DEVELOPING ROW SPACING AND PLANTING DENSITY RECOMMENDATIONS FOR SWEET SORGHUM PRODUCTION IN THE SOUTHERN GREAT PLAINS

By

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CHAPTER I

INTRODUCTION

ABSTRACT

Sweet sorghum is gaining in popularity as an alternative biofuel feedstock. Its potential for low nutrient and water requirement appears to fit well within the southern Great Plains arid climate. The objectives of this project were to determine the optimum row spacing and plant population for sweet sorghum production in the southern Great Plains. Three locations in Oklahoma were established, ranging in precipitation from 820 to 1,070 mm west to east, respectively. At each location two separate studies were conducted: row spacing and planting density. To determine the effect of row spacing on sweet sorghum production two varieties, Topper and M81, were evaluated in spacings of 20, 38, and 76 cm. To determine optimum plant density, plots were arranged in a randomized complete block design and seeded at rates of 74,100 to 172,900 seeds ha^{-1} in 20 and 76-cm row spacings using one cultivar, M81. Plots were harvested at soft dough stage to obtain wet yield. Samples were pressed to determine juice extraction and brix values. Observations from row spacing studies indicated 20 and 38-cm rows were superior to 76-cm rows. 175,000 to 250,000 plants ha^{-1} and narrow row spacing offers the maximum yield of biomass and juice extraction.

INTRODUCTION

Renewable sources of energy have been a topic of debate for many years. Dependence on fossil fuels has put the world between a rock and a hard place. Scientists know that fossil fuels won't be around forever and the call for new ideas for renewable sources of energy is needed to maintain the current level of energy used by today's population. To maintain this level of energy being consumed, different forms of renewable energy have been proposed, such as: wind energy, wave energy, solar power, hydro-electricity, and biofuel feedstocks.

Biofuel feedstocks are plants grown each year, collected and then converted to energy. Some examples of biofuel feedstocks are: algae, corn, miscanthus, soybeans, sugarcane, sweet sorghum, and switchgrass. These feedstocks can be grown every year supplying a renewable source of energy to meet the increasing demand. Sweet sorghum (*Sorghum bicolor* (L.) *Moench*) has great potential to be a leading producer of this renewable energy. The plant has become widely adopted to grow in arid climatic regions and can be grown in many variable soil types. Sweet sorghum is a phenotypically similar appearance to maize (*Zea mays* L.), until the reproductive stage. The crop originated in Africa and was brought to the United States in the 1700s. Up until the 1950s, most of the sweet sorghum production went into sugar and syrup development. Shortly after that, production of sweet sorghum shifted towards livestock feed. It wasn't until the 1980s that people started to realize its potential as an energy producer. The crop produces fermentable sugars within its stalk. The stalk can be pressed and the juice extracted and this extracted juice can then be fermented to produce ethanol.

Several studies from Georgia to Texas have shown that sweet sorghum can be grown in high heat, a range of precipitation gradients, and various soil types (Cummins and Dobson, 1973; Broadhead and Freeman, 1979; Bond et al., 1964; Monk et al., 1984). A study conducted in Nebraska showed that at times of high heat and low precipitation, the plant can go into a dormant condition, halting plant growth until adequate precipitation follows. The plant can then return to grow as long as there is time left in the growing season. The down side of this is that if the dormant stage is too long, the plant may never reach full maturity before winter sets in and the growing season is over.

To be grown on a large scale for energy production purposes, agronomic recommendations are needed. Research on row spacing and planting densities have been conducted in Botswana, Colorado, Kansas, Mississippi, New South Wales, and Texas to determine the best combination to produce the most biomass per hectare. Several studies worked with different row spacings such as: 20, 38, and 76 cm. These are common row spacings for growers. The 20-cm spacing represents a producer planting with a seed drill. The 38-cm spacing represents the same drill but with every other seeding unit plugged. The 76-cm spacing represents a planter, such as used for maize.

This research project entailed two studies: row spacing and planting density. The row spacing study was to determine which spacing provided the best chance to produce the most biomass per given area. Common sense would suggest that the narrower row spacing, the more plants that can be grown in that area would result in more biomass. Studies conducted have shown that narrower row spacing does indeed increase biomass. If nutrients and water are non-limiting then the next main factor for biomass production is light interception. Using narrower row spacing allows more light to be captured by the plants and turned into energy which is stored in carbohydrates. Employing wider row spacings allows light to be wasted on the soil surface. To increase light capture, one can increase planting densities. As stated before wider row spacings allows excess light to be wasted on the soil surface, but by implementing narrower row spacings and increasing planting densities, a person can capture more light radiation and potentially increase biomass.

There were two objectives for this project. The first objective was to determine the optimum row spacing for sweet sorghum production in western Oklahoma and eastern Oklahoma. The second objective was to determine the optimal planting density to maximize biomass and juice extracted.

CHAPTER II

REVIEW OF LITERATURE

Demand for sources of new energy is driving research towards renewable energy. Diminishing amounts of fossil fuels are causing a concern about reaching future energy demands of the world. To combat the increasing cost of fossil fuels, scientists have turned to renewable sources of energy. Examples of renewable energy sources are: solar, wind, hydro-electric, and bioenergy feedstocks. Although each one of these is a potential option for alternative energy, bioenergy feedstocks can be produced on large acreages across the U.S. Bioenergy feedstocks can be grown every year and converted into useable energy for transportation, heating, industrial use, etc. The largest source of renewable energy in the U.S. to date is the use of maize (*Zea mays* L.) (Baker and Zahniser, 2006). Maize is grown and harvested every year with the kernels being transported to processing facilities where they are converted into ethanol (Bothast and Schlicher, 2004). This is a perfect example of a renewable source of energy. However, because maize requires lots of water units for good yield production, a different crop is needed in a more arid climate. Sweet sorghum (*Sorghum bicolor* (L.) *Moench*) is such a crop that can be grown in arid climates and can be turned into energy.

Sorghum Production

Sorghum, in general, has been in production for thousands of years. Production originated in northeastern Africa but has extended to different parts of the world (Sorghum Growers, 2011). The expansion of sorghum may have contributed to the formation of different species while still in the same genus. Grain sorghum was brought to the United States in 1757. The main end-use for grain sorghum is livestock feed but is also used in food products and as an industrial feedstock. Annual production of grain sorghum is nearly 19.8 million hectares and generates $820 million dollars (EPA, 2009). The United States is the second leading producer of grain sorghum and the top exporter in the world market (U.S. Grains Council, 2010). The leading grain sorghum producing states are: Kansas, Texas, Nebraska, Oklahoma, and Missouri (U.S. Grains Council, 2010). The acreage of grain sorghum provides us with an idea of the area where sweet sorghum would fit best.

Sweet sorghum, a close relative to grain sorghum, has primarily been used for molasses or syrup production. The potential of sweet sorghum to use less nutrient and water requirements (Geng et al., 1989; Smith and Buxton, 1992; Cummins and Dobson, 1973) fits well into the Southern Great Plains climate and provides reasoning for researchers to rethink the possibility of sweet sorghum as their primary energy crop. Focus has been brought upon sweet sorghum for its potential to produce a renewable source of energy.

Row Spacing

Row spacing plays a large role in crop production. Knowledge of the most productive row spacing for each crop can make a significant yield difference. Cereal crops such as corn and sorghum are grown in rows that vary in width anywhere from 15 to 100 cm. Location and amount of precipitation for the given area are determinants of optimum row width. Numerous studies have been conducted worldwide to determine the correct row spacing for each crop. A study conducted by Stickler and Laude (1960) in Kansas regarding corn, grain sorghum, and forage sorghum found no significant difference in row spacing for corn grain or stover production when evaluating row width from 51 to 102 cm. Corn grain yield was numerically higher in the 102-cm row spacing but less productive in stover yield compared to the 20-cm row spacing. They noted that light interception at leaf canopy height was less at the 102-cm spacing than that of the 51-cm row spacing. These findings suggest solar radiation is being wasted on the top soil. Wasted solar radiation raised the soil temperature which was shown to increase soil evaporation potential. In the grain sorghum study, Stickler and Laude (1960) noted no significant difference between row spacings for grain yield. However, as stand population was increased, they noticed a trend towards higher yields at decreasing row spacing. This suggests narrow row grain sorghum production that coincides with a high planting density. The forage sorghum stover yield results were similar to the corn results. No significant difference was established in row spacing providing no clear results as to which row spacing produced higher biomass. Cummins and Dobson (1973) found similar results to that of Stickler and Laude (1960) regarding corn in the Piedmont Region of Georgia. They found that the 51-cm row spacing produced greater yield compared to 102-cm row spacing for the two year average. No significant difference was found in the Appalachian Region of GA.

In contrast, Giesbrecht (1969) found no significant difference in row spacing in corn production in Manitoba, Canada. This is also consistent with Bond et al. (1963) which found 51-cm row spacing limited grain production, especially in the presence of limited moisture in Texas. However, it is important to note that grain sorghum stover production was higher with 1.8 kg seeding rates and 51-cm row spacings compared to 0.9 kg seeding rate at 102-cm row spacing. The average mean stover yield was 136 to 544 kg greater than any combination of 0.9 to1.8 kg seeding rate with 51 to 102-cm row spacing. Concentrating on grain production may lead for wider row spacings (≥ 76 cm) but looking for biomass production may lead towards narrower row spacings. By concentrating on biomass production of the plant and not grain production, a different approach can be applied. Through a decrease in row spacing, growers can increase their biomass production of sweet sorghum (Broadhead and Freeman, 1979; Martin and Kelleher, 1984). Narrow rows can crowd plants similar to weed competition. This competition causes plants to grow quickly. Compared to narrow rows, plants grown in wider rows have more spatial room to grow and more nutrients within their root zone to utilize. Broadhead and Freeman (1979) noted that sweet sorghum plants in 105-cm rows weighed more but due to more plants per area within the 52.5-cm rows, the heavier stalks yielded less in biomass then the thinner stalks from the 52.5-cm rows within the same area.

Planting Density

Ideal plant populations are essential to reach maximum yield potential. Over population can be detrimental for crop production. Over populating can lead to excessive lodging and overall yield loss (Thomison and Jordan, 1995; Monk et al., 1984; Bond et al., 1964). Planting too low of a population causes increased weed competition (Norsworthy and Oliver, 2002), loss of light interception, and reduces the potential for maximum yield (Edwards and Purcell, 2005). Finding the right seeding rate leads to maximum net returns for the grower.

What seems to be the biggest factor that affects yield as a function of plant population is soil moisture (Giesbrecht, 1969; Bond et al., 1964). Different amounts of moisture during mid-season growth can determine yield potential. Less than optimal moisture allows for vegetative growth but not enough for full grain development while adequate moisture allows for both vegetative growth and seed development (Bond et al., 1964). The impact of row spacing in yield potential is important but plant population seems to be of more concern, especially for production in the Southern Great Plains. For areas that receive low moisture (322 mm), a lower population (30,000 to 45,000 plants ha^{-1}) produces better results than higher population (60,000 to 75,000 plants ha^{-1}) (Giesbrecht, 1969). Areas of greater moisture (>600 mm) can support higher plant populations (>75,000 plants ha^{-1}). These high populations can use a narrow row spacing to potentially increase yield. A lower population combined with wider rows produces more grain at lower moisture levels, but if moisture levels are increased narrow rows can produce greater results at the same population (Bond et al., 1964). Both Cummins and Dobson (1974) and Stickler and Laude (1960) concluded that both wide and narrow row spacings accompanied by a low population yielded no significant differences. However, they noted that by increasing population, they identified a trend for higher yields for narrower rows. Successfully combing row spacing with a population relies heavily upon precipitation levels. For high production of biomass yields a combination of good moisture with narrow row spacing and higher populations returns the best results.

Light Interception

An increase in biomass production is directly related to an increase in light interception. The effects of light interception can be observed by shaded plants versus plants in full sunlight. The influence of light on the plants in full sunlight can cause a profound growth increase compared to the shaded plants. To know how this light interception functions can explain how plants in greater densities produce more forage above optimal planting density recommendations.

There is a dependent relationship between light interception, water availability, and length of growing season. The length of a growing season and the availability of water determine the optimal row spacing and planting density of a crop. Row spacing and planting density influence quantity of light intercepted. For example; crops grown in a shorter growing season, from planting to first killing frost, need to intercept the greatest amount of photosynthetically active radiation (PAR). The combination of narrow rows and high planting densities allows the crop to capture PAR it requires to reach maximum yield potential. A long growing season provides the crop with an extended amount of PAR (Watson, 1947). Adequate amounts of PAR allow the option to plant in wider rows and at a lower plant density. Each method has advantages as well as disadvantages.

Narrow row and high density planting leads to greater seed input and increased use of water. However, this method allows for a quick crop production in a shorter growing season. The quick canopy closure for narrow rows and high populations shades the soil faster. Shading controls weeds (Teasdale, 1995) and cools the soil temperature which may potentially decrease soil evaporation loss (Taylor et al., 1983). However, the amount of water retained may not be enough to keep the crop growing unless frequency of precipitation is consistent (Taylor et al., 1983).

In contrast, wide rows and low stands are better adapted in the Southern Great Plains where the growing season is longer. The long season has more time to gather the necessary PAR for crop growth. One limitation of selecting a full season crop is available moisture. Full season growth is often dependent on frequency of moisture. Variables of available moisture include soil type, frequency of moisture, and canopy closure time. Various soil types have distinct water holding capacity. Clay and silt textured soils have higher water holding capacity compared to sandy soils (Hillel, 2004). The ability to hold water longer within the soil provides the crop with moisture for a prolonged period. Sandy soils have a lower water holding capacity. More precipitation is needed for sandy soils compared to clay or silt textured soils. Growing crops dependent on rainfall is stressful. Hard, intense rains cause erosion with little of the actual moisture penetrating deep into the soil profile. Light precipitation events over longer periods provide the soil time to absorb much of the water. The water stored between wide rows is like a reservoir, allowing the roots to take up water during periods of drought (Lyon, 2008; Bond et al., 1964). However, the wide row gives the light an opportunity to warm the soil, potentially increasing soil evaporation. Canopy closure shades the soil, limiting the amount of light reaching the soil surface. But, because more light is caught within the canopy, the transpiration potential of the plant may increase, thus increasing the amount of water use of the plant.

Processing

The last step before large scale implementation can take place is processing. Currently there are options for processing sweet sorghum into ethanol for small scale research. Finding one that is economically feasible for large scale production requires more insight. Some of these processing options are: whole stalk harvesting, forage harvesting, and in-field pressing. Whole stalk harvesting was developed for temperate regions and utilizes a swathing type method (Rains et al., 1990; Bellmer et al., 2010). The stalks are cut and arranged into windrows where they can be kept for up to 30 days. After this initial time period, the stalks are gathered and transported to a processing site nearby. There, the stalks are pressed and the juice collected. A forage harvester is similar to a silage cutter. The crop is cut and chopped and loaded onto wagons. The chopped forage must be processed soon as the forage material could soon dry out (Worley and Cundiff, 1991; Bellmer et al., 2010). The in-field harvest would cut the stalks whole and press them at the same time. The juice would be stored in a bladder pulled behind the press. The juice can then be transferred to larger storage bladders on site and fermented to eliminate the possibility of sugar degradation and prolong the shelf life. The fermented product can be transported to a processing site where the conversion from fermented juice into ethanol takes place (McClune, 2010; Bellmer et al., 2010).

CHAPTER III

METHODOLOGY

Three experimental sites were utilized in 2009 and 2010. Table 1 provides the soil taxonomic classification and series names of the soils at each location. These locations were selected to represent the different eco-regions (Central Great Plains and Cross Timbers) of Oklahoma varying in annual precipitation amounts from 820 to 1,070 mm from west to east, respectively. Two separate studies were conducted at each site to evaluate row spacing and plant density.

Row Spacing

Treatments were established in a randomized complete block design with four replications. The treatment structure was a two by three factorial for variety and row spacing, respectively. Varieties used were Topper and M 81, and row spacings investigated were 20, 38, and 76 cm. Individual plots were 3 m wide by 7.5 m in length. In 2009 a constant seeding density of 123,500 seeds ha^{-1} was used. In 2010 the same treatments were repeated with the addition of two new treatments: 20-cm row spacing at 247,000 seeds ha^{-1} for both varieties.

Plant Density

Treatments were established in a randomized complete block design with four replications. The treatment structure was a five by two factorial for planting density and

Table 1. Taxonomic soil classifications, soil chemical properties, location, and GPS Coordinates.

Locations	Soil Taxonomic Classification	Soil Series	pH	P	K	GPS Coordinates
				----kg ha^{-1}----		
Lahoma	Fine-silty, mixed, superactive, thermic Udic Argiustolls	Grant	6.7	48	387	36°23 N, 98°06 W
Stillwater	Fine-silty, mixed, active, thermic Udic Paleustolls	Norge	7.1	68	282	36°07 N, 97°05 W
Haskell	Fine, mixed, active, thermic Mollic Albaqualfs	Taloka	6.2	101	138	35°44 N, 95°38 W
Stillwater	Fine-loamy, mixed, superactive, thermic Fluventic Haplustolls	Easpur	6.1	115	197	36°08 N, 97°06 W
Chickasha	Fine-silty, mixed, superactive, thermic Pachic Haplustolls	Dale	6.0	65	433	35°02 N, 97°54 W

row spacing, respectively. Variety M81 was used, while the row spacings investigated were 20 and 76 cm. Individual plots were 3 m wide by 7.5 m in length. In 2009, seeding densities ranged from 74,100 to 172,900 in increments of 24,700 seeds ha^{-1} for both row spacings. In 2010, two treatments were removed; 20-cm row spacing at 74,100 and 98,800 seeds ha^{-1}, while three new treatments were added; 20-cm row spacing at 197,600, 222,300, and 247,000 seeds ha^{-1}. These treatments were added because in the first year of the study we did not reach a plateau of biomass production for the 20-cm row spacing. The 76-cm row spacing treatments remained unchanged.

Best management practices were implemented to limit yield loss from other variables. Nutrients were added as required by soil tests. Nitrogen was split applied, 56 kg ha^{-1} of actual N pre-plant and 56 kg ha^{-1} of actual N top dress as either UAN or urea. Planting took place between early May and early June and harvest coincided with soft dough stage of grain.

Digital photographs were taken each week at the Stillwater site in 2009. Pictures were taken from above with the camera lens pointing down encompassing approximately 1 m^2 of the plot. The camera was mounted on a monopod attached to a piece of polyvinyl chloride (PVC) pipe. The mount was 1m above the soil surface and the camera was inclined from the horizon to prevent the PVC pipe from being included in the picture. Digital photographs were batch analyzed using SigmaScan Pro (v. 5.0, systat software, Point Richmond, CA) (Karcher and Richardson, 2005). The software has selectable options defining hue and saturation values. Setting hue and saturation values will selectively include the green pixels in the digital image (Purcell, 2000). For this study the hue was set for the range 40 to 140 and saturation was set for the range 15 to

100. The output of the program is fractional canopy coverage defined as the number of scanned pixels divided by the total number of pixels per image (Purcell, 2000).

Pictures were taken of all treatments in blocks one and two and averaged to obtain the average fractional coverage for each treatment. Growing degree days (GDD) were obtained from the Oklahoma Mesonet website (http://agweather.mesonet.org/). Growing degree day units were calculated using the following equation:

$$GDD = \left[\frac{(T_{MAX}+T_{MIN})}{2}\right] - T_{BASE} \quad (1)$$

where T_{MAX} is the daily maximum air temperature, T_{MIN} is the daily minimum temperature, and T_{BASE} is the temperature below which the process of interest does not progress (McMaster and Wilhelm, 1997). The base temperature for sorghum is 50°F (10°C). Growing degree day measurements were taken 10 days after planting. The fractional coverage and GDD were plotted to estimate canopy closure of each treatment.

Harvest

A uniform 2.3 m^2 area was hand harvested from each treatment by cutting the plants at the base just above soil level. This biomass sample was weighed in field using an electronic scale (Transducer Techniques, Load Cell MPL-200). The wet biomass sample was pressed in field using a small-scale roller press. The press consists of three pairs of rollers, each 15 cm in diameter and 30.5 cm wide and is powered by a 5.5 horsepower motor. Each set of rollers has pressure control capability in order to maintain a constant pressure independent of stalk properties. The juice extracted from the wet biomass was collected, measured, and recorded as a ratio of juice extracted divided by the mass of sweet sorghum pressed. A Brix measurement was taken at location using a handheld refractormeter (Extech RF-10), which is usually within .5-1 percent of actual sugar content (Bellmer, 2010 unpublished data). The juice obtained and sugar content of the juice was recorded for each treatment.

Statistical Analysis

Biomass, extracted juice, and brix were analyzed using PC SAS Version 9.2 (SAS Institute, Cary, NC). The Levene's test was performed for each cultivar to determine homogeneity of variance for the two years of data. Regression analyses were performed using PROC REG function of SAS to determine the effect of planting densities on biomass, extracted juice, and brix measurements.

CHAPTER IV

RESULTS AND DISCUSSION

Overall, biomass yields were exceptional due to excellent growing conditions in most site years (Tables 2, 3, & 4). The only exceptions were Haskell 2009 and Stillwater

Table 2. Temperature, rainfall, and 30 year average for Stillwater, OK.

	2009		2010			
Month	Temp.	Rainfall	Temp.	Rainfall	30 yr avg.	
	C°	mm	C°	mm	mm	C°
May	19.2	82.8	19.9	181.1	141.2	19.4
June	27.2	43.9	26.9	139.5	108.7	24.4
July	27.2	126.0	27.7	111.5	68.3	27.2
August	25.3	190.5	28.2	63.8	75.7	26.7
4 month total		443.2		495.9	393.9	

Table 3. Temperature, rainfall, and 30 year average for Lahoma, OK.

	2009		2010			
Month	Temp.	Rainfall	Temp.	Rainfall	30 yr avg.	
	C°	mm	C°	mm	mm	C°
May	18.3	37.9	19.0	124.5	119.6	20.0
June	26.6	58.9	27.2	94.2	103.9	25.6
July	27.2	65.3	27.6	168.9	74.7	27.8
August	25.4	192.3	28.1	90.9	80.8	27.8
4 month total		354.4		478.5	379.0	

Table 4. Temperature, rainfall, and 30 year average for Haskell and Chickasha, OK.

	Haskell 2009				Chickasha 2010			
Month	Temp.	Rainfall	30 yr avg.		Temp.	Rainfall	30 yr avg.	
	C°	mm	mm	C°	C°	mm	mm	C°
May	16.4	113.0	148.6	20.6	20.7	50.6	130.3	21.1
June	25.8	60.7	126.5	25.6	27.6	78.7	100.8	25.6
July	26.1	45.2	66.6	26.7	27.3	141.2	52.1	27.8
August	25.1	21.8	69.6	26.7	28.7	12.2	65.0	27.2
4 month total		240.7	411.3			282.7	348.2	

Source: OK Mesonet, 2011.

2010. The Haskell location is in an area of high rainfall (Table 4) but during the growing season less than average rainfall fell. The poor growing conditions at Haskell induced severe lodging that only allowed for the data collection of three reps. Prior to planting Stillwater in 2010, ideal growing conditions were observed. Soil moisture was adequate along with soil temperatures and above air temperature. These conditions created nearly perfect stand establishment. However, shortly after emergence rainfall was sporadic. Stillwater received more rainfall in 2010 than the 30 year average (Table 2) but these events were intense and untimely. For example, 42% of May’s and 52% of June’s monthly average fell in one 24 hour period. These heavy precipitation events did not allow the soil to absorb moisture the crop needed. Yield potential was reduced due to these prolonged dry periods.

Row Spacing

Biomass

Row spacing by variety interaction and variety main effect were not significantly different at any location, so biomass yields were averaged across row spacing (Table 5). In 5 out of 6 site-years, wet biomass yields were increased when decreasing row width from 76 cm to 20 cm (Table 6). At these responsive locations, average wet biomass yield increased 34% when comparing a row spacing of 76 cm to 20 cm. The one non-responsive location was Haskell in 2009 where wet biomass yields were similar when comparing the 20 and 76-cm row spacing treatments. When comparing the 20-cm row spacing to the 38-cm row spacing, wet biomass yields were similar in 5 out of 6 site years (Table 6).

Table 5. Effect of row spacing on wet biomass production in 2009 and 2010.

	Stillwater		Lahoma		Haskell	Chickasha
Fixed Effect	2009	2010	2009	2010	2009	2010
Row Space	*	*	*	*	*	*
Variety	NS	NS	NS	NS	NS	NS
Row Space*Variety	NS	NS	NS	NS	NS	NS

* Denotes significant at the 5% level.

Table 6. Wet biomass sweet sorghum yields at sites in 2009 and 2010.

	Stillwater		Lahoma		Haskell	Chickasha
Row Spacing	2009	2010	2009	2010	2009	2010
- - - cm - - -	-----------------------t ha^{-1}-----------------------					
20	151a†	136a	102a	121a	58a	77a
38	127ab	124a	98ab	113a	84b	77a
76	114b	96b	88b	82b	63a	59b

† Within columns, means followed by the same letter are not significantly different according to LSD (0.05).

The addition of the two new treatments in 2010 had no effect at Stillwater and Chickasha but Lahoma (Pr > .04) wet biomass yield was increased 21,560 kg ha^{-1} at the higher seeding rate.

Juice Extraction

Juice extraction was highly correlated with wet biomass (Figure 1). Row spacing

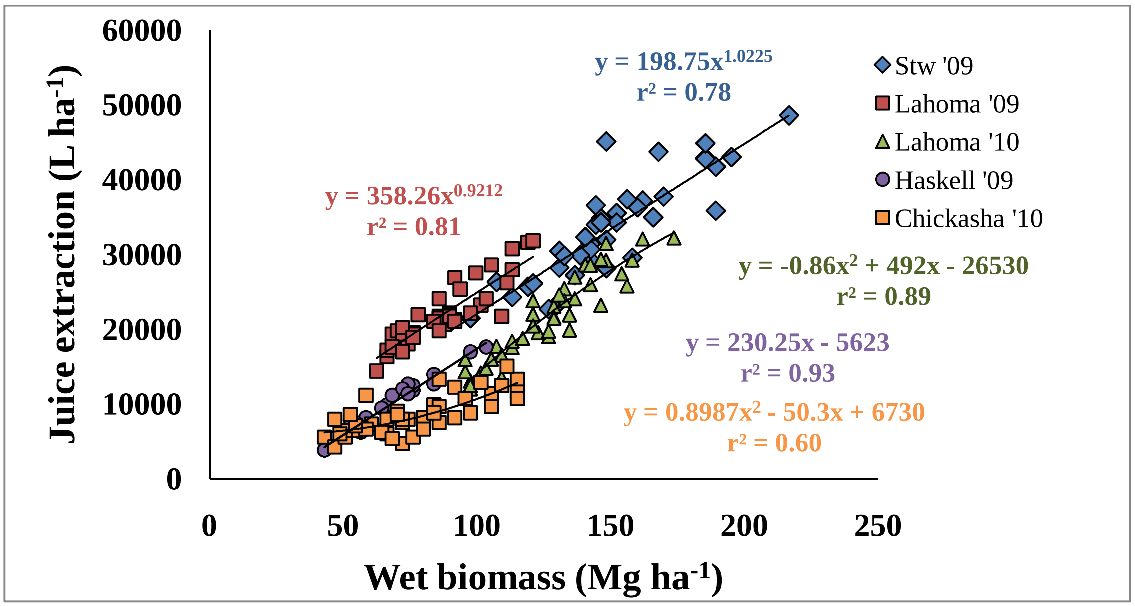

Figure 1. Juice extraction versus wet biomass for all site years in 2009-2010.

by variety interaction and variety main effect was not significant, so juice extraction was averaged across row spacing for each location (Table 7). Row spacing was significant at five out of six locations for juice extraction. Table 8 indicates juice extraction amounts by location and year. In 2009 at Stillwater, a 32% increase was observed when reducing row spacing from 76 cm to 20 cm. Similar to Stillwater, juice extracted at Lahoma increased by 1,351 L ha^{-1} when reducing row spacing from 76 cm to 20 cm. At Haskell, a 60% increase in juice extraction was observed when reducing row spacing from 76 cm to 38 cm. In 2010, both Stillwater and Lahoma increased juice extraction by 42% and

Table 7. Effect of row spacing on juice extraction and brix in 2009 and 2010.

	Stillwater				Lahoma				Haskell		Chickasha	
	2009		2010		2009		2010		2009		2010	
Fixed Effect	brix	juice extracted	brix	juice extracted	brix	juice extracted	brix	juice extracted	brix	juice extracted	brix	juice extracted
Row Spacing	NS	*	NS	*	NS	*	NS	*	NS	*	*	NS
Variety	*	NS	NS	NS	*	NS	NS	NS	*	NS	NS	NS
Row Spacing x Variety	NS	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	NS

* Denotes significant at the 5% level.

Table 8. Average brix and juice extraction for all site years.

	Stillwater				Lahoma				Haskell		Chickasha	
	2009		2010		2009		2010		2009		2010	
Row Spacing	brix	juice extracted	brix	juice extracted	brix	juice extracted	brix	juice extracted	brix	juice extracted	brix	juice extracted
----cm----	%	L ha^{-1}	%	L ha^{-1}	%	L ha^{-1}	%	L ha^{-1}	%	L ha^{-1}	%	L ha^{-1}
20	12.3	24557a†	15.7	11756a	15.1	12446a	14.6	8757a	16.6	4144b	15.3	4430a
38	11.9	20840ab	16.1	11668ab	15.5	11952a	14.6	7912ab	16.5	7494a	14.8	4691a
76	12.0	18603b	15.9	8292b	15.3	11095a	14.4	5969b	16.1	4689b	15.6	4371a

† Within columns, means followed by the same letter are not significantly different according to LSD (0.05).

47%, respectively, when reducing row spacing from 76 cm to 20 cm. However, Chickasha did not show a significant increase in juice extraction.

Brix

Brix measurements were not significantly different for the row spacing by variety interaction or row spacing main effect, so brix was averaged across variety. Variety was only significant in the 2009 season (Table 7) and the variety Topper was on average 1 degree higher than M81 (Figure 2).

Stalk Diameter, Plant Height, and Canopy Closure

Stalk diameter was not correlated with biomass, juice extraction, or brix at any location (data not shown). Observations did indicate that increasing seeding density decreased average stalk diameter (Figure 3). Plant height was not correlated with biomass, juice extraction, or brix at any location in both years (data not shown).

Fractional canopy coverage was averaged across both varieties for individual row spacings. Even though observations were not made for emergence, the fractional canopy coverage measurements indicated that the 76-cm row spacing emerged quicker compared to the narrower row spacings. This is believed to be due from the planter placing the seed in a more uniform pattern and depth compared to the drill planting method. However, the 38-cm row spacing reached full canopy closure earlier than the other two row spacings (Figure 4).

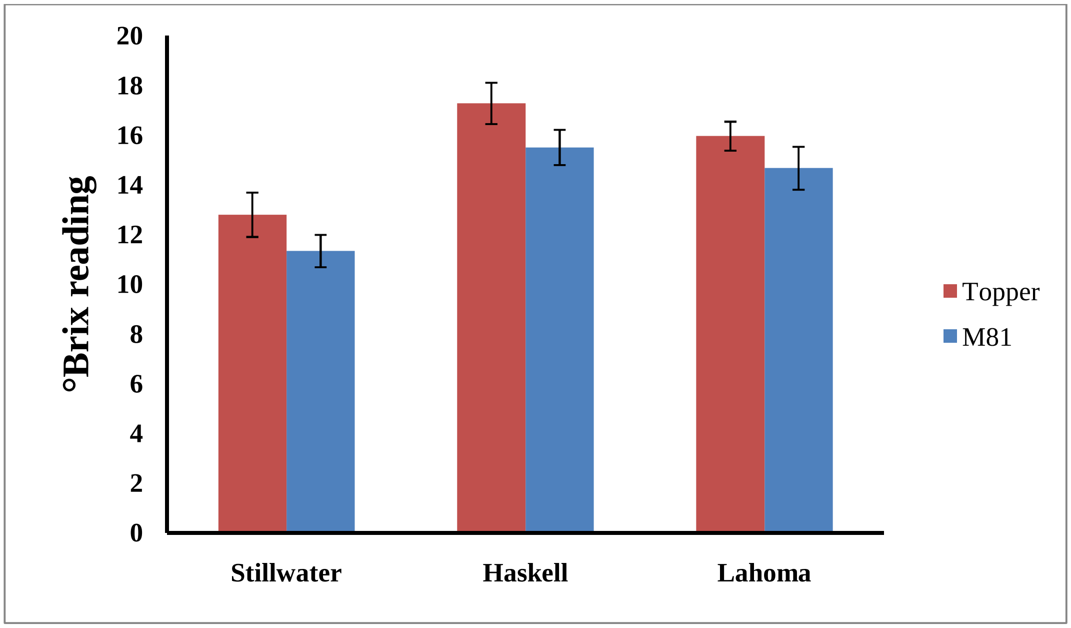

Figure 2. Brix readings across locations for 2009.

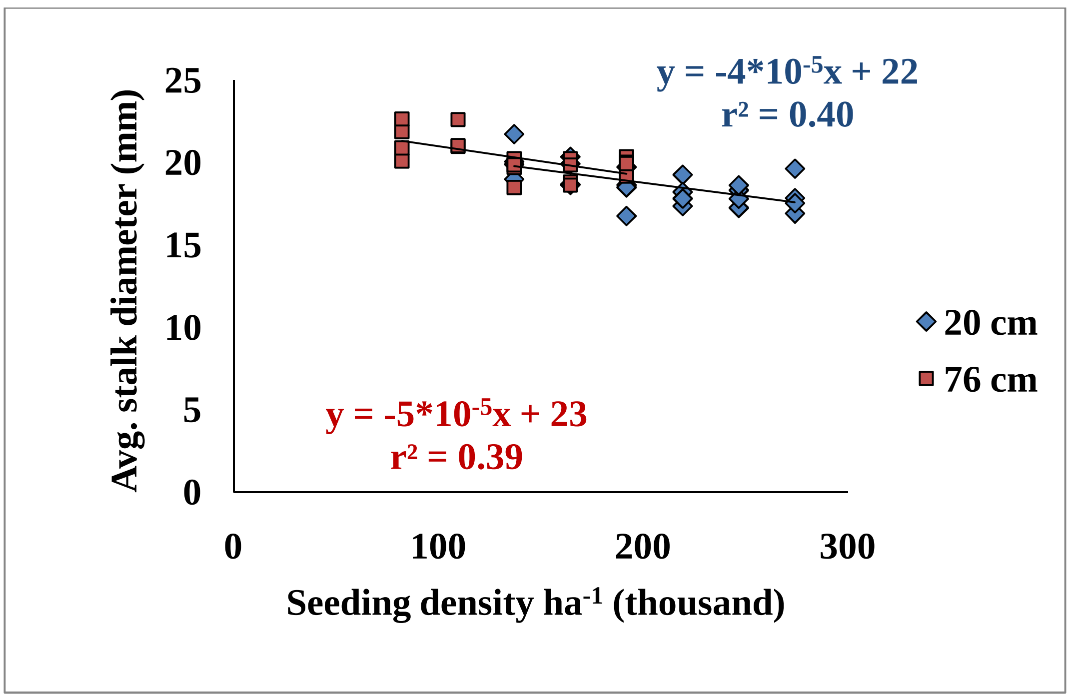

Figure 3. Stalk diameter related to increasing seeding density at Stillwater in 2010.

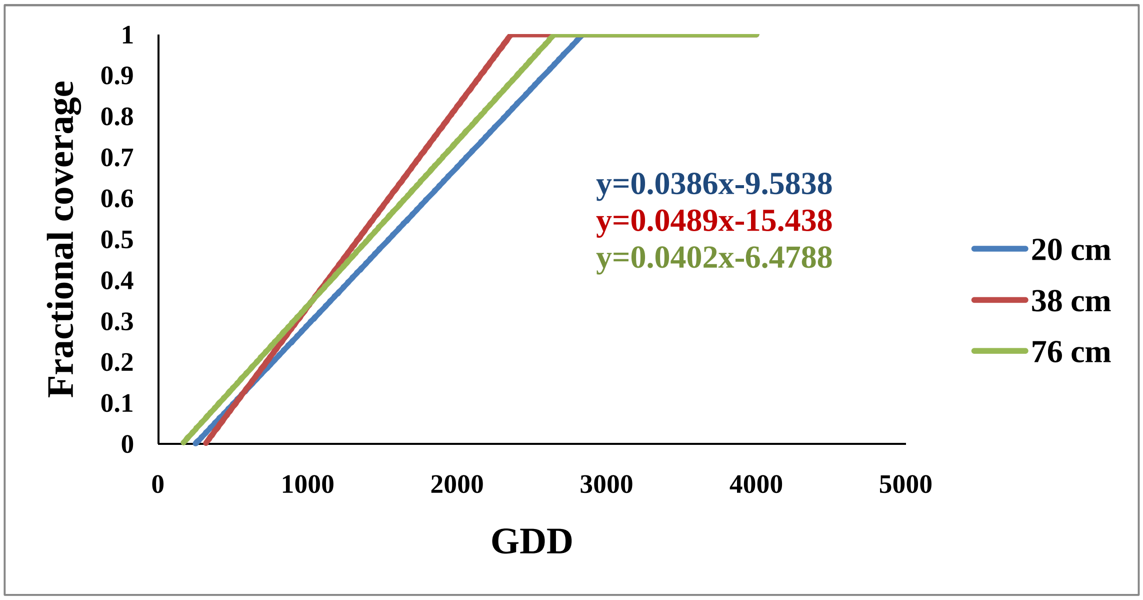

Figure 4. Fractional canopy coverage as a function of GDD in Row Spacing at Stillwater in 2009.

Plant Density

Biomass

Table 9 shows the regression analysis from the planting density study. Figures 5 through 10 show wet biomass versus harvested plant density for locations in 2009 and 2010. Row spacings were analyzed separately because 20-cm rows consistently produced greater biomass yields compared to the 76-cm row spacing. For both row spacings, tillering was evident especially at the lower seeding densities. No measurements were taken to determine the number of tillers. The response to seeding densities was performed using the number of harvested plants (including tillers) per ha^{-1} since seeds planted ha^{-1} did not necessarily correlate with the number of plants harvest.

For the 20-cm row spacing, 4 out of 6 site-years, (Lahoma 2009, Haskell 2009, Lahoma 2010, and Chickasha 2010) were considered to be responsive ($r^2 > 0.40$ and

Table 9. Regression analysis (y = wet biomass; x = planting density) from locations in 2009 and 2010.

Locations	Row Spacing	Equation	r^2	SE[§]	Pr > F
Stillwater 2009					
	20 cm	$y = 6*10^{-6}x^2-2.04x+329554$	.30	39522	.03
	76 cm	$y = -8*10^{-6}x^2+3.28x-191560$	.24	36583	.07
Lahoma 2009					
	20 cm	$y = -1*10^{-6}x^2+0.61x+27183$	.48	12541	<0.01
	76 cm	$y = -5*10^{-6}x^2+1.48x-31735$	.31	14233	.1
Haskell 2009					
	20 cm	$y = -7*10^{-7}x^2+0.5775x+17265$	.94	5603	<0.01
	76 cm	$y = 1*10^{-5}x^2-2.68x+180701$	.94	12701	<0.01
Stillwater 2010					
	20 cm	$y = 1*10^{-7}x^2-0.34x+200976$	.35	20062	<0.01
	76 cm	$y = -6*10^{-6}x^2+1.77x-47449$	.27	12052	.03
Lahoma 2010					
	20 cm	$y = -2*10^{-6}x^2+0.95x+18360$	.40	13596	<0.01
	76 cm	$y = -9*10^{-6}x^2+2.78x-88952$	.08	27397	.54
Chickasha 2010					
	20 cm	$y = -4*10^{-6}x^2+1.56x-54580$	.66	13015	<0.01
	76 cm	$y = -4*10^{-6}x^2+1.1605x-10474$	.17	16065	.1

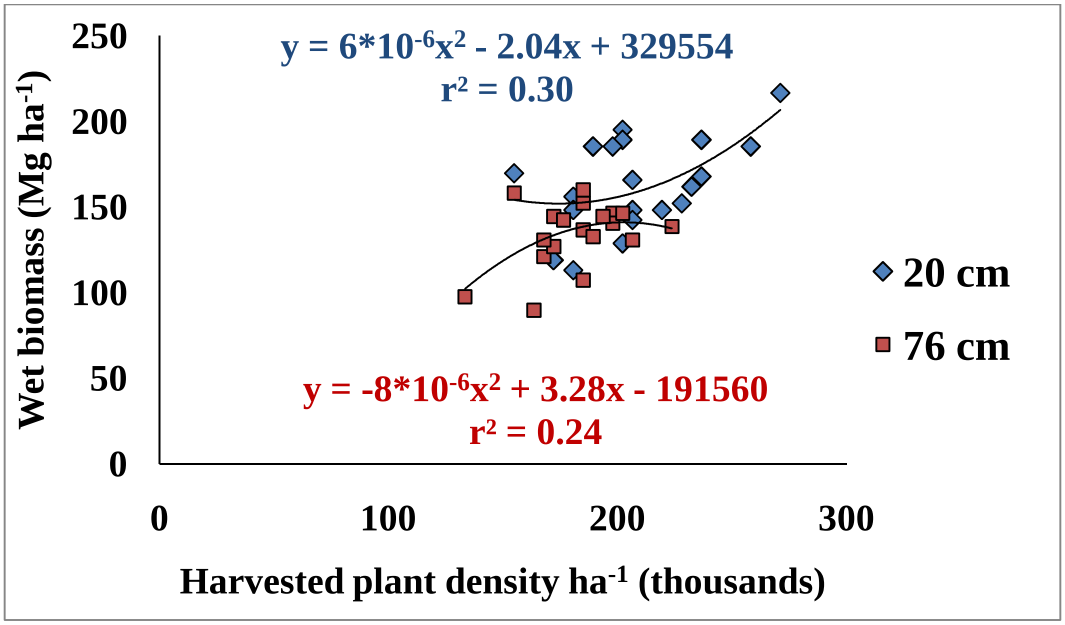

Figure 5. Wet biomass versus harvested plant density from Stillwater 2009.

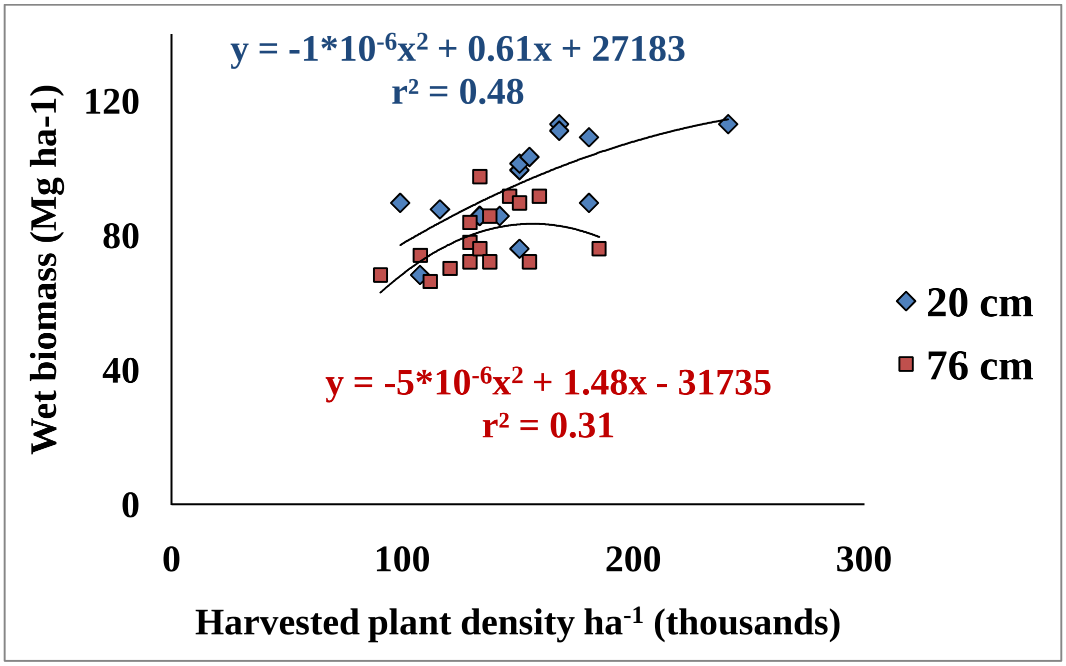

Figure 6. Wet biomass versus harvested plant density from Lahoma 2009.

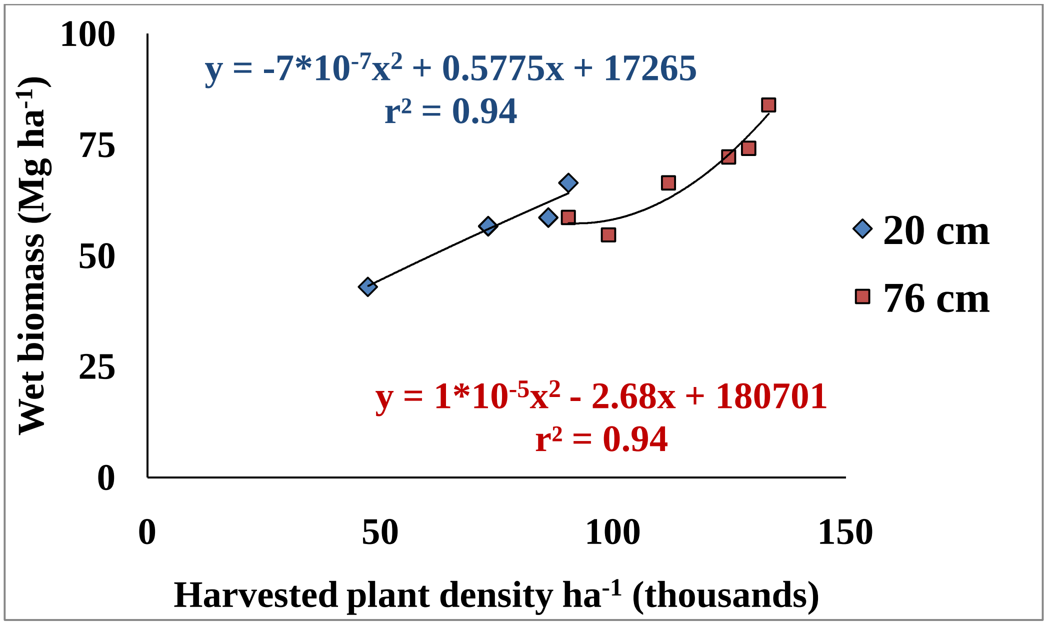

Figure 7. Wet biomass versus harvested plant density from Haskell 2009.

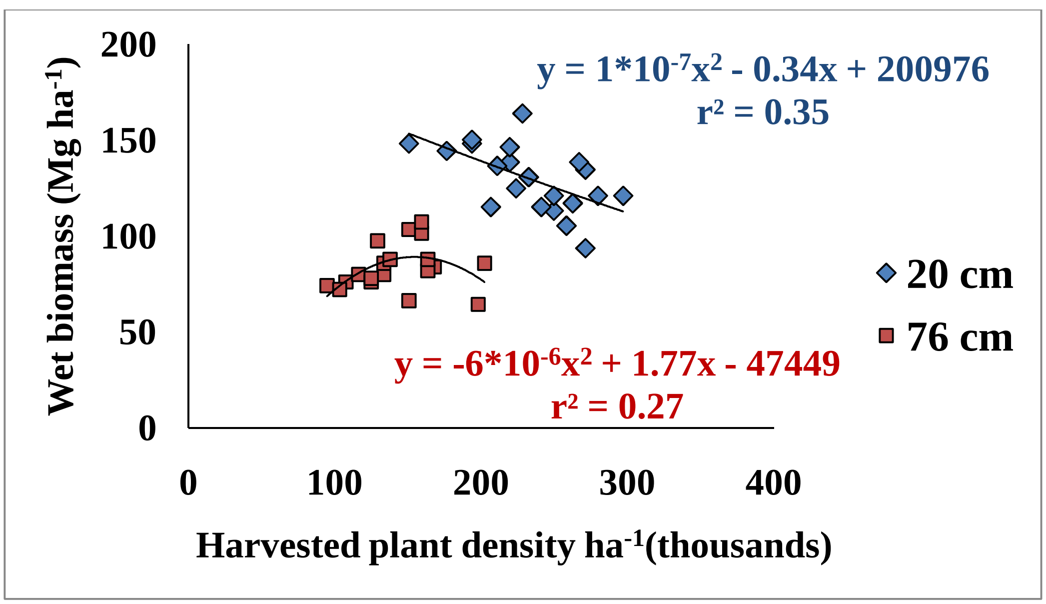

Figure 8. Wet biomass versus harvested plant density from Stillwater 2010.

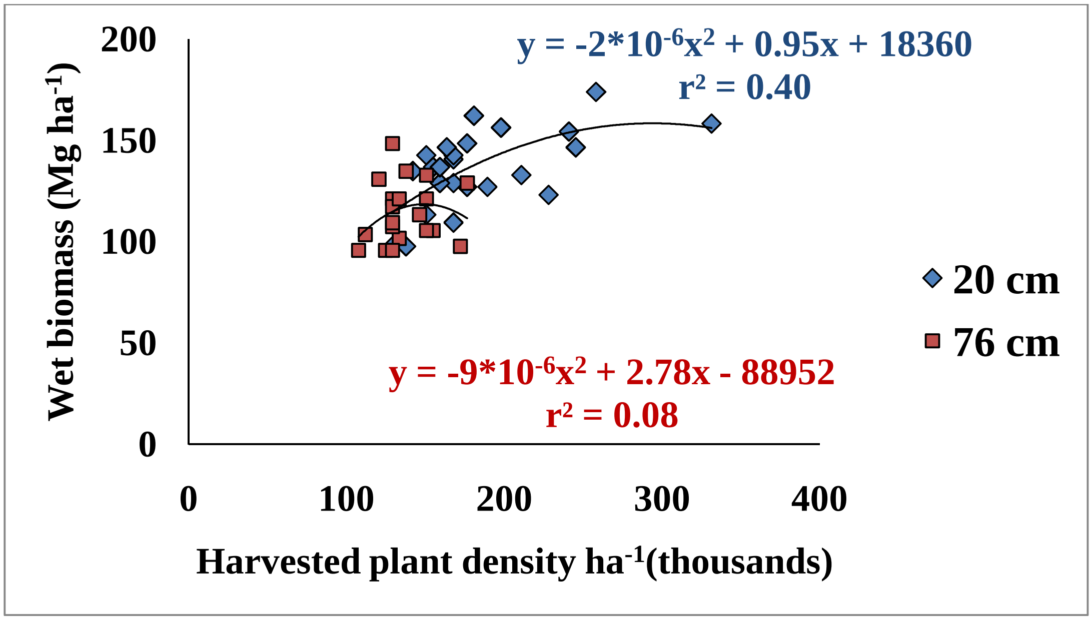

Figure 9. Wet biomass versus harvested plant density from Lahoma 2010.

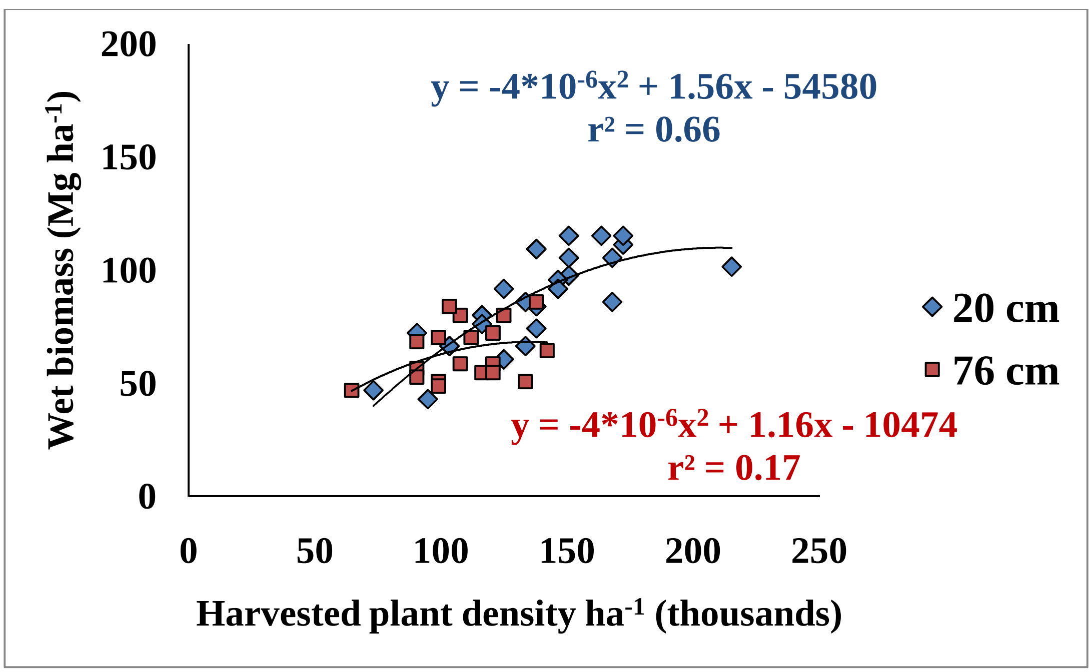

Figure 10. Wet biomass versus harvested plant density from Chickasha 2010.

significant model Pr > F 0.05 or less). At Lahoma and Haskell in 2009, maximum biomass yield was not achieved for the 20-cm row spacing populations (Figures 6 and 7). At Lahoma in 2009, the highest harvested plant population was 250,000 plants ha^{-1}. The curve-linear response at this location approximately approaches a maximum around 305,000 plants ha^{-1} when using the equation in Table 9. At the other two responsive locations (Lahoma 2010 and Chickasha 2010), wet biomass was maximized at 238,000 and 195,000 plants ha^{-1}, respectively (Figures 9 and 10). In Stillwater 2010, excellent seedling emergence was observed in the spring but the large amount of early season biomass coupled with late season heat and untimely rain events through the rest of the growing season were not conductive to maximize biomass yields.

In 2 out of 6 site-years a strong relationship existed between harvest population and wet biomass yield for the 76-cm row spacing (Table 9). At Haskell 2009 and Stillwater 2010, an increase in population increased wet biomass exponentially (Figures 7 and 8). At Haskell, biomass yield was still increasing at the highest seeding rate. At Stillwater 2010, a seeding rate of 147,000 plants ha^{-1} at harvest maximized wet biomass yield. No trends were observed at the non-responsive locations, indicating the lower seeding rates were sufficient to maximize biomass yield with the 76-cm row spacing.

Juice Extraction and Brix

Analysis for juice extraction followed the same trend as biomass (Table 10). As wet biomass increased, extracted juice increased in a corresponding relationship. Similar to the row spacing study, juice extraction was highly correlated with wet biomass (data not shown). Table 11 indicates brix measurements for all locations. Only cultivar M81

Table 10. Regression analysis (y = juice extraction; x = planting density) from locations in 2009 and 2010.

Locations	Row Spacing	Equation	r^2	SE[§]	Pr > F
Stillwater 2009					
	20 cm	$y = 1*10^{-6}x^2-0.56x+93187$	.04	9999	.08
	76 cm	$y = 3*10^{-6}x^2-1.3x+151623$	.09	18027	.71
Lahoma 2009					
	20 cm	$y = -1*10^{-7}x^2+0.0926x+12043$	.33	3391	.03
	76 cm	$y = -9*10^{-7}x^2+0.28x-982$	.33	2504	.10
Haskell 2009					
	20 cm	$y = 2*10^{-6}x^2-0.1243x+5620$	.97	1472	<0.01
	76 cm	$y = 3*10^{-6}x^2-0.61x+34210$	.91	3378	<0.01
Stillwater 2010					
	20 cm	$y = -7*10^{-7}x^2+0.26x+5198$	.17	7053	.12
	76 cm	$y = 4*10^{-7}x^2-0.12x+23423$	.02	4107	.84
Lahoma 2010					
	20 cm	$y = -4*10^{-7}x^2+0.24x-4776$	.23	4583	.04
	76 cm	$y = -2*10^{-6}x^2+0.69x-29381$	.04	8902	.98
Chickasha 2010					
	20 cm	$y = -4*10^{-7}x^2+0.2206x-8646$	.60	3062	<0.01
	76 cm	$y = -4*10^{-7}x^2+0.1461x+132$	.21	2823	.05

Table 11. Regression analysis (y = brix; x = planting density) from locations in 2009 and 2010.

Locations	Row Spacing	Equation	r^2	SE[§]	Pr > F
Stillwater 2009					
	20 cm	$y = -1*10^{-10}x^2+5*10^{-5}x+7$	.02	2.256	.85
	76 cm	$y = 3*10^{-10}x^2-0.0001x+23.1$	.13	1.384	.49
Lahoma 2009					
	20 cm	$y = -4*10^{-11}x^2+1*10^{-5}x+11.7$	.03	.716	.68
	76 cm	$y = 1*10^{-10}x^2-4*10^{-5}x+16.9$	.08	1.357	.33
Haskell 2009					
	20 cm	$y = 6*10^{-10}x^2-9*10^{-5}x+18.3$	.4	.653	.51
	76 cm	$y = -1*10^{-9}x^2+0.0002x+2.0$	.55	1.158	.28
Stillwater 2010					
	20 cm	$y = 3*10^{-11}x^2-2*10^{-5}x+15.9$	.09	.548	.23
	76 cm	$y = -6*10^{-11}x^2+2*10^{-5}x+12.3$	.01	.716	.96
Lahoma 2010					
	20 cm	$y = 1*10^{-10}x^2-5*10^{-5}x+18.9$	.10	1.06	.35
	76 cm	$y = 2*10^{-11}x^2-1*10^{-6}x+13.2$	.01	1.874	.68
Chickasha 2010					
	20 cm	$y = -4*10^{-11}x^2+1*10^{-5}x+13.9$	.01	.671	.77
	76 cm	$y = -1*10^{-10}x^2+1*10^{-5}x+14.4$	.17	.647	.09

was used in this study and no significant differences were observed in either row spacing or planting densities.

Stalk diameter, Plant Height, and Canopy Closure

Stalk diameter was not correlated with biomass, juice extraction, or brix at any location for both years (data not shown). It can be noted that increasing seeding density decreases average stalk yield (Figure 3). Plant height was not correlated with biomass, juice extraction, or brix at any location in both years (data not shown).

Fractional canopy closure for the 20-cm row spacing is shown in Figure 11. In general, the higher the seeding density the faster canopy closure occurs. This indicates greater light interception early in the season for the higher seeding densities. The 173,000 seeds ha^{-1} treatment reached full canopy closure earlier than the other planting densities. The lowest planting density of 74,000 plants ha^{-1} reached full canopy closure much later than the other planting densities. The 76-cm row spacing planting densities (Figure 12) was similar to the 20-cm row spacing. Higher seeding densities tended to have a greater slope, indicating quicker canopy development and increase light interception early in the growing season when compared to lower seeding rates.

Discussion

Row Spacing

Reducing the row spacing to less than 76 cm consistently increased wet biomass yield and juice extracted. Biomass yield was increased on average 34% when decreasing row spacing from 76 to 20 cm. When comparing 38 to 76-cm row spacing, the 38 cm

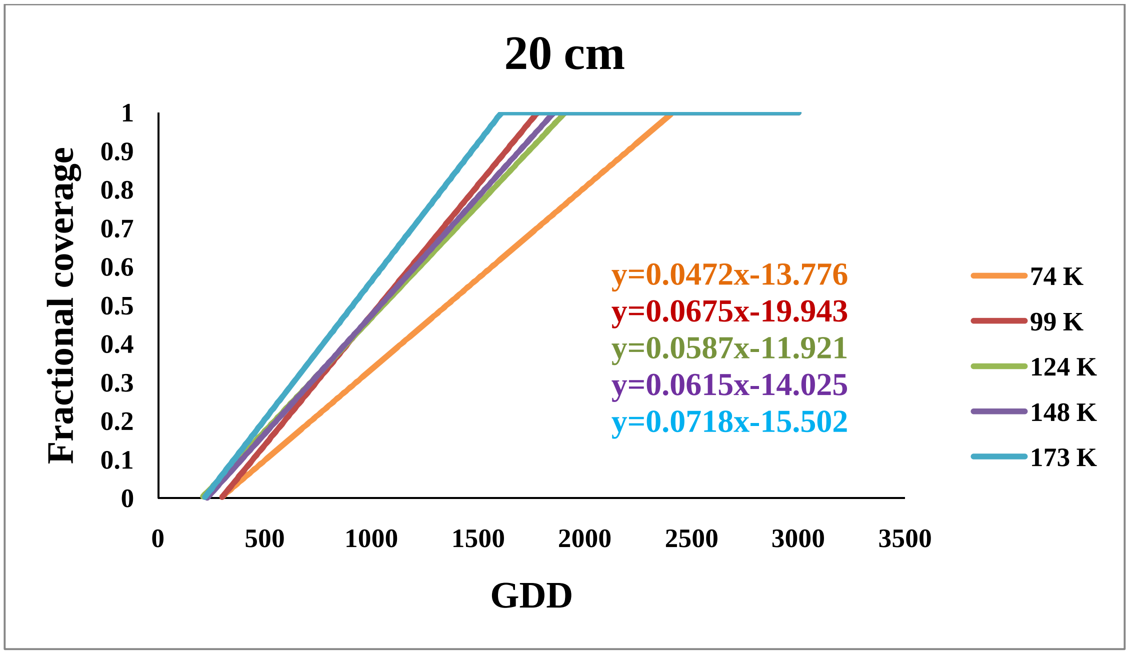

Figure 11. Fractional canopy coverage as a function of GDD at Stillwater in 2009.

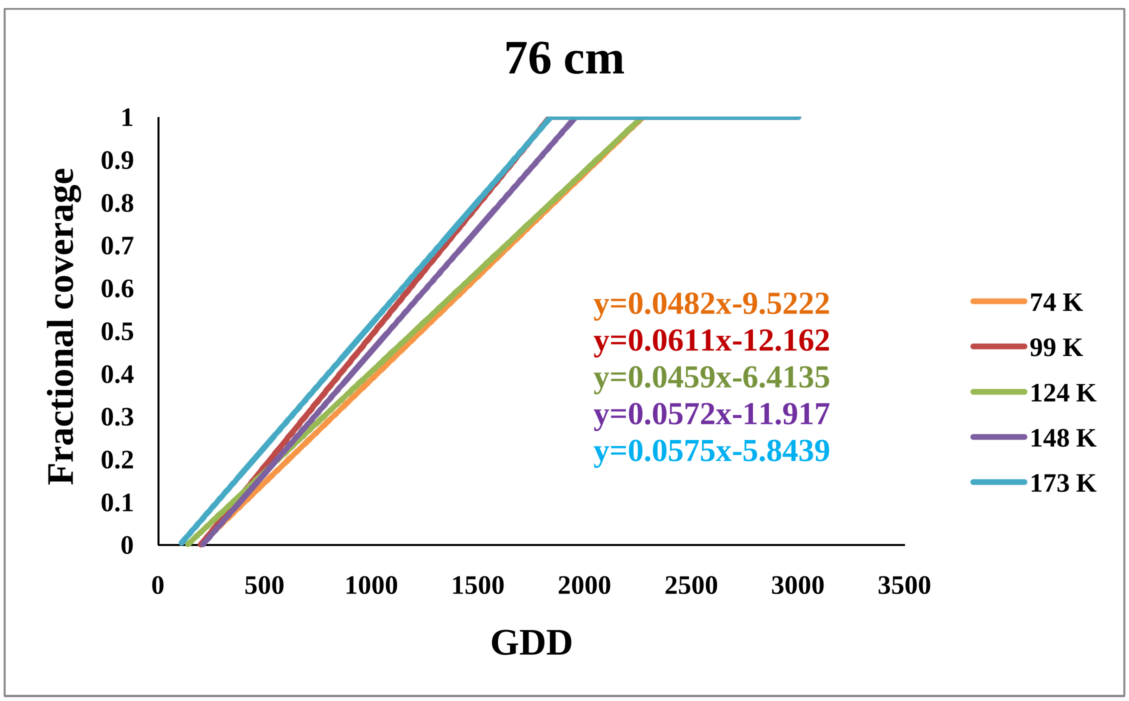

Figure 12. Fractional canopy coverage as a function of GDD at Stillwater in 2009.

was responsive 4 out of 6 site years and yielded on average 33% more wet biomass.

Juice extraction reacted positively 3 out of 6 site years when comparing 20 cm to 76 cm.

An average increase of 40% in juice extraction was observed when decreasing row spacing from 76 to 20 cm. The findings in our row spacing study were similar to what other researchers have observed (Broadhead and Freeman, 1979; Martin and Kelleher, 1984). Through a decrease in row spacing, growers can increase biomass production of sweet sorghum. Broadhead and Freeman (1979) noted that individual sweet sorghum plants in 105-cm rows weighed more but due to more plants per area within the 52.5-cm rows, the heavier stalks yielded less in biomass than the thinner stalks from the 52.5-cm rows within the same area.

On average, the 38-cm row spacing treatment developed a full canopy quicker compared to the 20 and 76-cm treatments. No explanation of why the 20-cm row spacing did not develop a full canopy quickest but may have been due to less in-row competition compared to the 38 and 76-cm treatments. Martin and Kelleher (1984) stated that sweet sorghum grown in narrow rows can crowd neighboring plants, similar to weed competition, causing plants to grow quickly in an effort to capture more sunlight.

One observation that was made was the increase in tillers as we moved to narrower row spacings. Unfortunately, tillers were not differentiated from the main plant at harvest as all stalks harvested were counted as a plant. This is similar to what Jones (1987) observed. He found that at a population of 75,000 plants ha^{-1}, plants in 38-cm row spacing had an average of 47% more tillers than 76-cm row spacing.

Seeding Density

Increasing planting density in the 20-cm rows consistently increased wet biomass yield and juice extracted. Optimum seeding density ranged from around 175,000 to

250,000 seeds ha^{-1} when sweet sorghum was grown in 20-cm row spacing. Seeding density only affected biomass yield 2 out of 6 site years. The non responsive locations observed no trends which signify lower seeding rates were satisfactory to reach max biomass yield at the 76-cm row spacing. The increases at the 20-cm row spacing are similar to what Cummins and Dobson (1974) and Stickler and Laude (1960) found. The highest seeding rate at the 20-cm row spacing reached full canopy closure the quickest, indicating greater light interception early in the season. This is consistent with what Jones (1987) found. The lower population with the 20-cm row spacing increased the amount of tillers per plant. Planting densities of 74,000 to 124,000 plants ha^{-1} exhibited much higher harvested plant density which can be explained by tillers. Under favorable growing conditions, sorghum can grow tall and tiller vigorously. Jones (1987) made the comment "plant low populations when rainfall is uncertain and let the plant decide how many tillers it can support". This is a safe idea where rainfall is low or inconsistent, such as western Oklahoma.

CHAPTER V

CONCLUSIONS

Sweet sorghum production appears to fit well into Oklahoma cropping systems. Although timely precipitation can increase wet biomass production significantly, sweet sorghum can grow and produce satisfactory results with limited moisture. The 20-cm row spacing produced the greatest amount of wet biomass and extracted juice. Determining the best row spacing and planting density can be described by moving west to east across the state. Because precipitation is less in the western part of the state and gradually increases more to the east, recommendations for 20-cm row spacing would be to drill at 175,000 to 250,000 seeds ha^{-1} moving from west to east across the state. Recommendations for 76 cm row spacing are planting 100,000-150,000 seeds ha^{-1} from west to east. Planting lower populations early in the growing season could increase the potential for sorghum to tiller, increasing total harvested plant density with minimal seed input.

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APPPENDICES

Appendix A. Stillwater Planting Density 2009

Plot	Rep	Row spacing (cm)	Seeding rate (seeds ha^{-1})	Height (m)	Plants harvested /$2.3m^2$	Weight (kg/2.3 m^2)	Subset weight (kg)	Juice extracted from subset (ml)	Brix	Average stalk diameter (mm)	Population (plants ha^{-1})	L ha^{-1}	Wet biomass (kg ha^{-1})	Dry biomass (kg ha^{-1})
101	1	20	74100	3.7	47	45	11	2400	12	22.71	202275	43037	195148.8	126847
102	1	20	98800	3.7	48	35	10	2150	11	22.40	206579	31965	148313.1	96404
103	1	20	123500	3.9	55	39	10	2600	11	22.02	236705	43742	167828	109088
104	1	20	148200	3.8	53	35	8	1800	9.5	19.83	228098	35544	152216.1	98940
105	1	20	172900	3.4	54	38	11	2500	12	22.24	232401	37209	161973.5	105283
106	1	76	74100	3.6	39	28	12	2550	12	21.63	167845	26170	120992.3	78645
107	1	76	98800	3.7	41	33	12	2700	14	21.66	176453	31417	142458.6	92598
108	1	76	123500	3.4	41	33	10	2150	13	21.93	176453	30703	142458.6	92598
109	1	76	148200	3.5	39	30	11	2450	13	21.16	167845	28258	130749.7	84987
110	1	76	172900	3.2	52	32	11	2350	14	20.41	223794	29920	138555.6	90061
201	2	76	74100	3.5	43	35	21	4800	13	21.41	185060	34283	152216.1	98940
202	2	76	98800	3.7	36	37	15	2800	13	23.45	154934	29578	158070.5	102746
203	2	20	148200	3.5	48	33	13	2700	.	20.55	206579	29251	142458.6	92598
204	2	76	148200	3.6	46	33	10	2400	12	21.62	197971	32334	140507.1	91330
205	2	20	98800	3.8	63	50	13	2950	.	20.75	271135	48595	216615.2	140800
206	2	76	172900	3.5	48	30	12	2750	13	21.73	206579	30499	130749.7	84987
207	2	20	74100	3.9	47	44	14	3100	12	19.99	202275	41746	189294.3	123041
208	2	20	123500	3.8	40	28	11	2350	.	19.32	172149	25706	119040.8	77376
209	2	76	123500	3.4	43	32	10	1900	13	20.00	185060	27257	136604.2	88793
210	2	20	172900	3.4	42	26	9	1950	11	22.03	180757	24338	113186.3	73571
301	3	76	98800	3.4	31	23	10	2300	12	20.27	133416	21519	97574.4	63423
302	3	76	123500	3.5	46	34	11	2700	.	21.30	197971	34860	146361.6	95135
303	3	76	172900	3.4	45	34	17	4250	.	22.65	193668	36582	144410.1	93867

304	3	20	74100	3.8	36	39	14	3125	.	23.62	154934	37744	169779.5	110357
305	3	20	123500	3.7	42	36	13	3150	13	20.51	180757	37398	156119	101477
306	3	76	74100	3.6	40	34	17	3950	13	21.50	172149	33999	144410.1	93867
307	3	20	98800	3.5	46	43	14	3150	13	22.00	197971	42930	185391.4	120504
308	3	20	148200	3.4	60	43	15	3350	13	19.83	258224	42802	185391.4	120504
309	3	20	172900	3.5	47	30	12	2100	12	20.98	202275	22942	128798.2	83719
310	3	76	148200	3.5	38	21	10	2400	12	20.19	163542	21597	89768.45	58349
401	4	20	148200	3.7	42	35	13	2500	13	21.23	180757	28197	148313.1	96404
402	4	76	98800	3.4	43	37	16	3600	12	21.20	185060	36299	160022	104014
403	4	20	98800	3.9	51	35	13	4000	12	20.22	219490	45115	148313.1	96404
404	4	20	172900	3.8	55	44	15	2750	12	21.22	236705	35876	189294.3	123041
405	4	76	123500	3.5	44	31	12	2650	12	20.61	189364	29828	132701.2	86256
406	4	76	74100	3.4	40	30	11	1950	12	22.42	172149	22729	126846.7	82450
407	4	20	123500	3.3	48	39	10	2200	13	20.58	206579	34991	165876.5	107820
408	4	20	74100	3.7	44	43	16	3950	11	22.29	189364	44860	185391.4	120504
409	4	76	148200	3.4	47	34	18	4250	13	18.64	202275	34295	146361.6	95135
410	4	76	172900	3.5	43	25	10	2450	11.5	21.06	185060	26360	107331.8	69766

Appendix B. Stillwater Row Spacing 2009

Plot	Rep	Row spacing (cm)	Variety	Height (m)	Plants harvested/ $2.3m^2$	Weight ($kg/2.3\ m^2$)	Juice extracted (ml)	Brix	Average stalk diameter (mm)	Population (plants ha^{-1})	L ha^{-1}	Wet biomass (kg ha^{-1})	Dry biomass (kg ha^{-1})
101	1	76	Topper	3.87	32	19.1	5050	11	22.29	137719	21734	81962	47538
102	1	20	M81	3.81	39	31.8	10600	11	23.58	167845	45620	136604	79230
103	1	38	M81	3.75	23	23.6	7500	10	21.88	98986	32278	101477	58857
104	1	76	M81	3.96	28	24.5	7250	11	22.60	120504	31202	105380	61121
105	1	20	Topper	3.57	42	31.3	9800	12	25.50	180757	42177	134653	78099
106	1	38	Topper	3.17	34	27.2	8500	13	23.51	146327	36582	117089	67912
201	2	38	M81	4.08	29	29.1	10250	11	25.16	124808	44113	124895	72439
202	2	76	M81	3.96	38	30.0	9500	12	21.32	163542	40885	128798	74703
203	2	20	M81	4.21	36	35.9	13000	12	26.26	154934	55948	154168	89417
204	2	76	Topper	3.54	45	32.2	9550	12	21.30	193668	41101	138556	80362
205	2	20	Topper	3.41	54	43.1	12000	14	20.92	232401	51645	185391	107527
206	2	38	Topper	3.63	38	25.0	7450	13.5	22.58	163542	32063	107332	62252
301	3	76	M81	3.66	39	29.5	8950	12	21.63	167845	38518	126847	73571
302	3	38	M81	3.87	37	27.7	8300	11	21.39	159238	35721	119041	69044
303	3	20	M81	3.90	52	45.4	12700	12	21.28	223794	54657	195149	113186
304	3	76	Topper	3.41	44	24.5	10100	13	21.38	189364	43468	105380	61121
305	3	20	Topper	3.35	35	25.0	8300	13	23.58	150630	35721	107332	62252
306	3	38	Topper	3.32	53	35.4	10350	13	21.60	228098	44544	152216	88285
401	4	38	M81	3.38	33	26.8	7650	12	22.36	142023	32924	115138	66780
402	4	76	Topper	3.72	44	30.0	7050	14	23.42	189364	30341	128798	74703
403	4	76	M81	3.26	37	22.2	6600	11	23.55	159238	28405	95623	55461
404	4	20	M81	3.75	37	40.0	11150	11	23.76	159238	47987	171731	99604
405	4	20	Topper	3.38	44	28.1	7000	13	23.02	189364	30126	120992	70176
406	4	38	Topper	3.05	61	42.2	11750	12	21.64	262527	50569	181488	105263

Appendix C. Lahoma Planting Density 2009.

Plot	Rep	Row spacing (cm)	Seeding rate (seeds ha^{-1})	Height (m)	Plants harvested /2.3m^2	Weight (kg/2.3m^2)	Juice extracted (ml)	Brix	Average stalk diameter (mm)	Population (plants ha^{-1})	L ha^{-1}	Wet biomass (kg ha^{-1})	Dry biomass (kg ha^{-1})
101	1	20	74100	3.4	.	27.69	7350	13	23.162	.	31632	119041	74996
102	1	20	98800	3.5	.	24.52	6650	13	23.224	.	28620	105380	66390
103	1	20	123500	3.1	.	21.34	6250	12	21.142	.	26898	91720	57784
104	1	20	148200	3.4	.	28.15	7400	12	23.106	.	31848	120992	76225
105	1	20	172900	3.2	.	21.79	5900	12	24.842	.	25392	93671	59013
106	1	76	74100	3.3	.	17.71	4500	12	22.764	.	19367	76108	47948
107	1	76	98800	3.0	.	14.53	3350	12	22.52	.	14417	62448	39342
108	1	76	123500	3.3	.	15.44	3800	12	24.82	.	16354	66351	41801
109	1	76	148200	3.4	.	19.98	5600	12.5	22.116	.	24101	85865	54095
110	1	76	172900	3.0	26	15.44	4000	12	23.106	111897	17215	66351	41801
201	2	76	74100	2.8	25	17.25	4200	14	23.208	107593	18076	74157	46719
202	2	76	98800	3.1	28	16.34	4600	14	23.748	120504	19797	70254	44260
203	2	20	148200	3.3	33	19.98	5050	13	22.618	142023	21734	85865	54095
204	2	76	148200	3.3	30	16.80	4500	13	21.756	129112	19367	72205	45489
205	2	20	98800	3.4	25	15.89	4500	12	21.766	107593	19367	68302	43030
206	2	76	172900	3.4	43	17.71	4500	13	21.328	185060	19367	76108	47948
207	2	20	74100	3.5	35	23.15	6400	13	22.228	150630	27544	99526	62701
208	2	20	123500	3.4	39	26.33	7150	12.5	21.538	167845	30772	113186	71307
209	2	76	123500	3.6	30	18.16	5100	12	21.368	129112	21949	78060	49177
210	2	20	172900	3.4	35	17.71	4550	12	21.524	150630	19582	76108	47948
301	3	76	98800	3.4	21	15.89	4100	14.5	22.624	90378	17645	68302	43030
302	3	76	123500	3.5	36	16.80	4700	14	21.876	154934	20228	72205	45489
303	3	76	172900	3.4	31	17.71	4400	15	20.04	133416	18936	76108	47948
304	3	20	74100	3.3	31	19.98	5000	14	20.728	133416	21519	85865	54095
305	3	20	123500	3.3	42	20.88	5150	14	20.946	180757	22164	89768	56554
306	3	76	74100	3.3	30	19.52	4900	14	20.742	129112	21088	83914	52866

307	3	20	98800	3.4	35	23.61	5400	13.5	21.696	150630	23240	101477	63931
308	3	20	148200	3.4	39	25.88	6100	13	24.126	167845	26253	111235	70078
309	3	20	172900	3.4	56	26.33	6500	13	20.59	241009	27974	113186	71307
310	3	76	148200	3.6	32	16.80	3950	13.5	21.77	137719	17000	72205	45489
401	4	20	148200	3.4	27	20.43	4800	13	21.812	116201	20658	87817	55325
402	4	76	98800	3.3	34	21.34	4950	13	21.162	146327	21303	91720	57784
403	4	20	98800	3.2	31	19.98	5000	13	22.462	133416	21519	85865	54095
404	4	20	172900	3.4	42	25.42	5050	12.5	20.924	180757	21734	109283	68848
405	4	76	123500	3.5	32	19.98	4600	13	21.204	137719	19797	85865	54095
406	4	76	74100	3.4	31	22.70	5150	14	23.752	133416	22164	97574	61472
407	4	20	123500	3.5	36	24.06	5600	13	19.434	154934	24101	103429	65160
408	4	20	74100	3.6	23	20.88	5100	13	26.74	98986	21949	89768	56554
409	4	76	148200	3.4	35	20.88	5050	12.5	22.384	150630	21734	89768	56554
410	4	76	172900	3.4	37	21.34	4900	13	21.698	159238	21088	91720	57784

Appendix D. Lahoma Row Spacing 2009.

Plot	Rep	Row spacing (cm)	Variety	Height (m)	Plants harvested/2.3 m^2	Weight (kg/2.3 m^2)	Juice extracted (ml)	Brix	Average stalk diameter (mm)	Population (plants ha^{-1})	L ha^{-1}	Wet biomass (kg ha^{-1})	Dry biomass (kg ha^{-1})
101	1	20	Topper	2.8	33	16	3350	15.5	22.024	189364	14417	91069	51910
102	1	38	Topper	3.0	41	21	4900	16	22.304	176453	21088	89768	51168
103	1	76	Topper	3.0	36	18	4000	16	19.636	154934	17215	76108	43382
104	1	20	M81	3.0	30	19	3850	15.5	20.074	129112	16569	80011	45606
105	1	38	M81	3.0	46	28	5500	15.5	22.816	197971	23671	119041	67853
106	1	76	M81	3.0	33	19	4200	16	21.82	142023	18076	81962	46719
201	2	20	Topper	2.9	35	16	3500	17	21.036	200841	15063	91069	51910
202	2	38	M81	.	17	17	4300	15	.	73163	18506	74157	42269
203	2	76	M81	3.5	27	19	4850	14	21.584	116201	20873	81962	46719
204	2	20	M81	3.4	36	25	6300	14	21.552	154934	27113	105380	60067
205	2	76	Topper	3.0	36	20	4450	15.5	20.182	154934	19152	83914	47831
206	2	38	Topper	3.0	41	20	4300	17	21.714	176453	18506	87817	50056
301	3	76	M81	3.0	19	15	3050	15	24.838	81771	13126	64399	36707
302	3	38	Topper	2.9	34	22	4500	16	20.19	146327	19367	93671	53393
303	3	20	Topper	3.1	44	25	5700	15	20.676	189364	24531	109283	62291
304	3	38	M81	3.4	22	19	4900	14	21.978	94682	21088	81962	46719
305	3	20	M81	3.5	41	24	6800	13	24.612	176453	29265	103429	58954
306	3	76	Topper	3.0	43	21	4850	16	20.61	185060	20873	89768	51168
401	4	38	M81	3.4	32	29	6600	15	.	137719	28405	124895	71190
402	4	38	Topper	3.2	50	26	6150	15.5	20.58	215186	26468	111235	63404
403	4	76	Topper	3.2	55	26	6300	16	20.4	236705	27113	113186	64516
404	4	20	Topper	3.4	46	26	6600	16	20.894	226252	28405	129355	73732
405	4	76	M81	3.6	38	25	6500	14	21.17	163542	27974	109283	62291
406	4	20	M81	3.7	34	25	6750	15	21.406	146327	29050	107332	61179

Appendix E. Haskell Planting Density 2009.

Plot	Rep	Row spacing (cm)	Seeding rate (seeds ha^{-1})	Plants harvested/2.3 m^2	Weight (kg/2.3 m^2)	Juice extracted (ml)	Brix	Population (plants ha^{-1})	L ha^{-1}	Wet biomass (kg ha^{-1})	Dry biomass (kg ha^{-1})
101	1	20	74100	31	24.062	4100	15	.	17645	103428.9	65160.18
102	1	20	98800	29	17.706	2750	14	.	11835	76108.03	47948.06
103	1	20	123500	23	17.706	2900	14	.	12481	76108.03	47948.06
104	1	20	148200	36	22.7	3950	14	.	17000	97574.4	61471.87
105	1	20	172900	17	12.258	1850	14	.	7962	52690.18	33194.81
106	1	76	74100	20	15.89	2600	15	.	11190	68302.08	43030.31
107	1	76	98800	26	17.252	2950	15	.	12696	74156.54	46718.62
108	1	76	123500	26	19.522	3250	14.5	.	13987	83913.98	52865.81
109	1	76	148200	28	14.982	2200	15	.	9468	64399.1	40571.44
110	1	76	172900	29	16.798	2800	15	124808	12050	72205.06	45489.19
201	2	76	74100	30	17.252	2650	15	129112	11405	74156.54	46718.62
202	2	76	98800	21	13.62	1550	15	90378	6671	58544.64	36883.12
203	2	20	148200	17	13.166	1600	15	73163	6886	56593.15	35653.69
204	2	76	148200	31	19.522	2950	14	133416	12696	83913.98	52865.81
205	2	20	98800	17	13.166	1450	15	73163	6240	56593.15	35653.69
206	2	76	172900	26	15.436	1700	15	111897	7316	66350.59	41800.87
207	2	20	74100	20	13.62	1900	15.5	86075	8177	58544.64	36883.12
208	2	20	123500	11	9.988	900	15.5	47341	3873	42932.74	27047.62
209	2	76	123500	23	12.712	1750	15	98986	7532	54641.66	34424.25
210	2	20	172900	21	15.436	2300	15	90378	9899	66350.59	41800.87

Appendix F. Haskell Row Spacing 2009.

Plot	Rep	Row spacing (cm)	Variety	Plants harvested/2.3 m^2	Weight (kg/2.3 m^2)	Juice extracted (ml)	Brix	Population (plants ha^{-1})	L ha^{-1}	Wet biomass (kg ha^{-1})	Dry biomass (kg ha^{-1})
101	1	20	Topper	21	14	1700	18	36590	7316	58545	37892.77
102	1	38	Topper	36	23	4200	18	62726	18076	99526	64417.70
103	1	76	Topper	32	14	1650	16	55757	7101	60496	39155.86
104	1	20	M81	22	15	2150	16	38333	9253	64399	41682.04
105	1	38	M81	27	20	3650	15	47045	15709	87817	56839.15
106	1	76	M81	38	15	2200	16	66211	9468	64399	41682.04
201	2	20	Topper	16	11	1100	18	27878	4734	46836	30314.21
202	2	38	M81	38	23	4350	16	66211	18721	99526	64417.70
203	2	76	M81	28	15	2100	16	48787	9038	62448	40418.95
204	2	20	M81	28	15	2300	16	48787	9899	66351	42945.14
205	2	76	Topper	33	13	1850	17	57499	7962	56593	36629.67
206	2	38	Topper	33	16	2250	18	57499	9683	68302	44208.23
301	3	76	M81	38	19	2600	15.5	66211	11190	80011	51786.78
302	3	38	Topper	39	20	2900	17	67954	12481	87817	56839.15
303	3	20	Topper	21	13	1600	17.5	36590	6886	56593	36629.67
304	3	38	M81	22	14	2000	15	38333	8607	60496	39155.86
305	3	20	M81	14	12	1850	14	24394	7962	52690	34103.49
306	3	76	Topper	40	13	1700	16	69696	7316	56593	36629.67

Appendix G. Stillwater Planting Density 2010.

Plot	Rep	Row spacing (cm)	Seeding rate (seeds ha^{-1})	Height (m)	Plants harvested (2.3 m^2)	Weight (kg/2.3 m^2)	Juice extracted (ml)	Brix	Average stalk diameter (mm)	Population (plants ha^{-1})	L ha^{-1}	Wet biomass (kg ha^{-1})	Dry biomass (kg ha^{-1})
101	1	20	123500	3.4	35	35	8000	14.5	20.05	150630	34430	148313	9936977
102	1	20	148200	3.5	45	35	6300	14	18.67	193668	27113	148313	9936977
103	1	20	172900	3.4	45	35	7750	14	16.75	193668	33354	150265	10067727
104	1	20	197600	3.4	51	32	5950	13.5	19.25	219490	25607	138556	9283228
105	1	20	222300	3.4	63	31	6300	14	18.31	271135	27113	134653	9021729
106	1	20	247000	3.6	46	20	6800	13.5	16.90	197971	29265	87817	5883736
107	1	76	74100	3.7	35	24	4100	13	20.09	150630	17645	103429	6929734
108	1	76	98800	3.7	25	32	5010	14	18.44	107593	21562	138556	9283228
109	1	76	123500	3.5	37	24	4050	14	19.70	159238	17430	101477	6798984
110	1	76	148200	3.6	47	20	4550	14	20.23	202275	19582	85865	5752987
111	1	76	172900	3.1	37	25	4300	15	20.34	159238	18506	107332	7191233
201	2	20	148200	3.5	49	32	6700	14	18.64	210883	28835	136604	9152479
202	2	76	74100	3.6	25	18	4250	13.5	20.88	107593	18291	76108	5099238
203	2	76	123500	3.6	27	19	4300	14	20.23	116201	18506	80011	5360738
204	2	20	247000	3.1	58	26	5900	14	17.83	249616	25392	113186	7583482
205	2	20	123500	3.5	30	20	4950	14	19.89	129112	21303	85865	5752987
206	2	76	98800	3.5	39	20	4400	13.5	20.97	167845	18936	83914	5622237
207	2	76	148200	3.4	46	15	2900	13	19.84	197971	12481	64399	4314740
208	2	20	197600	3.3	56	27	5500	13.5	18.20	241009	23671	115138	7714232
209	2	76	172900	3.4	35	15	2750	14	20.00	150630	11835	66351	4445490
210	2	20	222300	3.1	61	27	5250	14	17.24	262527	22595	117089	7844982
211	2	20	172900	3.3	58	28	5750	14	18.64	249616	24746	120992	8106481
301	3	76	148200	3.5	30	23	5050	15	18.80	129112	21734	97574	6537485
302	3	20	247000	3.4	54	30	6300	14	17.52	232401	27113	130750	8760230
303	3	20	172900	3.4	53	38	8050	14.5	19.73	228098	34645	163925	10982974
304	3	20	123500	3.3	51	34	7750	14	18.98	219490	33354	146362	9806227

305	3	76	172900	3.5	38	19	3300	13	19.16	163542	14202	81962	5491487
306	3	20	197600	3.4	62	32	6300	13	17.35	266831	27113	138556	9283228
307	3	20	148200	3.3	63	22	3850	13.5	19.92	271135	16569	93671	6275985
308	3	76	98800	3.3	38	20	3450	13.5	22.60	163542	14848	87817	5883736
309	3	76	74100	3.3	22	17	3650	13.5	21.86	94682	15709	74157	4968488
310	3	20	222300	3.5	65	28	5300	14	17.79	279742	22810	120992	8106481
311	3	76	123500	3.5	29	18	3350	14	18.48	124808	14417	76108	5099238
401	4	76	172900	3.6	31	19	3100	13.5	19.93	133416	13342	80011	5360738
402	4	20	123500	3.6	41	34	6750	14	21.72	176453	29050	144410	9675478
403	4	20	222300	3.4	54	30	5250	14	18.61	232401	22595	130750	8760230
404	4	76	123500	3.6	31	20	2500	13	19.85	133416	10759	85865	5752987
405	4	20	247000	3.5	69	28	1100	13	19.62	296957	4734	120992	8106481
406	4	76	74100	3.4	24	17	2400	13	22.64	103289	10329	72205	4837739
407	4	20	197600	3.3	60	25	3050	13.5	17.81	258224	13126	105380	7060484
408	4	20	172900	3.1	52	29	4500	12.5	18.49	223794	19367	124895	8367981
409	4	20	148200	3.2	48	27	3500	13.5	20.34	206579	15063	115138	7714232
410	4	76	98800	3.2	29	18	2500	13	21.01	124808	10759	78060	5229988
411	4	76	148200	3.2	32	20	3050	13	18.62	137719	13126	87817	5883736

Appendix H. Stillwater Row Spacing 2010.

Plot	Rep	Row spacing (cm)	Variety	Height (m)	Plants harvested /2.3 m^2	Weight ($kg/2.3\ m^2$)	Juice extracted (ml)	Brix	Average stalk diameter (mm)	Population (plants ha^{-1})	L ha^{-1}	Wet biomass (kg ha^{-1})	Dry biomass (kg ha^{-1})
101	1	20	Topper	3.0	37	32	4400	15	19.11	159238	18936	138556	97765
102	1	38	Topper	3.1	30	27	4050	15	23.56	129112	17430	117089	82618
103	1	76	Topper	3.3	32	25	3550	16	22.48	137719	15278	105380	74356
104	1	20	M81	3.7	35	29	4500	16	21.49	150630	19367	124895	88126
105	1	38	M81	3.3	45	27	4100	16.5	18.75	193668	17645	115138	81241
106	1	76	M81	3.7	22	18	3300	16	21.14	94682	14202	78060	55079
107	1	20	Topper	3.2	58	25	3750	15	18.34	249616	16139	107332	75733
108	1	20	M81	3.2	60	30	4400	16	17.99	258224	18936	128798	90880
201	2	38	Topper	3.2	46	29	4000	17	22.23	197971	17215	122944	86749
202	2	38	M81	3.7	48	29	5050	17	19.37	206579	21734	122944	86749
203	2	20	M81	4.0	39	32	6000	17.5	19.02	167845	25822	138556	97765
204	2	76	Topper	3.6	28	25	3550	17	21.76	120504	15278	105380	74356
205	2	20	Topper	3.5	40	32	5250	17	20.67	172149	22595	136604	96388
206	2	76	M81	3.5	35	24	3950	16.5	19.86	150630	17000	101477	71602
207	2	20	M81	3.6	42	29	5300	15	19.33	180757	22810	124895	88126
208	2	20	Topper	3.5	43	31	4600	15.5	22.91	185060	19797	132701	93634
301	3	20	Topper	3.1	58	35	5250	16.5	26.72	249616	22595	152216	107404
302	3	76	M81	3.6	36	23	3800	15.5	21.44	154934	16354	97574	68848
303	3	76	Topper	3.2	37	21	3250	16	22.56	159238	13987	91720	64718
304	3	20	M81	3.7	44	32	6050	15	20.24	189364	26038	136604	96388
305	3	38	M81	3.9	87	53	9150	16	18.25	374424	39379	226373	159729
306	3	20	M81	3.5	62	41	7200	15.5	20.19	266831	30987	175634	123927

307	3	38	Topper	3.3	70	43	5900	15.5	18.70	301261	25392	183440	129435
308	3	20	Topper	3.3	64	33	4500	16.5	24.00	275439	19367	142459	100519
401	4	20	Topper	3.4	54	29	4300	16	20.99	232401	18506	122944	86749
402	4	20	M81	3.6	39	30	5950	15	20.22	167845	25607	130750	92257
403	4	38	Topper	3.2	52	30	3950	16	18.12	223794	17000	128798	90880
404	4	38	M81	3.6	43	31	4500	15.5	18.35	185060	19367	132701	93634
405	4	20	M81	3.6	45	28	4500	14.5	19.43	193668	19367	119041	83995
406	4	76	M81	3.4	25	21	3900	15	20.10	107593	16785	91720	64718
407	4	20	Topper	3.4	56	34	5000	15.5	26.71	241009	21519	144410	101896
408	4	76	Topper	3.1	37	23	3250	15.5	21.33	159238	13987	97574	68848

Appendix I. Lahoma Planting Density 2010.

Plot	Rep	Row spacing (cm)	Seeding rate (seeds ha^{-1})	Height (m)	Plants harvested /2.3 m^2	Weight (kg/2.3 m^2)	Subset weight (kg)	Juice extracted from subset (ml)	Brix	Population (plants ha^{-1})	L ha^{-1}	Wet biomass (kg ha^{-1})	Dry biomass (kg ha^{-1})
101	1	20	123500	2.96	30	23	15	1950	15	129112	13113	97574	64399
102	1	20	148200	3.26	41	30	16	2450	15	176453	19038	126847	83719
103	1	20	172900	3.29	39	25	15	1800	15	167845	13557	109283	72127
104	1	20	197600	3.35	32	23	15	1850	15	137719	12063	97574	64399
105	1	20	222300	3.38	53	29	20	3250	14	228098	19582	122944	81143
106	1	20	247000	2.93	57	34	23	3600	14	245312	23240	146362	96599
107	1	76	74100	3.38	29	22	16	2450	13.5	124808	14352	95623	63111
108	1	76	98800	3.38	31	24	19	2600	15	133416	14192	101477	66975
109	1	76	123500	3.44	30	22	16	1850	15	129112	11147	95623	63111
110	1	76	148200	3.41	36	25	18	2700	15	154934	16089	105380	69551
111	1	76	172900	3.26	40	23	17	2150	15	172149	12504	97574	64399
201	2	20	148200	3.11	44	30	21	3250	14	189364	19764	126847	83719
202	2	76	74100	3.41	25	22	17	2800	14	107593	15959	95623	63111
203	2	76	123500	3.47	30	25	18	3000	13.5	129112	17753	107332	70839
204	2	20	247000	3.44	77	37	23	4200	13	331387	29283	158071	104327
205	2	20	123500	3.54	35	33	25	4550	14	150630	25991	142459	94023
206	2	76	98800	3.63	26	24	17	2400	14	111897	14796	103429	68263
207	2	76	148200	3.54	30	25	18	2750	13	129112	16569	109283	72127
208	2	20	197600	3.47	39	30	22	3900	13	167845	23079	128798	85007
209	2	76	172900	3.44	35	25	17	2550	14	150630	16017	105380	69551
210	2	20	172900	3.51	33	31	20	3250	14	142023	21934	134653	88871
211	2	20	222300	3.17	35	26	18	2750	13.5	150630	17601	113186	74703
301	3	76	148200	3.41	34	26	19	3100	14	146327	18424	113186	74703
302	3	20	247000	3.35	49	31	21	4000	13	210883	25448	132701	87583
303	3	20	172900	3.54	36	32	23	4000	12	154934	24101	136604	90159
304	3	20	123500	3.41	37	30	20	3350	12	159238	21626	128798	85007

305	3	76	172900	3.47	41	30	21	3550	12	176453	21455	128798	85007
306	3	20	197600	3.66	46	36	26	4350	12	197971	25822	156119	103039
307	3	20	148200	3.69	42	38	27	5300	12	180757	32088	161974	106903
308	3	76	98800	3.69	30	28	20	3550	13	129112	22029	120992	79855
309	3	76	74100	3.63	30	35	25	5200	12	129112	31497	148313	97887
310	3	20	222300	3.44	37	32	22	4300	11.5	159238	26988	136604	90159
311	3	76	123500	3.41	35	31	21	3750	13	150630	23858	132701	87583
401	4	76	172900	3.35	35	28	20	3300	13.5	150630	20478	120992	79855
402	4	20	123500	3.57	39	33	21	4250	12.5	167845	28629	140507	92735
403	4	20	222300	3.69	39	33	23	4550	12	167845	28590	142459	94023
404	4	76	123500	3.78	30	27	16	2550	13	129112	18813	117089	77279
405	4	20	247000	3.78	56	36	20	3550	12	241009	27431	154168	101751
406	4	76	74100	3.99	31	28	21	4200	12	133416	23844	120992	79855
407	4	20	197600	3.84	60	40	27	5050	11.5	258224	32239	173682	114630
408	4	20	172900	3.78	41	35	25	5000	11.5	176453	29204	148313	97887
409	4	20	148200	3.84	38	34	23	4550	12	163542	29373	146362	96599
410	4	76	98800	4.02	28	30	22	4100	12	120504	24630	130750	86295
411	4	76	148200	3.78	32	31	19	2750	13	137719	19918	134653	88871

Appendix J. Lahoma Row Spacing 2010.

Plot	Rep	Row spacing (cm)	Variety	Height (m)	Plants harvested /2.3 m^2	Weight (kg/2.3 m^2)	Subset weight (kg)	Juice extracted (ml)	Brix	Population (plants ha^{-1})	L ha^{-1}	Wet biomass (kg ha^{-1})	Dry biomass (kg ha^{-1})
101	1	20	Topper	3.0	42	24	12	2100	16	45505	18423	103429	68263
102	1	38	Topper	2.9	52	20	11	1800	16	35877	14525	87817	57959
103	1	76	Topper	2.9	30	15	11	2250	16	30615	12395	62448	41215
104	1	20	M81	3.2	44	21	11	2250	16	44966	18205	91720	60535
105	1	38	M81	3.1	63	21	12	2450	15	47080	19061	91720	60535
106	1	76	M81	3.3	27	17	10	2300	15	42231	17098	74157	48943
107	1	20	Topper	3.0	47	25	12	2650	16.5	56340	22810	105380	69551
108	1	20	M81	3.3	41	30	16	3650	15	74275	30071	130750	86295
201	2	38	Topper	3.0	51	27	13	2950	15.5	63800	25830	115138	75991
202	2	38	M81	3.2	50	28	19	4650	15	71792	29066	119041	78567
203	2	20	M81	3.4	41	24	13	2900	14	55277	22379	101477	66975
204	2	76	Topper	3.2	35	21	9	2100	15	52460	21239	91720	60535
205	2	20	Topper	3.1	43	24	15	3500	15	59755	24192	103429	68263
206	2	76	M81	3.5	31	20	12	3050	14	53621	21709	83914	55383
207	2	20	M81	3.5	38	32	15	4300	14	94109	38101	136604	90159
208	2	20	Topper	3.2	40	25	17	4100	15	63082	25539	107332	70839
301	3	20	Topper	3.0	41	30	15	3200	14.5	69096	27974	126847	83719
302	3	76	M81	3.4	30	21	12	2750	13.5	50887	20602	91720	60535
303	3	76	Topper	3.1	42	25	14	3350	14	64100	25951	105380	69551
304	3	20	M81	3.7	51	38	27	7650	12	112494	45544	161974	106903
305	3	38	M81	3.5	58	29	14	3350	13	72371	29300	122944	81143
306	3	20	M81	3.6	35	28	14	2950	14	63764	25815	119041	78567
307	3	38	Topper	3.2	52	29	16	3800	14	72711	29437	122944	81143
308	3	20	Topper	2.9	50	33	19	4500	14	83143	33661	142459	94023

401	4	20	Topper	3.3	44	33	17	3950	14	79559	32210	140507	92735
402	4	20	M81	3.1	47	32	16	2800	15	57876	23431	136604	90159
403	4	38	Topper	3.2	57	31	17	3450	14	67401	27288	132701	87583
404	4	38	M81	3.3	45	41	19	4800	14.5	109339	44267	175634	115918
405	4	20	M81	3.4	53	34	26	7250	14	99658	40347	146362	96599
406	4	76	M81	3.5	32	20	12	3050	13	54037	21877	87817	57959
407	4	20	Topper	3.1	44	25	13	2550	14	50475	20435	105380	69551
408	4	76	Topper	3.0	36	15	9	1700	15	28914	11706	62448	41215

Appendix K. Chickasha Planting Density 2010.

Plot	Rep	Row spacing (cm)	Seeding rate (seeds ha^{-1})	Height (m)	Plants harvested /2.3 m^2	Weight (kg/2.3 m^2)	Subset weight (kg)	Juice extracted (ml)	Brix	Average stalk diameter (mm)	Population (plants ha^{-1})	L ha^{-1}	Wet biomass (kg ha^{-1})
101	1	20	123500	3.0	39	24.516	14.528	2650	13	23.91	167845	19246	105380
102	1	20	148200	2.9	32	19.522	12.258	2300	14	19.90	137719	15764	83914
103	1	20	172900	2.9	31	19.976	13.62	3100	14	17.66	133416	19568	85865
104	1	20	197600	3.0	38	26.786	15.89	3100	14	19.02	163542	22490	115138
105	1	20	222300	3.0	40	25.878	16.344	3500	14	20.85	172149	23850	111235
106	1	20	247000	3.0	29	14.074	9.534	1700	14	22.06	124808	10800	60496
107	1	76	123500	2.8	21	13.166	9.988	1600	14	22.10	90378	9077	56593
108	1	76	98800	2.8	29	18.614	11.804	1900	14	22.97	124808	12895	80011
109	1	76	74100	3.0	28	16.798	10.442	1750	14	21.68	120504	12116	72205
110	1	76	148200	3.1	27	12.712	8.172	1500	14	20.66	116201	10042	54642
111	1	76	172900	3.0	31	11.804	8.626	1300	14	20.37	133416	7656	50739
201	2	20	148200	3.0	50	23.608	14.982	3000	14.5	18.99	215186	20345	101477
202	2	76	123500	3.2	32	19.976	11.35	2250	14.5	21.29	137719	17043	85865
203	2	76	74100	3.2	28	16.798	11.804	1850	14.5	20.74	120504	11330	72205
204	2	20	247000	3.0	29	21.338	14.982	2850	14.5	20.63	124808	17469	91720
205	2	20	123500	3.0	32	25.424	16.798	2900	15	23.04	137719	18890	109283
206	2	76	98800	2.9	23	11.804	8.626	1500	14	20.93	98986	8834	50739
207	2	76	148200	3.0	28	13.62	8.626	1550	14	20.64	120504	10533	58545
208	2	20	197600	3.1	35	22.7	11.35	2050	14	21.69	150630	17645	97574
209	2	76	172900	3.0	33	14.982	8.626	1450	14	21.94	142023	10839	64399
210	2	20	222300	2.9	39	19.976	10.442	1750	14	21.88	167845	14408	85865
211	2	20	172900	2.8	32	17.252	12.258	1850	13.5	21.12	137719	11206	74157
301	3	76	148200	3.1	28	12.712	9.534	1650	14.5	21.46	120504	9468	54642
302	3	20	247000	3.0	22	9.988	8.172	1300	14	19.21	94682	6838	42933
303	3	20	172900	3.0	34	22.246	15.89	2500	15.5	22.19	146327	15063	95623
304	3	20	123500	3.1	21	16.798	7.718	1100	15	22.42	90378	10304	72205

305	3	76	172900	2.9	23	11.35	8.172	1400	15	19.37	98986	8368	48787
306	3	20	197600	3.3	34	21.338	13.166	1900	15.5	21.22	146327	13253	91720
307	3	20	148200	2.9	40	26.786	16.798	2700	15.5	21.65	172149	18529	115138
308	3	76	98800	3.0	21	15.89	8.172	1250	15.5	21.42	90378	10460	68302
309	3	76	123500	3.1	25	18.614	10.442	1550	15.5	22.40	107593	11891	80011
310	3	20	222300	2.9	17	10.896	6.356	1000	14	19.57	73163	7378	46836
311	3	76	74100	2.9	26	16.344	11.804	2100	14	21.07	111897	12514	70254
401	4	76	172900	3.1	25	13.62	13.62	2600	14	18.47	107593	11190	58545
402	4	20	123500	3.0	27	18.614	12.258	1800	15	23.95	116201	11764	80011
403	4	20	222300	3.0	35	26.786	17.252	2500	14	19.00	150630	16705	115138
404	4	76	74100	3.0	23	16.344	11.804	2000	14.5	20.25	98986	11918	70254
405	4	20	247000	3.0	24	15.436	12.712	1850	14.5	22.36	103289	9668	66351
406	4	76	123500	3.1	21	12.258	12.258	2000	15	21.37	90378	8607	52690
407	4	20	197600	3.0	31	15.436	11.35	1400	15.5	26.32	133416	8194	66351
408	4	20	172900	3.0	35	24.516	15.436	2250	15	18.93	150630	15379	105380
409	4	20	148200	3.0	27	17.706	11.35	1300	15	23.40	116201	8728	76108
410	4	76	98800	3.2	24	19.522	12.712	2050	14.5	23.15	103289	13549	83914
411	4	76	148200	3.0	15	10.896	10.896	1850	14.5	21.32	64556	7962	46836

Appendix L. Chickasha Row Spacing 2010.

Plot	Rep	Row spacing (cm)	Variety	Height (m)	Plants harvested /2.3 m^2	Weight (kg/2.3 m^2)	Subset weight (kg)	Juice extracted (ml)	Brix	Average stalk diameter (mm)	Population (plants ha^{-1})	L ha^{-1}	Wet biomass (kg ha^{-1})
101	1	20	Topper	2.7	20	17	9	1100	15	25.94	86075	9219.04	72205
102	1	38	Topper	2.8	40	21	13	2150	16	23.72	172149	15201.38	89768
103	1	76	Topper	2.8	10	5	5	950	16.5	23.96	43037	4088.54	23418
104	1	20	M81	3.2	19	15	10	1600	16	24.08	81771	10179.25	66351
105	1	38	M81	3.1	33	14	14	2600	14	18.14	142023	11189.69	58545
106	1	76	M81	3.0	20	14	14	2500	15	23.87	86075	10759.32	58545
107	1	20	Topper	2.7	30	15	11	1900	16	23.56	129112	11120.83	66351
108	1	20	M81	2.9	27	16	12	2100	14.5	21.82	116201	12513.92	70254
201	2	38	Topper	2.7	54	21	10	1600	15.5	19.99	232401	15083.54	89768
202	2	38	M81	3.0	32	18	13	2300	14	21.11	137719	13787.30	76108
203	2	20	M81	3.2	40	25	12	1950	14.5	19.97	172149	17430.10	105380
204	2	76	Topper	3.0	28	15	9	1350	15.5	21.33	120504	9296.05	62448
205	2	20	Topper	2.7	40	19	11	1800	14.5	22.40	172149	13556.74	81962
206	2	76	M81	3.1	27	16	13	2100	15.5	21.69	116201	11297.29	68302
207	2	20	M81	2.9	24	12	12	1900	15.5	19.48	103289	8177.08	50739
208	2	20	Topper	2.7	27	22	12	2100	16	20.57	116201	16401.99	95623
301	3	20	Topper	2.7	18	14	14	2200	15.5	21.91	77467	9468.20	60496
302	3	76	M81	3.0	29	17	17	2800	15	20.56	124808	12050.44	72205
303	3	76	Topper	3.0	39	19	11	1750	16	23.62	167845	12652.96	81962
304	3	20	M81	3.1	20	13	13	2200	15	22.52	86075	9468.20	56593
305	3	38	M81	3.0	44	19	12	2200	13.5	21.07	189364	15294.79	81962
306	3	20	M81	3.0	18	12	12	1900	15	22.19	77467	8177.08	52690

307	3	38	Topper	2.7	19	10	10	1500	15.5	21.80	81771	6455.59	42933
308	3	20	Topper	2.6	48	18	10	1100	15	21.18	206579	9017.33	78060
401	4	20	Topper	2.7	29	29	16	2450	16.5	19.83	124808	19280.70	124895
402	4	20	M81	3.0	34	26	11	1850	15	19.63	146327	18153.12	111235
403	4	38	Topper	2.8	15	20	10	1600	15.5	20.26	64556	13472.54	87817
404	4	38	M81	2.9	29	20	15	2200	14	20.85	124808	12531.44	87817
405	4	20	M81	3.0	28	16	16	2400	15	20.73	120504	10328.95	68302
406	4	76	M81	2.9	44	9	9	1200	15.5	19.97	189364	5164.47	39030
407	4	20	Topper	2.6	39	24	14	1950	16.5	21.05	167845	14826.34	103429
408	4	76	Topper	2.7	57	15	15	2400	16	19.80	245312	10328.95	66351

Appendix M. Row Spacing percent canopy coverage for Stillwater 2009.

Date		6/2/2009	6/9/2009	6/16/2009	6/24/2009	7/1/2009	7/15/2009
Rep	TRT	--------------------% Cover--------------------					
1	1	0	5	6	30	67	55
2	1	1	18	41	47	21	66
1	2	1	8	20	33	60	61
2	2	1	8	39	34	67	41
1	3	1	16	22	41	51	63
2	3	4	20	31	39	44	46
1	4	1	3	15	23	36	38
2	4	1	5	16	42	34	53
1	5	0	1	6	10	49	54
2	5	1	2	12	34	63	43
1	6	1	10	16	31	22	43
2	6	2	17	23	35	48	55

Appendix N. Planting Density percent canopy closure for Stillwater 2009.

Date		6/2/2009	6/9/2009	6/16/2009	6/24/2009	7/1/2009	7/15/2009
Rep	TRT	--------------------% Cover--------------------					
1	1	1	7	28	21	51	40
2	1	1	9	24	30	48	71
1	2	1	9	18	55	73	74
2	2	1	10	52	33	58	83
1	3	1	11	40	55	94	70
2	3	5	15	30	42	46	64
1	4	1	9	29	31	54	71
2	4	4	9	48	60	93	67
1	5	1	15	47	48	77	89
2	5	3	13	43	65	84	78
1	6	4	11	17	29	40	51
2	6	5	15	29	59	64	65
1	7	5	18	27	41	70	69
2	7	5	16	35	53	83	71
1	8	3	20	29	42	53	61
2	8	3	9	26	43	75	41
1	9	7	14	31	41	67	67
2	9	5	20	31	45	49	79
1	10	7	15	34	52	92	67
2	10	8	26	40	48	71	70

VITA

Jacob W. Linneman

Candidate for the Degree of

Master of Science

Thesis: DEVELOPING ROW SPACING AND PLANTING DENSITY RECOMMENDATIONS FOR SWEET SORGHUM PRODUCTION IN THE SOUTHERN GREAT PLAINS

Major Field: Plant and Soil Sciences

Biographical:

Education: Completed the requirements for the Master of Science in Plant and Soil Sciences at Oklahoma State University, Stillwater, Oklahoma in May, 2011.

Completed the requirements for the Bachelor of Science in Plant Sciences at North Dakota State University, Fargo, ND in May, 2008.

Experience: Graduate Research Assistant August 2008-current

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Name: Jacob W. Linneman Date of Degree: May, 2011

Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: DEVELOPING ROW SPACING AND PLANTING DENSITY RECOMMENDATIONS FOR SWEET SORGHUM PRODUCTION IN THE SOUTHERN GREAT PLAINS

Pages in Study: 61 Candidate for the Degree of Master of Science

Major Field: Plant and Soil Sciences

Scope and Method of Study: A two year study was established in Oklahoma in 2009. Locations were Stillwater, Lahoma, and Haskell. In 2010 the locations were Stillwater, Lahoma, and Chickasha. Two separate studies were conducted each year: row spacing and planting density, to determine agronomic recommendations for sweet sorghum production in the Southern Great Plains. The experimental design used for both studies was a randomized complete block design. The aim of these studies was to find the optimum row spacing combined with the best planting density for maximum wet biomass production as a bioenergy feedstock.

Findings and Conclusions: Decreasing row spacing from 76 to 20 cm increases potential biomass yields. Planting density is dependent on location and the amount of precipitation for the area. Planting densities for 20-cm row spacing range from 175,000 to 250,000 seeds ha^{-1} moving west to east across the state. 76-cm row spacing ranges from 100,000 to 150,000 seeds ha^{-1} moving west to east across the state. Juice extraction is highly correlated with wet biomass production. Brix measurements were unaffected by row spacing, planting densities, stalk diameter, and plant height. Lower planting densities offered a greater chance for tillering which helped increase wet biomass yields at lower populations.

ADVISER'S APPROVAL: Dr. Chad Godsey