvested in late summer. However, dry matter losses may occur during the winter months if feedstocks remain in the field. A study by Martin and Wedin (1974) reported that grain sorghum dry matter may decrease by as much as 30 % by early December.

The objectives of this research were to evaluate photoperiod sensitive sorghum plant densities and harvest dates for optimal biomass yields. Various types of sorghum were also compared to determine optimal biomass yields. To this end, photoperiod sensitive sorghum was grown at four site-years in northeast and northcentral Kansas. Photoperiod sensitive sorghum was also harvested at two intervals during the winter months to determine the winter weathering effect on biomass yield at one site-year in northeast Kansas. Finally, several sorghum types were evaluated at two site-years in northeast Kansas.

Materials and Methods

Research was conducted in 2008 and 2009 at one dryland location in northcentral Kansas, the Kansas State University (KSU) North Central Kansas Experiment Field near Belleville, KS (39°49'N, 97°40'W) and one dryland location in northeast Kansas, the KSU Agronomy Research Field at Manhattan, KS (39°12'N, 96°36'W). The soil series at Belleville was a Crete silt loam (fine, smectitic, mesic Pachic Argiustolls), and either a Smolan silt loam (Fine, smectitic, mesic Pachic Argiustolls) or a Wymore silty clay loam (Fine, smectitic, mesic Aquertic Argiudolls) at Manhattan. Soil samples were taken at the 0-15 cm and 15-30 cm depths after planting at Manhattan in June 2008, and 0-15 cm at both locations before planting in 2009. Twenty individual cores were taken across the entire plot area and thoroughly mixed to form samples which were analyzed for: pH, Mehlich 3 P, K, N [ammonia (NH_4^+) and nitrate (NO_3^-)], and organic matter (OM) (Table 2.1). Cumulative in-season growing degree units (GDUs), precipitation amounts, and 30 year normals for all site years were calculated from nearby weather station data (High Plains Regional Climate Center, 2010). Growing degree units were calculated using a maximum temperature of 38°C and a minimum temperature of 5.6°C (Table 2.2.)

Photoperiod Sorghum Plant Density Trial

A randomized complete block design was used for this study. Individual plot size was 3.1 m wide by 9.2 m long. All plots were planted to '1990CA' (Sorghum Partners, Inc., New Deal, TX) photoperiod sensitive sorghum. Plots were no-till planted 10 June 2008 in a Smolan soil and 8 June 2009 in a Wymore soil at Manhattan with sorghum as the previous crop both years. The Belleville location was planted into conventionally tilled soil 11 June 2008 and no-till planted into burned sorghum residue 19 June 2009 (Table 2.3). Planting was delayed at Belleville in 2009 due to wet soil conditions. All crops were planted using a no-till row crop planter on 76 cm row spacing.

Nitrogen fertilizer was broadcast applied after planting both years at Manhattan, and at Belleville, N was pre-plant knife applied in 2008 and surface dribble applied after planting in 2009 (Table 2.3). Dry urea (46-0-0) was used both years at Manhattan, and liquid urea ammonium nitrate solution (28-0-0) was used both years at Belleville. Fertilization rates were reduced in 2009 to limit rapid and excessive early growth in an attempt to decrease lodging.

Plots were planted using the highest seeding rate possible. At approximately the three leaf stage plant density was measured in all plots. The plant density was averaged in the highest treatment plots and those plots were hand thinned to that value. Remaining plots were hand thinned to the desired plant density treatments. Plant density treatments in 2008 were: 87 000, 173 000, 260 000, and 309 000 plants ha^{-1}. In 2009, treatments were: 43 000, 87 000, 130 000, 173 000, and 260 000 plants ha^{-1}. The highest rate was slightly lower in 2009 due to poor seed germination.

Weed control at both locations was through pre-emergence herbicides applied at labeled rates in combination with recommended carrier volume and adjuvant rates (Table 2.4). Hand weeding was used as necessary through the growing season to minimize weed pressure. Herbicides were applied with an all-terrain vehicle mounted boom sprayer at Manhattan and a tractor mounted boom sprayer at Belleville.

Plots were harvested after a killing freeze (Table 2.3). A 4.6 m length of the center two rows was hand harvested from the four row plots to avoid border effects. The sample was weighed to obtain total biomass wet weight. A 10 plant sub-sample was randomly selected from each sample and weighed to determine sub-sample wet weight. Four random plants were selected from the sub-sample to be measured for plant height and above-ground node number. Wet biomass sub-samples were dried in a forced air dryer at 65°C for 72 hours, then weighed to obtain biomass dry weight.

Biomass moisture content at harvest was calculated on a wet mass basis. Dry biomass was corrected using the respective plant moisture content. Total dry biomass yield included all above-ground harvested biomass and was corrected to oven dry moisture content. Final biomass yields were calculated from individual plot weights. Equality of population variances for plant moisture content, total dry biomass, node number, and plant height were tested using Hartley's test for homogeneity (Ott, 1988). Variances for Hartley's test were obtained through PROC MEANS (SAS Institute, 2005). Analysis of variance was performed using PROC ANOVA (SAS Institute, 2005). Mean separations were performed for the treatment effects (plant density) if the pairwise t-tests were significant ($p = 0.05$). Regression analysis was performed using PROC REG (SAS Institute, 2005) on significant linear or quadratic responses.

Photoperiod Sorghum Harvest Date Trial

A randomized complete block design was used for this study. Individual plot size was 3.1 m wide by 9.2 m long. All plots were planted to '1990CA' (Sorghum Partners, Inc., New Deal, TX) photoperiod sensitive sorghum. Plots were no-till planted only at Manhattan on 8 June 2009 in Wymore soil with sorghum as the previous crop (Table 2.3). Crops were planted using a no-till row crop planter on 76 cm row spacing. Nitrogen fertilizer as dry urea (46-0-0) was broadcast applied after planting (Table 2.3).

Weed control was through pre-emergence herbicide applied at labeled rates in combination with recommended carrier volume and adjuvant rates (Table 2.4). Hand weeding was used as necessary through the growing season to minimize weed pressure. Herbicides were applied with an all-terrain vehicle mounted boom sprayer.

Plots were harvested 4 December 2009 and 18 March 2010 (Table 2.3). A 4.6 m length of the center two rows was hand harvested from the four row plots to avoid border effects. The sample was weighed to determine total biomass wet weight. A 10 plant sub-sample was randomly selected from each sample and weighed for sub-sample wet weight. Wet biomass sub-samples were dried in a forced air dryer at 65°C for 72 hours, then weighed to obtain biomass dry weight.

Biomass moisture content at harvest was calculated on a wet mass basis. Dry biomass was corrected using the respective plant moisture content. Total dry biomass yield included all above-ground harvested biomass and was corrected to oven dry moisture content. Final biomass yields were calculated from individual plot weights. Analysis of variance was performed using PROC ANOVA (SAS Institute, 2005). Mean separations were performed for the treatment effects (harvest date) if the pairwise t-tests were significant ($p = 0.05$).

Biofuel Feedstocks Trial

A randomized complete block design was used for this study. Individual plot size was 6.1 m wide by 9.2 m long. Plots in 2008 were planted to: ‘22053’, ‘Graze All 3’, ‘Graze-N-Bale’, and ‘Sugar T’ (Texas A&M University, College Station, TX). In 2009, plots were planted to: ‘22053’, ‘Graze All 3’, ‘Graze-N-Bale’, ‘M81E’, ‘Sugar T’, and ‘TAMUXH08001’ (Texas A&M University, College Station, TX). Plots were no-till planted 10 June 2008 and 8 June 2009 at Manhattan with sorghum as the previous crop both years (Table 2.3). All crops were planted using a no-till row crop planter on 76 cm row spacing. Nitrogen fertilizer as dry urea (46-0-0) was broadcast applied after planting both years (Table 2.3). Seeding and nitrogen fertilizer rates were reduced in 2009 in an attempt to reduce lodging.

Weed control was through pre-emergence herbicides applied at labeled rates in combination with recommended carrier volume and adjuvant rates (Table 2.4). Hand weeding was used as necessary through the growing season to minimize weed pressure. Herbicides were applied with an all-terrain vehicle mounted boom sprayer. The application on 8 July was applied with a tractor mounted hooded type sprayer as crop plants were actively growing.

Sweet sorghum plots were harvested before a killing freeze (Table 2.3). A 4.6 m length of the center two rows was hand harvested from the eight row plots to avoid border effects. The sample was weighed to determine total biomass wet weight. A 10 plant sub-sample was randomly selected from each sample and weighed for sub-sample wet weight. Grain heads from all plants in both the sample and sub-sample were counted, removed, and weighed for head wet weight. Four random plants were selected from the sub-sample to be measured for plant height and above-ground node number. Leaves were removed from plants in the sub-sample, leaving only stalks that were pressed once in a triple-roll sorghum mill. Bagasse (stalk after pressing) was collected and combined with removed leaves for the bagasse wet weight. Juice was weighed and a sub-sample was collected and stored in a cooler at approximately 5°C within five minutes of extraction for transport to the laboratory. Brix values were obtained in the laboratory utilizing a pocket refractometer (Model PAL-1, ATAGO, Tokyo, Japan). Bagasse and grain heads were dried in a forced air dryer at 65°C for 72 hours, then weighed to obtain head dry weight and bagasse dry weight. Grain heads were threshed in a stationary thresher (Model LDB, ALAMACO, Nevada, IA), saving the grain for grain weight. A grain sub-sample was processed (GAC 2000, DICKEY-john Corp., Springfield, IL) for moisture content and test weight. A 200 seed sub-sample was then counted, dried at 105°C for two days, and weighed to obtain seed dry weight.

Remaining plots with sorghum types other than sweet sorghum were harvested after a killing freeze (Table 2.3). A 4.6 m length of the center two rows was hand harvested from the eight row plots to avoid border effects. The sample was weighed to determine total biomass wet weight. A 10 plant sub-sample was randomly selected from each sample and weighed for sub-sample wet weight. Four random plants were selected from the sub-sample to be measured for plant height and above-ground node number. Wet biomass sub-samples were dried in a forced air dryer at 65°C for 72 hours, then weighed to obtain biomass dry weight.

Biomass moisture content at harvest was calculated on a wet mass basis. Dry biomass and grain yield were corrected using the respective plant and grain moisture content. Total dry biomass yield included all above-ground harvested biomass and was corrected to oven dry moisture content. Grain yield was calculated from threshed grain weight and adjusted to 13 % moisture using measured moisture content at threshing. Final biomass, grain, and juice yields were calculated from individual plot weights. Equality of population variances for plant moisture content, total dry biomass, grain yield, juice yield, brix value, node number, and plant height were tested on appropriate types of sorghums using Hartley's test for homogeneity (Ott, 1988). Variances for Hartley's test were obtained through PROC MEANS (SAS Institute, 2005). Analysis of variance was performed using PROC ANOVA (SAS Institute, 2005). Mean separations were performed for the treatment effects (sorghum type) if the pairwise t-tests were significant ($p = 0.05$).

Results and Discussion

In-season (1 May – 31 October) cumulative precipitation was above normal at both locations in both years (Table 2.2). Cumulative in-season GDUs in 2008 were below normal at Manhattan and approximately normal at Belleville (Table 2.2), but both locations received nearly the same GDUs. In 2009, GDUs were below normal at both locations, with Belleville accumulating fewer GDUs than Manhattan. Wet soil conditions delayed planting by approximately one week at Belleville in 2009. Severe lodging in sweet sorghum plots was observed in the feedstocks trial in 2008, leading to a reduction in seeding rates and standard nitrogen fertilization rates in 2009.

Photoperiod Sorghum Plant Density Trial

Testing of population variances revealed large differences between locations, so results are presented for each separate site-year, in addition plant density treatments were modified in 2009. Very little plant lodging was observed in all site-years. At Belleville in 2009, planting was delayed by one week due to wet weather.

Total Dry Matter

A significant treatment effect was found for total dry matter only at Belleville in 2008 (Table 2.5). Total dry matter was found to increase linearly with increasing plant density from 16.7 to 20.6 Mg ha^{-1} (Figure 2.1). Without differences from 87 000 to 309 000 plants ha^{-1}, the ideal plant density rate will be determined by economics.

Previous research has not found a definitive dry matter response to plant density or a lack thereof. Caravetta et al. (1990b) found that as plant density increased, forage sorghum yields increased. Olson (1971) also found that forage sorghum biomass yield generally increased with increasing population. However, Marsalis et al. (2010) found that high planting rates, or plant density, did not necessarily contribute to increased sorghum biomass yields. Research by Stickler and Laude (1960) found that neither row spacing nor plant density affected forage sorghum biomass yields.

It was observed during the growing season that plants at lower densities created additional tillers. This increase in tillering as plant density decreases was also observed by Caravetta et al. (1990a) as well as by Stickler and Laude (1960). These results indicate that at 87 000 plants ha^{-1}, the plant density was lower than photoperiod sensitive sorghum could correct for. At densities greater than 87 000 plants ha^{-1}, photoperiod sorghum could compensate for plant spacing through additional tillers. The correlation of height to total dry biomass (Figure 2.4) should indicate a significant effect with plant height at Belleville in 2008. However, this difference in height was not observed. Since plant heights were not different across treatments, the differences in dry biomass must be due to plant or tiller number. Plots at Belleville in 2008 received the most GDUs in this study. These additional heat units could have allowed the additional plants and tillers in the higher plant densities to increase total dry biomass more than lower densities.

Plant Moisture

A significant treatment effect was found for plant moisture content only at Belleville in 2009 (Table 2.5). These results indicate that plant moisture decreased linearly with increasing plant density, from roughly 73 to 69 % (Figure 2.2). .

These results may be partially influenced by differences in plant diameter. It was observed that stem diameter decreased with increasing plant density. This observation is supported by previous research which found that stem diameter increased as plant density decreased (Caravetta et al., 1990a) and (Stickler and Laude, 1960). Larger stems may increase drying time for photoperiod sensitive sorghum, as plots were harvested after a killing freeze and the plants should have begun to air dry while standing in the field. Conversely, smaller diameter plants appear to have air dried faster. Plots at Belleville in 2009 were harvested once considerable time had passed after the killing freeze, allowing ample drying of smaller stemmed plants before harvest. Plots in other site-years did not have much time to dry before harvest, which may have accounted for the lack of differences in other site-years.

Above-ground Node Number

A significant treatment effect was found for the above-ground node number only at Belleville in 2009 (Table 2.5). It was observed that the above-ground node number decreased linearly from approximately 13 to 10 above-ground nodes plant^{-1} (Figure 2.3). Even though these results show that the average node number plant^{-1} decreased with increasing density, a similar trend was not observed in plant height. This indicates that node length must have also increased with increasing plant density to maintain similar plant heights across the plant density range. Research by Caravetta et al. (1990a) found that forage sorghum leaf number was influenced more by genotype and environment than by plant density. This further supports the results in this study that indicate the above-ground node number did not change as plant density changed.

Plant Height

No significant treatment effect was found for plant height at any site-year in this study (Table 2.5). These results are in disagreement with forage sorghum research by Caravetta et al. (1990a) which found that plant height decreased as plant density decreased. However, in this study, plant height and total dry matter increased (Figure 2.4). Since plant height and total dry biomass are related, the lack of significance in plant height may generally account for the lack of difference observed in total dry biomass.

Photoperiod Sorghum Harvest Date Trial

This study was conducted to determine if dry matter yield losses occur due to weathering under winter conditions. Plots were harvested 4 December 2009 and 18 March 2010. Almost no lodging was observed at the first harvest, but plants had completely lodged by the second harvest date. Very few snapped plants were observed at either harvest date.

Total Dry Matter

A significant harvest date effect was found for total dry matter yield (Table 2.6). Total dry matter yield was found to decrease with time from 17.0 to 10.5 Mg ha^{-1}. Few snapped plants were observed, however, numerous leaves were observed on the ground. The results from this study indicate that these plant material losses reduce photoperiod sensitive sorghum dry matter yield over the winter months.

These results also indicate that if weather conditions force a late harvest, or if ethanol production methods demand that photoperiod sensitive sorghum over winter in the field for as-needed harvesting, dry matter yield losses will be observed. Previous research by Martin and Wedin (1974) supports the results found in this study. The researchers found a significant grain sorghum dry matter loss during the winter months. In their research, Martin and Wedin observed that grain sorghum dry matter decreased 30 % between the original and early December harvest dates.

Plant Moisture

Plant moisture decreased significantly from the early to the late harvest dates (Table 2.6). Plant moisture decreased with time by approximately 7 %. These results found that even though low air temperatures typically occur from December through March, moisture content still decreased, indicating this material will dry as it stands in the field. However, the moisture content is likely still high enough to require extra drying between cutting in the field and processing at an ethanol plant. The March harvest date moisture content is also likely high enough to create spoilage issues if the material was to be harvested and stored without additional drying time.

Biofuel Feedstocks Trial

Different feedstocks types were grown in each year, so results are presented separately for each year. The feedstock 'Sugar T' lodged severly in 2008, with only slight lodging noted in other feedstocks. Lodging issues were very slight in 2009. Considerable volunteer sorghum pressure was present in several plots in 2009, likely leading to high variability in certain yield components.

Total Dry Matter

A significant treatment effect was found for total dry matter in 2008 (Table 2.7). Due to high variability in 2009, no significant effects were observed. In 2008, the feedstocks 'Graze All 3' and 'Sugar T' were not different. The highest yield was observed with the feedstock type 'Graze-N-Bale'.

These results indicate that feedstock selection may play an important role in maximizing total dry matter yield. The feedstocks 'Sugar T' and 'Graze-N-Bale' were full season sorghums, which allowed them to continue active growth until plot harvest. Other feedstock types senesced earlier in the season, limiting the growth period length and, therefore, dry biomass they could accumulate. However, 'Sugar T' did not yield as expected in 2008, likely due to lodging. The lodged plants may have become more brittle, allowing plants to break apart when harvested. Any plant parts left in the field during harvest would have resulted in lower recorded yields. However, the height of 'Sugar T' was not different from 'Graze-N-Bale' at harvest. Because plant height is correlated to total dry matter yield, 'Sugar T' and 'Graze-N-Bale' should not have had different yields.

Plant Moisture

A significant treatment effect was found for plant moisture in 2008 (Table 2.7). The feedstocks '22053' and 'Graze All 3' were not different in harvest moisture content. Both 'Graze-N-Bale' and 'Sugar T' had a moisture content greater than 70 %. In 2008, the killing freeze occurred later in the year, allowing continued growth in 'Graze-N-Bale' and 'Sugar T'. However, '22053' and 'Graze All 3' senesced and began to dry before plots were harvested. In 2009, due to weed competition and an early freeze, most feedstocks were either actively growing or had recently senesced when plots were harvested. This limited the time in 2009 available for early maturing sorghums to dry before plot harvest, which accounted for the lack of differences.

Above-ground Node Number

A significant treatment effect was found for the above-ground node number both years (Tables 2.7 and 2.8). In 2008, the above-ground node number was greatest with 'Graze-N-Bale' and least with 'Graze All 3'. The above-ground node number in 2009 was the greatest with 'Sugar T' and least with 'TAMUXH08001'. A greater node number should indicate greater plant height and total dry matter yields, through the addition of material to the plants.

Plant Height

A significant treatment effect was found for plant height in both years (Tables 2.7 and 2.8). In 2008, plant height was found to be different only with 'Graze All 3'. Other feedstocks were not different. Plant height in 2009 was the shortest with 'Graze All 3' and the highest with 'Sugar T'. It was observed that 'Graze All 3' had the shortest plant height both years. A lack of plant height should indicate lower total dry matter, which was observed in both years. Similar trends in plant height and the above-ground node number were observed. These results indicate that little difference in node length exists between feedstocks.

Juice Yield

No significant treatment effects were found for juice yield in 2009 (Table 2.8). Only one feedstock was examined for juice yield in 2008, so mean separations were not performed in 2008. Under conditions in this study, no differences in juice yield were found, indicating feedstock selection does not impact juice yield. The difference in juice yield between years may be attributed to the shorter growing season, less precipitation, or the severe weed pressure experienced in 2009. Any of these factors could have stressed the plants, leading to lower juice yields. The plots were also sampled for juice yields before the plants had reached physiological maturity due to the poor growing season conditions. This lack of maturity may have prevented maximum juice production.

Brix

A significant treatment effect was found for brix values in 2009 (Table 2.8). Only one feedstock was examined for brix values in 2008, so mean separations were not performed in 2008. In 2009 brix values were different between 'Sugar T' and 'M81E'. Brix values correlate with the amount of FC present in juice. These results found a difference in FC between feedstocks, indicating feedstock selection may be important in maximizing the potential ethanol yield. The difference in brix values found with 'Sugar T' between years may be due to lower plant moisture in 2009. Lower plant moisture would result in FC being more concentrated in the juice, leading to a higher brix reading.

Grain Heads

A significant treatment effect was found for the grain head number ha^{-1} in 2008 (Table 2.7). Variability due to excessive volunteer sorghum pressure in 2009 may have lead to a lack of differences. In 2008, the lowest head number was found with 'Sugar T' and greatest with 'Graze All 3'. The feedstock 'Graze-N-Bale' is a photoperiod sensitive sorghum, implying that it will not enter the reproductive stage until late in the growing season in this region. A few grain heads were observed to be emerging at harvest.

These results indicate that the grain head number ha^{-1} varies greatly between feedstocks even though all types were planted at the same rate. Considerable axillary heading was observed with 'Graze All 3' and much less was observed with '22053'. The feedstock 'Sugar T' experienced severe lodging during grain fill which may have impacted the head number $plant^{-1}$ that was recovered during plot harvest. In 2009, the grain head number with 'Sugar T' was observed to be more in line with the other feedstocks, indicating the severe lodging in 2008 may have caused a lower head number ha^{-1}.

Grain Yield

A significant treatment effect was found for grain yield in 2008 (Table 2.7). Variability due to excessive volunteer sorghum pressure in 2009 may have lead to a lack of differences. Grain yield in 2008 was found to be the least with 'Sugar T' and greatest with 'Graze All 3'. The feedstock 'Graze-N-Bale' is a photoperiod sensitive sorghum, implying that it will not enter the reproductive stage until late in the growing season in this region, thereby preventing any grain production. These results indicate that grain yield is impacted by feedstock selection. Grain yield in 2008 also increased as the grain head number increased, indicating grain yield is likely increased through additional grain heads.

Summary and Conclusions

These studies found some general characteristics of photoperiod sensitive sorghum growth and harvestability. Total dry matter increased as plant height increased (Figure 2.4). Across all site-years, a linear increase in total dry biomass with increasing plant height was found. The relationship of total dry biomass to plant height was expected as plant height is increased by adding more biomass to the plant.

Results from the photoperiod sensitive sorghum plant density trial found few significant differences in yield. Other measured components were also generally not different. This demonstrates that photoperiod sensitive sorghum may be insensitive to plant density, in the range of plant densities evaluated in these studies, due in part to its ability to compensate for plant spacing. Plant height was found to be not different in all site-years, and total dry biomass was generally not different. The general lack of differences in dry biomass is likely due to the correlation of plant height to total dry biomass; since plant height is not different, dry biomass would also be expected to be not different. In one site-year, dry biomass was found to be not different from 173 000 to 309 000 plants ha^{-1}, with the lowest plant density (87 000 plants ha^{-1}) yielding less than the other treatments. Growing conditions in that environment were exceptional for sorghum growth, perhaps favoring the additional plants and tillers at greater plant densities. In one site-year, lower plant moisture contents were observed at higher plant densities. Because plot harvest occurred well after a killing freeze at that location, it is suspected that higher plant densities will air dry faster than lower plant densities. Previous research and field observations in this study indicate that plant diameter decreases with increasing plant density, implying that smaller stemmed plants will air dry faster.

The photoperiod sensitive sorghum harvest date study found that total dry biomass decreased due to winter weathering. Results found that the dry biomass yield decrease with time, resulting in a rapid yield decrease if photoperiod sensitive sorghum is required to stay in fields for a long period. Nearly all plants had lodged by the late winter harvest date, however, few snapped plants were observed. Numerous leaves were found to be on the ground, in addition to a few detached stem fragments. Plant moisture content was found to decrease with time between harvest dates. Although a decrease in moisture content was observed, the moisture content only decreased by approximately 7 %.

The biofuel feedstock trial in 2008 found several differences between the feedstock types. Plot conditions in 2009 increased variability and limited the differences found. Total dry biomass yield in 2008 was the greatest with 'Graze-N-Bale', which is a photoperiod sensitive sorghum. Differences were also observed in plant moisture content in 2008. Both '22053' and 'Graze All 3' had much lower moisture content than both 'Graze-N-Bale' and 'Sugar T'. These differences are likely due to ‘22053’ and ‘Graze All 3’ requiring a shorter growing season, which caused those types to senesce and began to dry down, but ‘Graze-N-Bale’ and ‘Sugar T’ were actively growing until plot harvest. Plant height was different between feedstock type in both years, which should have indicated differences in total dry biomass in both years. These differences were generally observed in 2008, but not in 2009.

These results indicate that the sorghum type selected as a cellulosic biofuel feedstock will be very important, as yields vary greatly between types. The photoperiod sensitive sorghum type was found to have greater yields than all other types in one site-year. In addition, it was found that photoperiod sensitive sorghum should be seeded at a rate not less than 173 000 plants ha^{-1} as it appears that lower plant densities may not reach maximum yields in years with exceptional growing conditions. In less ideal years, the additional plants and tillers experienced at higher densities may not reach full potential and yield may not differ across a range from 43 000 to 309 000 plants ha^{-1}. It was also noted that the total dry biomass yield decreased with time but plant moisture decreased only 10 % over the winter months. If photoperiod sensitive sorghum is to overwinter in the field, dry matter yield losses will occur. In addition, moisture content may be high enough during a spring harvest to require additional drying time before baling or storage. However, it was also found that after a killing freeze, moisture content decreases more quickly in smaller stemmed plants. Managing an overwintering photoperiod sensitive sorghum crop for small plant diameter by increasing plant density may increase the drying experienced during the winter months.

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Chapter 2 – Tables

Table 2.1. Soil test results for two locations in Kansas in 2008 and 2009.

Year	Location	Study	Depth	pH	P	K	NH_4^+N	NO_3^-N	OM
			cm		- - - - - - - - - - -	- - ppm - -		- - - - - - - - - - -	%
2008	Manhattan	Both[†]	0-15	5.6	78	483	7.6	42.5	2.4
			15-30	6.3	62	423	19.8	19.8	2.1
2009	Manhattan	PS[‡]	0-15	5.8	32	293	5.6	9.3	2.1
		RBFT[§]	0-15	6.3	87	492	3.7	6.5	3.0
2009	Belleville	PS	0-15	5.2	48	449	5.5	22.4	-

[†] Soil test results are for regional biofuel feedstocks and photoperiod sorghum plant density trials.

[‡] Photoperiod sensitive sorghum.

[§] Regional biofuel feedstock trial.

Table 2.2. In season cumulative growing degree units and precipitation for two locations in Kansas.

	Growing Degree Units[†‡]			Precipitation[†]		
Location	2008	2009	Normal	2008	2009	Normal
	- - - - - - - -	GDUs	- - - - - - - - -	- - - - - - - - - -	mm	- - - - - - - - - -
Manhattan	4860	4534	5251	879	674	613
Belleville	4963	4241	4904	748	560	551

[†] Growing season set as 1 May – 31 October of each year. Data from High Plains Regional Climate Center.

[‡] Base temperature set as 5.6°C for GDU calculation.

Table 2.3. Planting, nitrogen fertilization, and harvest dates and seeding and fertilization rates in 2008 and 2009 at Manhattan and Belleville, KS.

Year	Location	Study	Planting Date	Target Seeding Rate	Nitrogen Rate[†]	Nitrogen Application Date	Harvest Date
2008				seeds ha^{-1}	kg N ha^{-1}		
	Manhattan	PS[‡] Density	10-Jun	185 000	162	11-Jun	29-Oct
		RBFT[§]	10-Jun	185 000	162	11-Jun	26 & 29 Oct[¶]
	Belleville	PS Density	11-Jun	346 000	112	Pre-plant	30-Oct
2009							
	Manhattan	PS Density	08-Jun	319 000	112	04-Jun	25-Nov
		PS Harvest Date	08-Jun	319 000	112	04-Jun	By Treatment
		RBFT	08-Jun	158 000	112	04-Jun	10-Oct & 1-Dec[#]
	Belleville	PS Density	19-Jun	321 000	112	13-Jul	27-Nov

[†] Nitrogen fertilizer applied as 46-0-0 at Manhattan and 28-0-0 at Belleville.

[‡] Photoperiod sensitive sorghum.

[§] Regional biofuel feedstock trial.

[¶] Sweet sorghum plots harvested 26-Oct, remaining plots harvested 29-Oct.

[#] Sweet sorghum plots harvested 10-Oct, remaining plots harvest 1-Dec.

Table 2.4. PRE-emergence herbicide application information for 2008 and 2009 at Manhattan and Belleville, KS.

Year	Location	Herbicide and rate	Date
		kg a.i. ha^{-1}	
2008			
	Manhattan	1.7 atrazine[†] + 1.3 S-Metolachlor[‡] + 1.5 glyphosate[§]	13-Jun
2009			
	Manhattan	1.4 atrazine + 1.1 S-Metolachlor + 1.1 glyphosate	04-Jun
		1.5 glyphosate	13-Jun
		1.1 glyphosate	08-Jul
	Belleville	1.1 glyphosate	19-Jun

[†] Atrazine [2-chloro-4(ethylamino-6-(isopropylamino)-s-triazine]

[‡] S-Metolachlor [2-chloro-N-(2-ethyl-6-Methylphenyl)-N-[(1S)-2-methoxy-1-methylethyl]acetamide]

[§] Glyphosate [N-(phosphonomethyl)glycine]

Table 2.5. Results and analysis of variance results for total dry biomass, plant moisture, above-ground nodes, and plant height of photoperiod sensitive sorghum under different plant densities at Manhattan and Belleville, KS in 2008 and 2009.

		Source	Total Dry Biomass	Plant Moisture	Above-ground Nodes	Plant Height
2008	Manhattan		- - - - - - - - - - - - - - -Pr > F - - - - - - - - - - - - - - -			
		Rep	0.9135	0.3382	0.9207	0.9933
		Treatment	0.3262	0.9360	0.9730	0.8068
		C.V.	17.13	1.89	11.81	10.78
2008	Belleville					
		Rep	0.5705	0.9427	0.6217	0.6233
		Treatment	0.0054*	0.0624	0.0598	0.3303
		C.V.	4.16	2.11	9.44	4.60
2009	Manhattan					
		Rep	0.0777	0.0384	0.7388	0.1007
		Treatment	0.2708	0.3254	0.0626	0.1706
		C.V.	13.74	3.56	6.88	5.76
2009	Belleville					
		Rep	0.0082	0.0001	0.0525	0.0228
		Treatment	0.1051	0.0018*	0.0012*	0.3034
		C.V.	7.31	1.12	4.58	3.64

*Results are significant at the *p*=0.05 level.

Table 2.6. Results and analysis of variance results for total dry biomass and plant moisture of photoperiod sensitive sorghum under different harvest dates at Manhattan in 2009.

		Total Dry Biomass	Plant Moisture
		Mg ha^{-1}	%
Harvest Date			
	4 December 2009	17.0	67.2
	18 March 2010	10.5	60.4
Source		- - - - - - Pr > F	- - - - - - -
	Rep	0.9687	0.7035
	Treatment	0.0506*	0.0130*
	C.V.	20.96	2.81

*Results are significant at the *p*=0.05 level.

Table 2.7. Results and analysis of variance results for total dry biomass, plant moisture, above-ground nodes, plant height, juice yield, brix, grain heads, and grain yield of different feedstocks at Manhattan, KS in 2008.

		Total Dry Biomass	Plant Moisture	Above-ground Nodes	Plant Height	Juice Yield	Brix	Grain Heads	Grain Yield
		Mg ha^{-1}	%	# plant^{-1}	m	L ha^{-1}	%	# ha^{-1}	kg ha^{-1}
Cultivar									
	22053	16.9	63.4	13.4	3.4	-	-	101 506	1726
	Graze All 3	14.6	61.6	9.4	2.8	-	-	242 826	2209
	Graze-N-Bale	19.5	73.8	14.0	3.4	-	-	-	-
	Sugar T	14.8	78.2	12.3	3.4	21 102	10.07	27 260	558
	LSD	2.7	3.5	1.4	0.2	-	-	46 913	833
Source		- - - - - - - - - -	- - - - - - - - - -	- - - - - - - - - -	Pr > F	- - - - - - - - - -	- - - - - - - - - -	- - - - - - - - - -	- - - - - - - - - -
	REP	0.2391	0.6637	0.0264	0.0042	-	-	0.7356	0.2082
	Cultivar	0.0097*	<0.0001*	0.0001*	<0.0001*	-	-	<0.0001*	0.0073*
	C.V.	10.45	3.14	6.88	3.83	-	-	21.89	32.13

*Results are significant at the *p*=0.05 level.

Table 2.8. Results and analysis of variance results for total dry biomass, plant moisture, above-ground nodes, plant height, juice yield, brix, grain heads, and grain yield of different feedstocks at Manhattan, KS in 2009.

		Total Dry Biomass	Plant Moisture	Above-ground Nodes	Plant Height	Juice Yield	Brix	Grain Heads	Grain Yield
		Mg ha^{-1}	%	# plant^{-1}	m	L ha^{-1}	%	# ha^{-1}	kg ha^{-1}
Cultivar									
	22053	9.5	69.5	13.0	3.2	-	-	99 527	140
	Graze All 3	7.1	63.0	10.4	2.5	-	-	121 046	1264
	Graze-N-Bale	12.3	67.5	11.3	2.6	-	-	-	-
	M81E	11.2	72.0	12.0	3.1	12 491	13.6	92 533	617
	Sugar T	11.9	66.0	13.6	3.6	10 682	16.0	68 862	694
	TAMUXH08001	13.2	63.3	10.4	2.8	-	-	97 554	387
	LSD	NS	NS	2.1	0.6	NS	1.6	NS	NS
Source					Pr > F				
	Rep	0.3742	0.4162	0.2612	0.8369	0.2910	0.4946	0.9090	0.4957
	Treatment	0.2802	0.2064	0.0214*	0.0085*	0.3791	0.0175*	0.7148	0.0667
	C.V.	34.60	8.22	11.78	12.20	21.46	4.71	53.30	79.16

*Results are significant at the *p*=0.05 level.

Chapter 2 – Figures

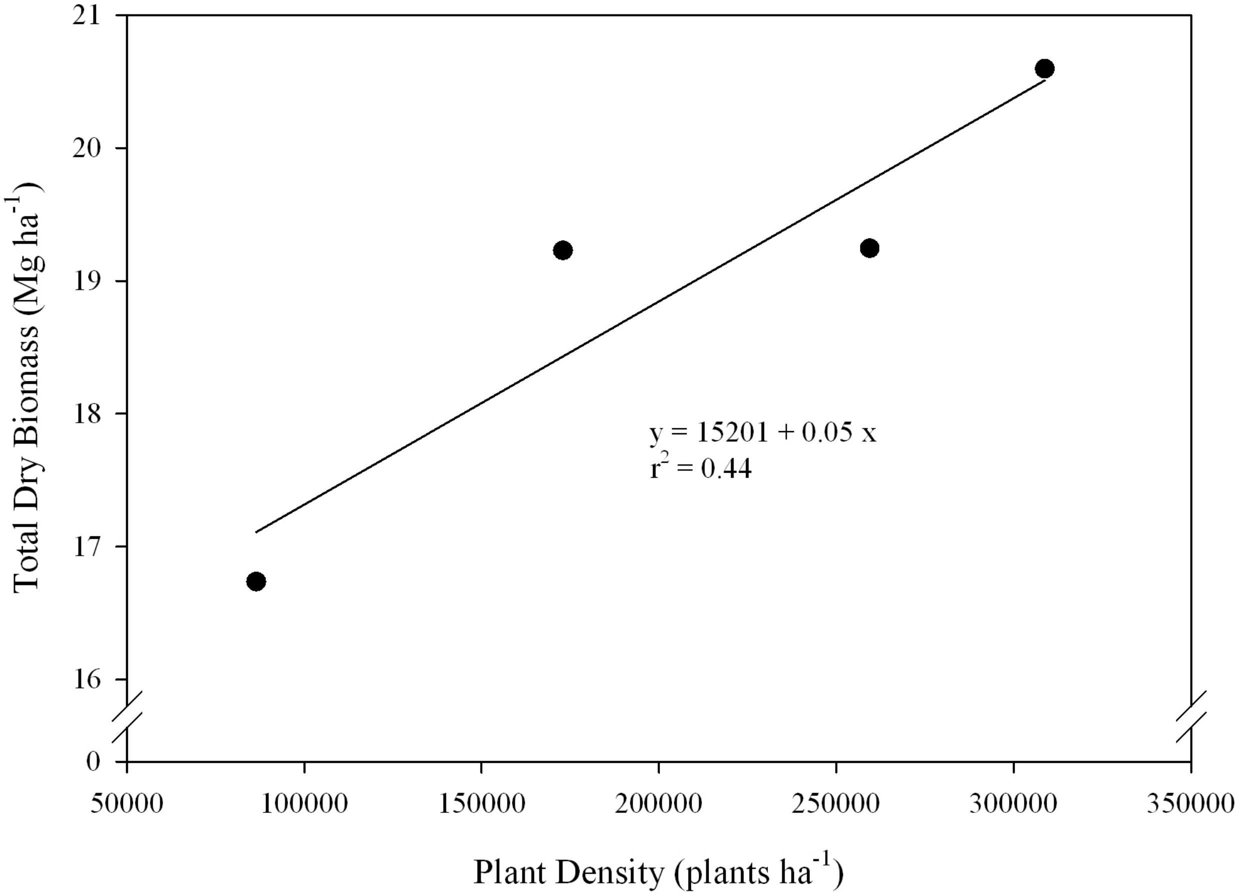

Figure 2.1. Relation of total dry biomass to plant density of photoperiod sensitive sorghum at Belleville in 2008.

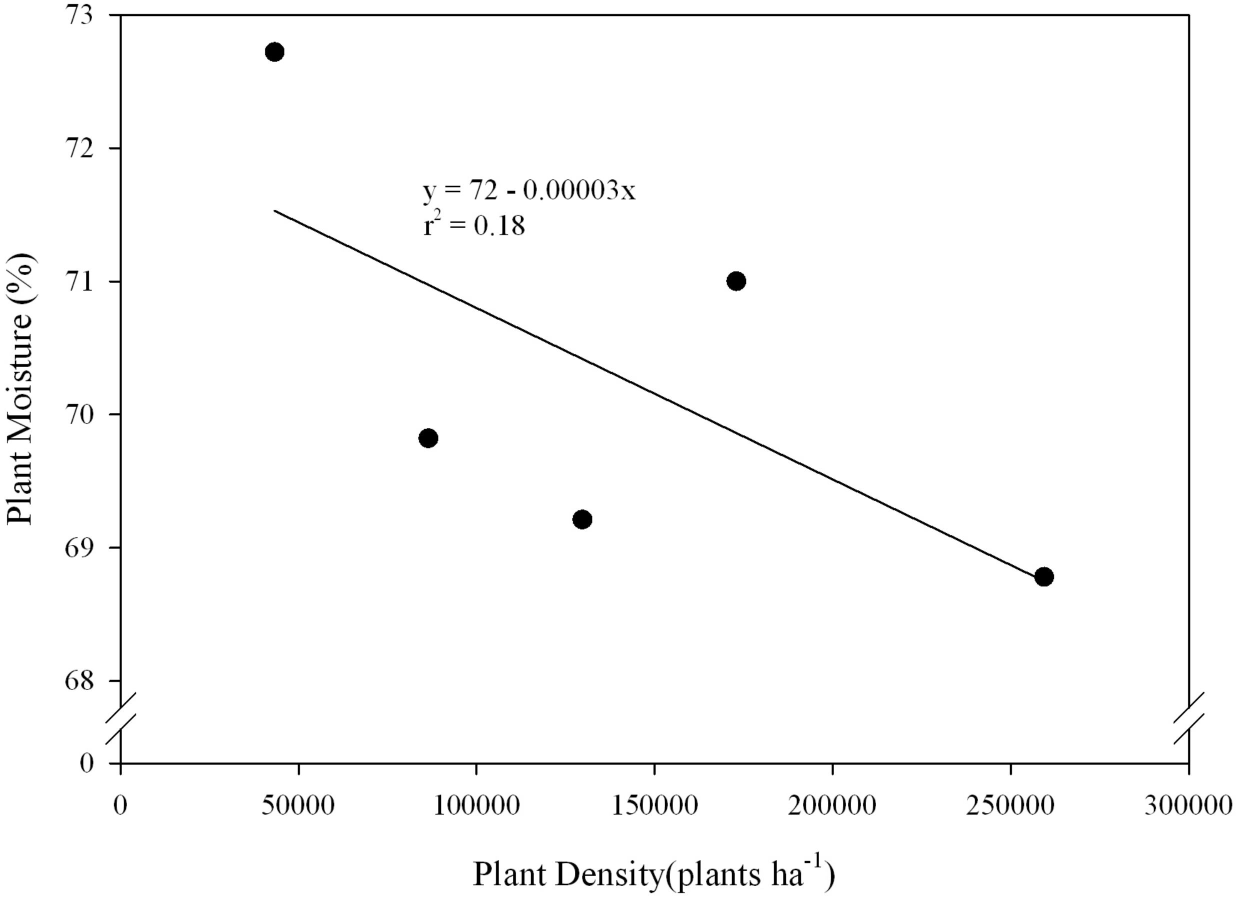

Figure 2.2. Relation plant moisture to photoperiod sensitive sorghum plant density at Belleville in 2009.

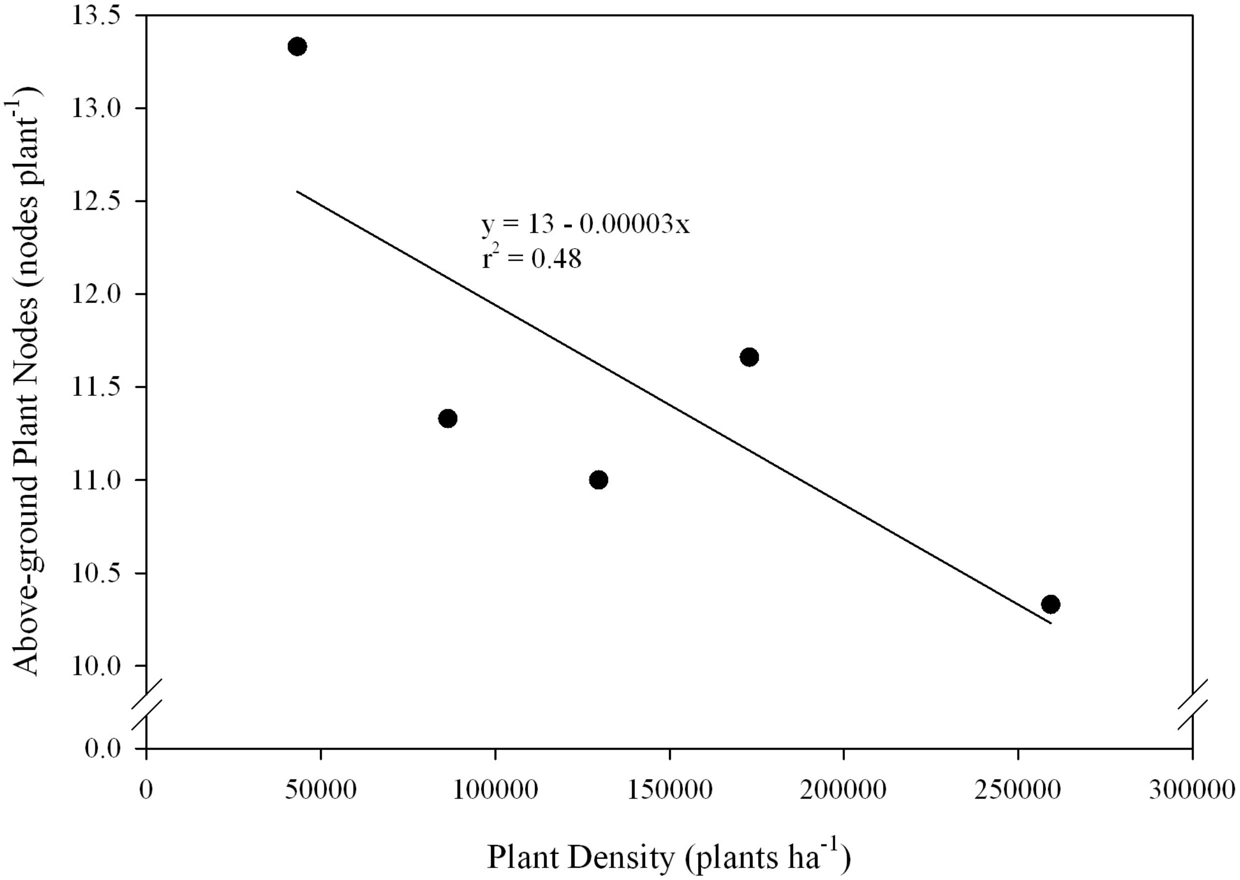

Figure 2.3. Relation of above-ground node number to plant density of photoperiod sensitive sorghum at Belleville in 2009.

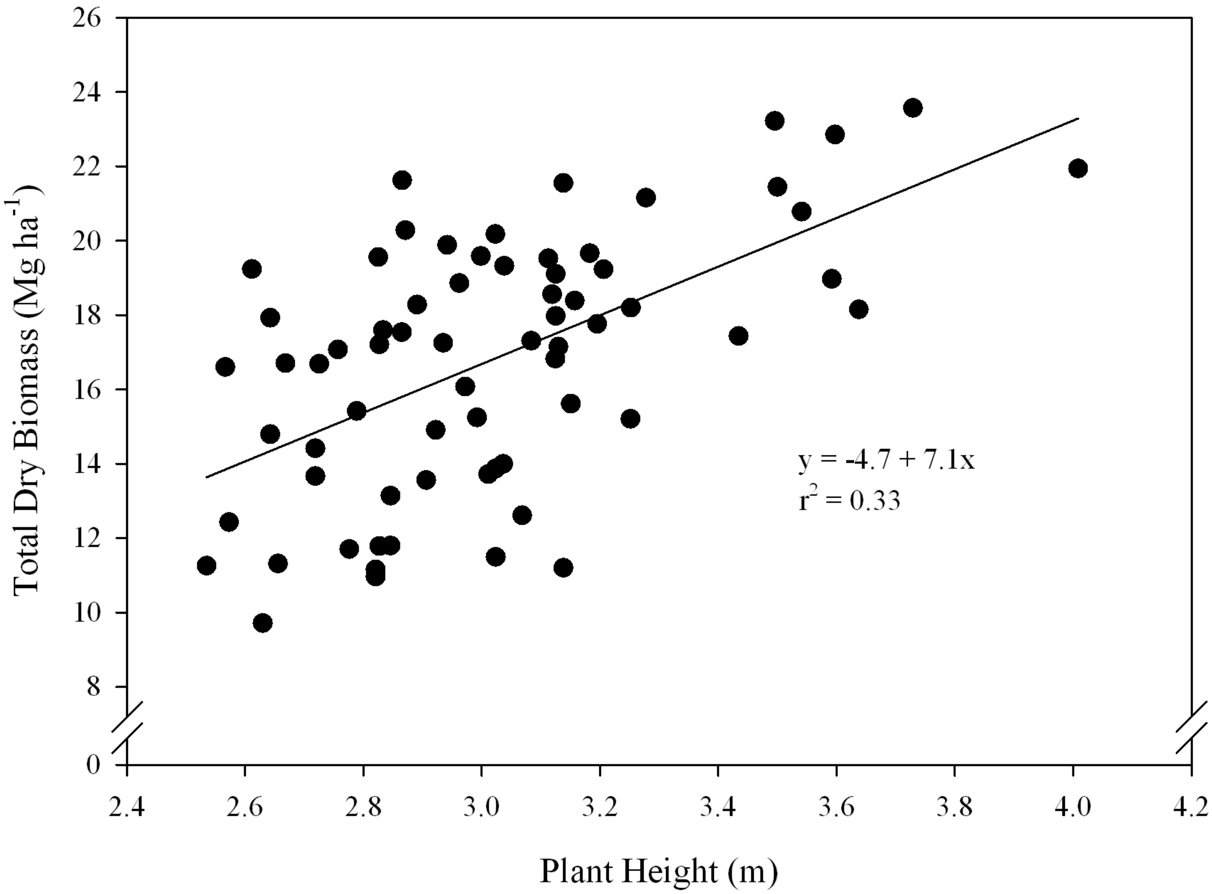

Figure 2.4. Relation of total dry biomass to plant height of photoperiod sensitive sorghum at Manhattan and Belleville in 2008 and 2009.

Appendix Table 1. Riley & Republic County Sweet Sorghum Variety Trial 2008 & 2009

Year	Location	Plot #	Treatment	Plant Moisture	Total Dry Biomass	Grain Heads	Grain Yield	Juice Yield	Brix	Above-Ground Nodes	Plant Height
				%	Mg ha^{-1}	# ha^{-1}	kg ha^{-1}	L ha^{-1}	%	# plant^{-1}	m
2008	Manhattan	101	XH007	73.2	16.1	147826	4920	13084	12.5	11.0	2.9
2008	Manhattan	102	XH012	73.3	16.6	121739	4620	13380	10.1	10.0	2.9
2008	Manhattan	103	XH019	67.4	21.5	93478	5213	14802	15.9	10.5	2.9
2008	Manhattan	104	XH011	73.5	18.0	141304	3850	18289	13.1	10.5	2.9
2008	Manhattan	105	XH001	76.6	16.6	160870	4494	16661	11.5	9.8	3.1
2008	Manhattan	106	M81E	76.3	25.3	115217	2286	34668	13.1	12.8	3.8
2008	Manhattan	201	XH007	73.3	18.2	167391	4920	13936	13.3	10.0	2.8
2008	Manhattan	202	XH011	75.7	17.2	184783	4739	16489	12.4	10.8	3.1
2008	Manhattan	203	XH012	75.1	16.2	145652	3570	15471	12.9	10.8	2.9
2008	Manhattan	204	XH019	71.2	21.8	202174	4704	21271	12.0	10.3	2.9
2008	Manhattan	205	M81E	76.6	24.7	110870	2331	33355	11.1	13.0	3.9
2008	Manhattan	206	XH001	76.0	14.4	123913	4619	14949	11.1	10.3	2.9
2008	Manhattan	301	M81E	77.8	25.9	117391	3022	34432	11.8	15.3	4.0
2008	Manhattan	302	XH001	74.1	12.4	100000	3403	10427	7.8	9.8	2.9
2008	Manhattan	303	XH007	71.6	17.0	158696	4804	12276	9.8	9.3	2.8
2008	Manhattan	304	XH011	73.2	16.0	123913	4180	12678	11.0	10.5	2.8
2008	Manhattan	305	XH012	73.6	13.5	86957	2407	12125	12.7	11.0	3.1
2008	Manhattan	306	XH019	72.2	16.6	89130	2780	12443	13.8	10.3	2.9
2008	Manhattan	401	XH007	76.4	14.2	152174	4151	13545	13.0	11.0	3.0
2008	Manhattan	402	XH001	75.6	17.5	167391	4879	17743	9.0	10.0	2.8
2008	Manhattan	403	M81E	78.0	23.8	132609	2681	31761	11.9	15.0	4.2
2008	Manhattan	404	XH012	78.5	14.9	128261	2895	17102	9.6	11.0	3.0
2008	Manhattan	405	XH019	75.5	15.5	158696	4142	13047	12.2	10.8	2.9
2008	Manhattan	406	XH011	75.7	13.6	165217	3688	14601	10.1	9.3	2.7
2008	Belleville	101	XH001	74.0	16.1	130435	2897	13297	3.8	11.3	2.8
2008	Belleville	102	XH011	72.7	19.1	132609	2028	15990	10.1	11.8	2.8
2008	Belleville	103	XH019	74.5	12.9	130435	2093	12069	10.3	11.3	2.7
2008	Belleville	104	M81E	82.6	15.3	121739	589	30528	7.7	14.8	3.4
2008	Belleville	105	XH007	70.9	17.9	108696	1507	15620	12.5	10.5	2.8
2008	Belleville	106	XH012	72.2	14.3	108696	825	12408	10.4	10.8	2.7
2008	Belleville	201	XH019	74.3	15.3	130435	2028	13555	4.3	11.0	2.8
2008	Belleville	202	M81E	81.5	16.9	139130	646	32003	9.7	14.8	3.6

Appendix Table 1. Riley & Republic County Sweet Sorghum Variety Trial 2008 & 2009

Year	Location	Plot #	Treatment	Plant Moisture	Total Dry Biomass	Grain Heads	Grain Yield	Juice Yield	Brix	Above-Ground Nodes	Plant Height
				%	Mg ha^{-1}	# ha^{-1}	kg ha^{-1}	L ha^{-1}	%	# plant^{-1}	m
2008	Belleville	203	XH001	72.8	19.7	130435	3243	17494	8.3	11.5	2.8
2008	Belleville	204	XH011	73.9	18.6	141304	2859	17341	6.4	10.8	2.9
2008	Belleville	205	XH007	75.5	16.9	173913	3517	17667	6.5	11.5	2.8
2008	Belleville	206	XH012	74.3	16.9	141304	2921	14902	11.0	11.0	2.8
2008	Belleville	301	XH001	75.2	16.5	156522	3195	16838	8.9	12.3	2.9
2008	Belleville	302	XH019	74.2	16.8	152174	2252	20129	11.3	11.5	2.9
2008	Belleville	303	XH007	73.2	15.8	121739	2076	14995	10.5	11.8	2.7
2008	Belleville	304	XH012	76.2	16.2	154348	3173	15913	5.2	12.0	2.9
2008	Belleville	305	XH011	74.2	15.7	121739	2225	16135	9.1	12.0	3.0
2008	Belleville	306	M81E	82.1	18.1	163043	894	33443	9.6	15.3	3.6
2009	Manhattan	101	M81-E	80.0	17.7	-	11	22702	15.1	11.3	3.65
2009	Manhattan	102	TX09017	80.1	9.8	-	158	12106	13.0	11.3	3.39
2009	Manhattan	103	TX09020	74.9	13.8	-	38	13321	18.3	10.0	3.80
2009	Manhattan	104	TX09023	70.2	12.3	-	291	4282	18.1	9.3	2.90
2009	Manhattan	105	TX09021	75.1	6.9	-	467	7655	16.1	10.5	3.43
2009	Manhattan	201	TX09021	74.9	11.4	-	224	9324	16.2	9.8	3.18
2009	Manhattan	202	TX09017	74.9	12.3	-	260	15236	16.9	9.8	3.26
2009	Manhattan	203	TX09023	78.4	10.6	-	356	15248	14.6	10.0	3.13
2009	Manhattan	204	TX09020	79.5	19.3	-	23	30010	15.4	9.8	3.94
2009	Manhattan	205	M81-E	83.5	16.5	-	25	38410	12.2	12.3	3.64
2009	Manhattan	301	TX09023	75.9	13.9	-	226	14023	16.0	11.8	3.37
2009	Manhattan	302	TX09017	76.7	9.7	-	136	10932	15.4	7.8	2.66
2009	Manhattan	303	TX09020	79.7	11.7	-	31	15286	13.6	10.5	3.42
2009	Manhattan	304	TX09021	74.5	8.0	-	396	5435	14.2	10.8	3.46
2009	Manhattan	305	M81-E	80.8	16.9	-	22	38286	15.1	13.0	3.76
2009	Manhattan	401	M81-E	79.1	15.5	-	1142	25006	16.4	12.0	3.65
2009	Manhattan	402	TX09021	79.8	10.8	-	1496	14220	11.3	10.3	3.27
2009	Manhattan	403	TX09023	76.6	17.4	-	3459	20860	15.1	13.0	3.42
2009	Manhattan	404	TX09020	79.7	16.4	-	157	23943	15.1	11.3	3.59
2009	Manhattan	405	TX09017	79.0	15.7	-	1595	21152	14.7	12.3	3.35
2009	Belleville	101	TX09023	75.2	15.4	124808.112	3200	13355	15.8	8.8	2.77
2009	Belleville	102	TX09020	80.8	13.2	107593.2	676	19672	15.1	9.8	3.06

Appendix Table 1. Riley & Republic County Sweet Sorghum Variety Trial 2008 & 2009

Year	Location	Plot #	Treatment	Plant Moisture	Total Dry Biomass	Grain Heads	Grain Yield	Juice Yield	Brix	Above-Ground Nodes	Plant Height
				%	Mg ha^{-1}	# ha^{-1}	kg ha^{-1}	L ha^{-1}	%	# plant^{-1}	m
2009	Belleville	103	TX09017	78.7	12.7	159237.936	2241	15278	17.0	8.3	2.54
2009	Belleville	104	TX09021	78.0	12.0	140588.448	2685	12862	15.6	9.5	2.92
2009	Belleville	105	M81-E	81.6	13.2	113331.504	410	21439	13.4	11.3	3.37
2009	Belleville	201	TX09017	78.6	11.8	139153.872	3468	12883	16.4	9.0	2.67
2009	Belleville	202	TX09021	79.0	10.6	114766.08	2511	11563	14.7	10.5	2.95
2009	Belleville	203	TX09020	81.5	12.8	76032.528	598	20074	12.4	9.3	2.71
2009	Belleville	204	TX09023	77.7	12.3	106158.624	2917	12869	15.8	9.0	2.79
2009	Belleville	205	M81-E	81.5	14.5	142023.024	489	27570	13.9	11.5	3.19
2009	Belleville	301	M81-E	80.7	14.4	152065.056	565	16843	13.5	8.5	2.84
2009	Belleville	302	TX09021	79.7	10.6	101854.896	3153	13906	13.3	9.5	2.94
2009	Belleville	303	TX09020	79.6	13.5	117635.232	583	20590	16.0	10.0	3.11
2009	Belleville	304	TX09023	74.8	13.8	137719.296	3110	13030	16.4	8.8	2.47
2009	Belleville	305	TX09017	76.5	13.7	152065.056	2772	11283	18.8	7.5	2.56

Appendix Table 2. Riley & Republic County Sweet Sorghum Nitrogen Rate Trial 2008 & 2009

Year	Location	Plot #	Treatment	Plant Moisture	Total Dry Biomass	Grain Heads	Grain Yield	Juice Yield	Brix	Above-Ground Nodes	Plant Height
				%	Mg ha^{-1}	# ha^{-1}	kg ha^{-1}	L ha^{-1}	%	# plant^{-1}	m
2008	Manhattan	101	0	77.3	21.8	191304	1875	27103	11.3	13.3	3.8
2008	Manhattan	102	135	73.4	28.7	180435	3321	33642	13.2	13.3	3.6
2008	Manhattan	103	180	77.9	25.3	200000	3032	37177	10.4	12.0	3.8
2008	Manhattan	104	45	75.8	24.3	167391	2158	31224	12.2	11.8	3.3
2008	Manhattan	105	90	75.4	24.9	160870	1308	30098	12.5	13.0	3.6
2008	Manhattan	201	135	74.4	27.5	156522	2875	34552	12.7	12.3	3.8
2008	Manhattan	202	45	75.6	27.5	189130	2927	35921	13.0	14.3	3.9
2008	Manhattan	203	90	75.5	25.1	173913	2298	33021	14.0	12.0	3.6
2008	Manhattan	204	180	77.4	25.9	163043	3197	36469	11.0	13.0	3.8
2008	Manhattan	205	0	73.7	27.0	132609	909	32120	15.0	14.0	3.8
2008	Manhattan	301	0	72.8	22.6	167391	1490	19848	13.0	12.8	3.5
2008	Manhattan	302	45	75.4	20.9	173913	2125	24858	11.4	12.3	3.4
2008	Manhattan	303	90	74.9	32.3	232609	4140	40147	13.3	14.3	3.6
2008	Manhattan	304	180	71.7	33.6	173913	3046	35649	16.2	13.0	3.7
2008	Manhattan	305	135	75.4	29.0	182609	3091	35726	12.5	12.3	3.5
2008	Manhattan	401	135	74.3	35.9	193478	3848	43460	13.4	13.3	3.8
2008	Manhattan	402	0	73.2	31.3	154348	2213	30686	13.7	12.8	3.6
2008	Manhattan	403	180	72.9	30.5	89130	1244	31367	13.0	13.8	3.7
2008	Manhattan	404	45	73.1	27.0	108696	1761	26808	13.3	12.5	3.6
2008	Manhattan	405	90	75.8	30.8	178261	3750	33590	11.1	11.5	3.8
2009	Manhattan	101	135	83.1	17.9	120504	1541	39277	13.0	15.5	4.1
2009	Manhattan	102	0	82.8	17.5	111897	1945	37546	12.4	15.8	4.3
2009	Manhattan	103	180	81.0	20.9	131981	2061	38763	12.6	12.8	4.0
2009	Manhattan	104	45	81.5	18.1	104724	990	44674	12.3	15.8	4.4
2009	Manhattan	105	90	83.2	18.2	124808	1806	35559	13.0	14.3	3.9
2009	Manhattan	201	0	82.8	16.8	114766	1795	38965	12.0	14.8	3.8
2009	Manhattan	202	45	84.2	15.8	120504	1727	39817	11.9	15.3	4.2
2009	Manhattan	203	180	83.0	15.3	93247	1252	33020	12.2	15.5	4.0
2009	Manhattan	204	135	83.3	18.6	130546	1760	44036	12.6	15.5	4.1
2009	Manhattan	205	90	81.7	20.0	133416	2235	30041	13.2	15.0	4.2
2009	Manhattan	301	135	83.6	18.0	110462	1437	39288	11.6	14.5	4.2
2009	Manhattan	302	180	83.1	19.1	117635	1754	36449	11.6	14.8	4.2

Appendix Table 2. Riley & Republic County Sweet Sorghum Nitrogen Rate Trial 2008 & 2009

Year	Location	Plot #	Treatment	Plant Moisture	Total Dry Biomass	Grain Heads	Grain Yield	Juice Yield	Brix	Above-Ground Nodes	Plant Height
				%	Mg ha^{-1}	# ha^{-1}	kg ha^{-1}	L ha^{-1}	%	# plant^{-1}	m
2009	Manhattan	303	0	82.2	18.8	100420	1884	33738	12.3	14.8	4.4
2009	Manhattan	304	45	83.3	19.3	124808	2353	35072	12.0	14.8	4.2
2009	Manhattan	305	90	83.1	18.7	109028	2139	40202	12.5	14.0	4.2
2009	Manhattan	401	0	76.8	21.3	109028	2211	37800	12.4	14.0	4.2
2009	Manhattan	402	180	83.1	19.0	127677	1717	39224	11.2	14.3	4.1
2009	Manhattan	403	90	82.8	21.1	134850	2023	39176	11.6	14.3	4.1
2009	Manhattan	404	45	82.4	19.9	121939	1814	38104	12.7	14.8	4.1
2009	Manhattan	405	135	82.4	19.3	130546	1727	34313	12.6	13.8	4.0
2009	Belleville	101	135	82.1	14.5	110462	-	25714	12.5	12.3	3.3
2009	Belleville	102	180	82.2	13.7	110462	-	23819	12.2	12.3	3.3
2009	Belleville	103	90	82.5	12.8	91813	-	24714	13.3	11.8	3.3
2009	Belleville	104	45	82.2	14.9	109028	-	27254	12.7	11.0	3.3
2009	Belleville	105	0	82.8	14.3	113332	-	27836	11.8	12.3	3.3
2009	Belleville	201	180	81.0	15.4	109028	-	27563	13.0	12.8	3.3
2009	Belleville	202	45	80.2	14.9	106159	-	24707	13.6	12.0	3.1
2009	Belleville	203	90	81.6	13.5	114766	-	22584	12.6	11.8	3.1
2009	Belleville	204	0	80.6	13.3	110462	-	19819	13.0	11.0	2.9
2009	Belleville	205	135	81.4	13.7	114766	-	21863	12.6	12.0	3.1
2009	Belleville	301	90	79.7	12.7	84640	-	18017	13.7	9.8	2.6
2009	Belleville	302	45	80.0	12.9	114766	-	17609	14.4	11.5	2.9
2009	Belleville	303	135	80.3	13.4	113332	-	18331	13.9	11.0	2.8
2009	Belleville	304	180	78.3	16.4	120504	-	21692	14.7	10.5	2.9
2009	Belleville	305	0	80.1	14.3	110462	-	20939	14.2	10.5	3.0

Appendix Table 3. Riley & Republic County Sweet Sorghum Plant Density Trial 2008 & 2009

Year	Location	Plot #	Treatment	Plant Moisture	Total Dry Biomass	Grain Heads	Grain Yield	Juice Yield	Brix	Above-Ground Nodes	Plant Height
				%	Mg ha^{-1}	# ha^{-1}	kg ha^{-1}	L ha^{-1}	%	# plant^{-1}	m
2008	Manhattan	101	260000	76.3	25.3	115217	2286	34668	13.1	12.8	3.8
2008	Manhattan	102	173000	77.6	20.7	100000	2101	28646	9.4	15.5	4.2
2008	Manhattan	103	309000	77.0	29.5	210870	3212	38710	10.8	13.5	3.9
2008	Manhattan	104	87000	76.1	25.0	102174	2122	32813	11.4	14.3	4.0
2008	Manhattan	201	260000	76.6	24.7	110870	2331	33355	11.1	13.0	3.9
2008	Manhattan	202	309000	76.4	28.9	184783	3591	35539	10.5	13.0	3.7
2008	Manhattan	203	87000	76.2	22.6	89130	2409	29268	11.2	15.3	4.0
2008	Manhattan	204	173000	76.9	24.4	117391	2115	29847	10.3	14.8	3.9
2008	Manhattan	301	309000	76.9	24.6	141304	2955	31047	10.4	14.3	3.9
2008	Manhattan	302	173000	77.0	25.6	143478	2493	33120	11.4	13.5	3.9
2008	Manhattan	303	260000	77.8	25.9	117391	3022	34432	11.8	15.3	4.0
2008	Manhattan	304	87000	76.9	21.8	89130	2439	32515	9.9	15.5	3.9
2008	Manhattan	401	309000	78.4	20.6	150000	2355	25293	6.7	14.0	3.4
2008	Manhattan	402	173000	76.8	20.1	102174	2402	26190	12.8	15.5	3.9
2008	Manhattan	403	87000	79.8	17.7	65217	1265	32754	10.9	14.5	3.9
2008	Manhattan	404	260000	78.0	23.8	132609	2681	31761	11.9	15.0	4.2
2008	Manhattan	101	260000	81.5	22.7	178261	1014	40726	10.4	13.3	3.4
2008	Manhattan	102	173000	82.6	15.3	121739	589	30528	7.7	14.8	3.4
2008	Manhattan	103	87000	81.4	17.6	117391	786	34662	13.3	15.0	3.5
2008	Manhattan	104	309000	79.4	25.4	234783	1277	40051	7.4	14.3	3.2
2008	Manhattan	201	173000	81.5	16.9	139130	646	32003	9.7	14.8	3.6
2008	Manhattan	202	260000	81.2	18.7	121739	688	35040	10.5	14.5	3.5
2008	Manhattan	203	309000	81.9	19.4	182609	863	34833	7.8	13.3	3.3
2008	Manhattan	204	87000	78.8	20.4	115217	826	39441	13.2	14.8	3.7
2008	Manhattan	301	309000	78.2	21.6	186957	920	34444	11.3	13.5	3.3
2008	Manhattan	302	173000	82.1	18.1	163043	894	33443	9.6	15.3	3.6
2008	Manhattan	303	260000	80.5	20.4	202174	906	35400	11.0	14.3	3.4
2008	Manhattan	304	87000	81.5	16.0	106522	539	31401	9.9	15.5	3.5
2009	Manhattan	101	173000	83.4	16.6	134850		36746	12.8	14.5	4.1
2009	Manhattan	102	260000	82.4	16.8	203710		33700	12.9	12.0	3.8
2009	Manhattan	103	87000	83.5	17.8	110462		40732	12.0	12.3	3.7
2009	Manhattan	104	130000	83.6	19.7	139154		40910	12.8	13.5	4.1

Appendix Table 3. Riley & Republic County Sweet Sorghum Plant Density Trial 2008 & 2009

Year	Location	Plot #	Treatment	Plant Moisture	Total Dry Biomass	Grain Heads	Grain Yield	Juice Yield	Brix	Above-Ground Nodes	Plant Height
				%	Mg ha^{-1}	# ha^{-1}	kg ha^{-1}	L ha^{-1}	%	# plant^{-1}	m
2009	Manhattan	105	43000	82.1	24.4	134850		50213	11.8	14.3	4.0
2009	Manhattan	201	87000	83.2	17.6	126243		35251	12.0	16.5	4.1
2009	Manhattan	202	260000	82.0	22.9	235270		45088	13.1	15.0	3.9
2009	Manhattan	203	43000	83.6	15.7	126243		37786	11.3	14.5	3.9
2009	Manhattan	204	173000	83.1	19.3	160673		44303	12.9	16.3	4.1
2009	Manhattan	205	130000	81.6	18.7	104724		39324	12.9	15.8	4.1
2009	Manhattan	301	173000	82.3	20.4	124808		39372	10.9	13.5	4.0
2009	Manhattan	302	260000	81.5	24.2	253920		34591	12.7	13.5	3.9
2009	Manhattan	303	130000	82.7	21.3	142023		42694	12.5	14.8	4.0
2009	Manhattan	304	87000	82.8	18.6	101855		38760	11.8	13.3	4.0
2009	Manhattan	305	43000	84.1	19.2	140588		42079	11.2	14.8	4.1
2009	Manhattan	401	260000	82.3	23.5	200841		33050	11.4	10.8	3.6
2009	Manhattan	402	130000	83.4	19.8	131981		40218	11.6	13.0	4.2
2009	Manhattan	403	173000	82.9	22.5	139154		42626	12.4	13.8	4.0
2009	Manhattan	404	87000	83.3	18.8	121939		38429	11.7	13.8	4.1
2009	Manhattan	405	43000	83.4	20.3	136285		37557	11.1	13.0	4.1
2009	Belleville	101	87000	82.3	12.6	106159		24526	12.0	12.0	3.3
2009	Belleville	102	43000	82.6	12.4	86075		25898	11.0	12.3	3.4
2009	Belleville	103	130000	82.3	12.3	88944		23526	13.0	12.3	3.2
2009	Belleville	104	173000	83.8	11.3	91813		23253	11.4	12.8	3.3
2009	Belleville	105	260000	80.5	16.5	142023		28120	12.0	11.5	3.3
2009	Belleville	201	130000	80.7	14.4	133416		23641	12.8	10.8	3.0
2009	Belleville	202	87000	81.0	13.6	98986		24221	12.4	11.8	3.2
2009	Belleville	203	43000	82.5	9.5	80336		18663	11.4	11.8	3.1
2009	Belleville	204	260000	79.1	17.2	206579		23553	12.8	9.8	2.9
2009	Belleville	205	173000	79.4	14.8	110462		27047	14.3	11.5	3.2
2009	Belleville	301	43000	81.3	11.1	78902		20488	15.3	12.5	2.9
2009	Belleville	302	130000	79.7	13.3	116201		18615	15.3	9.8	2.8
2009	Belleville	303	87000	81.2	11.6	113332		20351	12.7	12.3	3.1
2009	Belleville	304	173000	81.1	13.2	146327		21321	15.7	10.0	2.9
2009	Belleville	305	260000	79.6	14.9	215186		20677	14.0	10.3	2.8

Appendix Table 4. Riley & Republic County Photoperiod Sensitive Sorghum Plant Density Trial 2008 & 2009

Year	Location	Plot #	Treatment	Total Dry Biomass	Plant Moisture	Above-Ground Nodes	Plant Height
				Mg ha^{-1}	%	# $plant^{-1}$	m
2008	Manhattan	101	260000	20.8	70.0	14.2	3.5
2008	Manhattan	102	173000	19.0	70.5	14.6	3.6
2008	Manhattan	103	309000	17.1	71.8	12.4	3.1
2008	Manhattan	104	87000	18.2	68.6	13.4	3.6
2008	Manhattan	201	87000	17.4	70.4	15.4	3.4
2008	Manhattan	202	260000	23.2	68.4	12.8	3.5
2008	Manhattan	203	173000	15.2	70.2	12.2	3.3
2008	Manhattan	204	309000	22.9	68.5	16.0	3.6
2008	Manhattan	301	173000	21.9	67.5	15.2	4.0
2008	Manhattan	302	309000	23.6	69.1	13.6	3.7
2008	Manhattan	303	260000	19.2	69.0	13.4	3.2
2008	Manhattan	304	87000	13.6	69.4	12.8	2.9
2008	Belleville	101	260000	18.9	71.2	13.0	3.0
2008	Belleville	102	173000	19.2	67.7	10.4	2.6
2008	Belleville	103	87000	17.3	71.1	14.4	3.1
2008	Belleville	104	309000	21.6	67.0	12.6	2.9
2008	Belleville	201	87000	16.1	71.1	14.4	3.0
2008	Belleville	202	260000	19.3	70.8	12.6	3.0
2008	Belleville	203	173000	20.2	66.3	12.6	3.0
2008	Belleville	204	309000	20.3	67.5	11.0	2.9
2008	Belleville	301	173000	18.3	70.0	12.2	2.9
2008	Belleville	302	87000	16.8	71.0	14.6	3.1
2008	Belleville	303	260000	19.6	68.1	10.2	2.8
2008	Belleville	304	309000	19.9	67.6	10.6	2.9
2009	Manhattan	101	130000	15.2	73.8	12.8	3.0
2009	Manhattan	102	260000	13.7	77.7	10.5	3.0
2009	Manhattan	103	173000	9.7	76.0	9.3	2.6
2009	Manhattan	104	43000	17.2	68.7	12.0	2.8
2009	Manhattan	105	87000	19.6	67.9	10.8	3.0
2009	Manhattan	201	87000	21.4	68.0	11.0	3.5
2009	Manhattan	202	43000	18.0	69.2	11.5	3.1
2009	Manhattan	203	260000	17.6	68.6	9.5	2.8
2009	Manhattan	204	173000	18.6	68.1	11.0	3.1
2009	Manhattan	205	130000	19.1	68.7	10.8	3.1
2009	Manhattan	301	130000	21.2	68.5	11.5	3.3
2009	Manhattan	302	43000	15.6	66.3	12.3	3.2
2009	Manhattan	303	173000	18.4	69.6	11.0	3.2
2009	Manhattan	304	87000	18.2	68.9	10.8	3.3
2009	Manhattan	305	260000	17.1	68.9	10.0	2.8
2009	Manhattan	401	173000	19.7	68.1	11.5	3.2
2009	Manhattan	402	43000	19.5	66.7	11.5	3.1
2009	Manhattan	403	260000	21.5	66.9	9.5	3.1
2009	Manhattan	404	130000	17.8	67.4	12.3	3.2
2009	Manhattan	405	87000	17.2	60.3	12.5	2.9
2009	Belleville	101	260000	11.7	70.5	10.3	2.8
2009	Belleville	102	173000	11.8	71.6	10.8	2.8

Appendix Table 4. Riley & Republic County Photoperiod Sensitive Sorghum Plant Density Trial 2008 & 2009

Year	Location	Plot #	Treatment	Total Dry Biomass	Plant Moisture	Above-Ground Nodes	Plant Height
				Mg ha^{-1}	%	# $plant^{-1}$	m
2009	Belleville	103	130000	11.8	70.8	10.5	2.8
2009	Belleville	104	87000	11.2	71.6	11.8	2.8
2009	Belleville	105	43000	11.0	73.1	12.8	2.8
2009	Belleville	201	43000	11.2	74.1	14.0	3.1
2009	Belleville	202	87000	14.0	71.6	12.0	3.0
2009	Belleville	203	173000	12.6	72.2	12.3	3.1
2009	Belleville	204	260000	13.1	69.6	10.8	2.8
2009	Belleville	205	130000	11.5	69.9	11.5	3.0
2009	Belleville	301	43000	11.3	71.0	13.3	2.7
2009	Belleville	302	260000	15.4	66.2	10.0	2.8
2009	Belleville	303	87000	14.4	66.2	10.3	2.7
2009	Belleville	304	173000	13.9	69.1	12.0	3.0
2009	Belleville	305	130000	14.9	67.0	11.0	2.9

Appendix Table 5. Riley Regional Sorghum Feedstock Trial 2008 & 2009

Year	Plot #	Treatment	Plant Moisture	Total Dry Biomass	Grain Heads	Grain Yield	Juice Yield	Brix	Above-Ground Nodes	Plant Height
			%	Mg ha^{-1}	# ha^{-1}	kg ha^{-1}	L ha^{-1}	%	# plant^{-1}	m
2008	101	Graze-N-Bale	73.1	21.5	-	-	-	-	15.5	3.5
2008	102	22053	61.7	18.2	110473	1617	-	-	14.3	3.6
2008	103	GrazeAll3	63.7	12.8	185079	1321	-	-	10.3	3.1
2008	104	SugarT	76.5	16.7	32999	355	22394	9.7	13.0	3.4
2008	201	Graze-N-Bale	76.0	18.2	-	-	-	-	14.0	3.5
2008	202	SugarT	75.7	13.7	22956	999	19605	8.4	13.0	3.7
2008	203	22053	64.3	15.3	83214	1219	-	-	14.3	3.7
2008	204	GrazeAll3	60.7	15.0	265423	2434	-	-	9.0	2.8
2008	301	Graze-N-Bale	73.3	21.2	-	-	-	-	15.0	3.4
2008	302	22053	62.6	18.9	114778	2673	-	-	12.5	3.2
2008	303	GrazeAll3	58.4	16.3	252511	2848	-	-	10.0	2.8
2008	304	SugarT	80.2	13.3	18651	558	17838	9.8	11.5	3.3
2008	401	Graze-N-Bale	72.8	16.9	-	-	-	-	11.5	3.2
2008	402	SugarT	80.5	15.4	34433	321	24569	12.5	11.8	3.2
2008	403	22053	64.7	14.9	97561	1394	-	-	12.5	3.2
2008	404	GrazeAll3	63.5	14.1	268293	2233	-	-	8.3	2.4
2009	101	GrazeAll3	68.2	4.4	133419	1501	-	-	8.8	2.2
2009	102	M81-E	79.0	7.4	215193	1692	10575	13.2	9.5	2.6
2009	103	22053	70.9	9.9	90381	129	-	-	13.0	3.3
2009	104	Graze-n-Bale	58.4	8.6	-	-	-	-	9.8	2.3
2009	105	SugarT	65.0	13.9	94685	815	12003	15.6	14.5	3.7
2009	106	TAMUXH08001	67.4	18.1	17215	129	-	-	10.3	3.1
2009	201	Graze-n-Bale	72.5	15.4	-	-	-	-	12.3	3.0
2009	202	GrazeAll3	70.2	6.1	98989	821	-	-	10.8	2.7
2009	203	22053	72.6	6.0	96837	129	-	-	11.5	3.0
2009	204	TAMUXH08001	64.2	8.5	131267	430	-	-	9.3	2.5
2009	205	SugarT	67.0	13.9	51646	904	12800	16.3	13.0	3.5
2009	206	M81-E	70.0	13.7	68862	258	14353	12.7	12.3	3.5
2009	301	GrazeAll3	51.0	10.5	126964	2218	-	-	9.0	2.2
2009	302	M81-E	71.0	14.5	38735	258	16676	13.7	13.0	3.2
2009	303	22053	70.5	12.1	122660	215	-	-	14.5	3.7
2009	304	Graze-n-Bale	66.3	11.1	-	-	-	-	10.5	2.3

Appendix Table 5. Riley Regional Sorghum Feedstock Trial 2008 & 2009

Year	Plot #	Treatment	Plant Moisture	Total Dry Biomass	Grain Heads	Grain Yield	Juice Yield	Brix	Above-Ground Nodes	Plant Height
			%	Mg ha^{-1}	# ha^{-1}	kg ha^{-1}	L ha^{-1}	%	# plant^{-1}	m
2009	305	SugarT	65.9	10.8	66710	495	9924	15.9	14.0	3.7
2009	306	TAMUXH08001	65.5	19.8	97554	387	-	-	12.0	3.1
2009	401	Graze-n-Bale	72.7	14.1	-	-	-	-	12.5	2.9
2009	402	GrazeAll3	62.6	7.3	124812	517	-	-	13.3	3.0
2009	403	22053	64.2	9.9	88229	86	-	-	13.0	2.9
2009	404	TAMUXH08001	57.1	6.3	144179	603	-	-	10.0	2.6
2009	405	SugarT	66.0	8.9	62406	560	8000	16.1	13.0	3.4
2009	406	M81-E	68.0	9.3	47342	258	8359	14.9	13.3	3.0

Appendix Table 6. Riley County Sweet Sorghum Harvest Date Trial 2009

Plot #	Harvest #	Plant Moisture	Total Dry Biomass	Grain Heads	Grain Yield	Juice Yield	Brix	Above-Ground Nodes	Plant Height
		%	Mg ha^{-1}	# ha^{-1}	kg ha^{-1}	L ha^{-1}	%	# plant^{-1}	m
101	136	82.0	20.9	130546	2106	44288	13.3	15.3	4.1
102	126	81.9	19.0	-	-	38443	11.8	17.3	4.2
103	155	79.1	22.0	106159	804	40008	14.5	13.0	4.2
104	87	87.1	14.8	-	-	37108	5.9	13.3	3.5
201	136	82.3	20.2	130546	1142	38614	12.9	15.5	4.1
202	87	88.3	14.5	-	-	46532	5.0	13.0	3.4
203	126	82.0	22.2	-	-	46650	12.2	16.0	4.2
204	155	80.4	19.3	116201	1199	37854	12.5	14.5	4.2
301	126	82.6	20.7	-	-	43883	11.5	15.8	4.1
302	155	80.5	17.1	106159	791	32165	12.9	13.0	3.9
303	87	87.2	14.7	-	-	45666	5.9	12.5	3.4
304	136	83.0	16.1	101855	1208	34843	12.0	15.3	4.1
401	136	82.7	18.7	103289	1079	38182	12.3	16.5	4.2
402	155	80.4	18.1	114766	997	34048	12.8	15.8	4.0
403	126	81.3	22.2	-	-	41543	12.2	15.0	4.1
404	87	87.3	14.6	-	-	42086	5.7	13.3	3.5
104	Regrowth	86.7	0.4	-	-	-	-	3.0	0.4
202	Regrowth	86.1	0.4	-	-	-	-	3.8	0.5
303	Regrowth	86.5	0.5	-	-	-	-	4.3	0.6
404	Regrowth	86.3	0.4	-	-	-	-	2.5	0.4

Appendix Table 7. 2009 Riley Co. Photoperiod Sorghum Harvest Date Trial

Plot #	Treatment	Total Dry Biomass	Plant Moisture
	Days	Mg ha^{-1}	%
101	0	13.7	67.4
102	105	12.8	62.6
201	105	9.2	61.6
202	0	19.4	65.9
301	105	11.1	58.1
302	0	17.2	67.5
401	105	9.0	59.4
402	0	17.6	67.8