Sweet Sorghum Alternative Fuel and Feed Pilot Project

The University of Arizona –EE0004132

Subcontractor: Pinal Energy, LLC, Maricopa, Arizona

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Executive Summary:

The University of Arizona undertook a “pilot” project to grow sweet sorghum on a field scale (rather than a plot scale), produce juice from the sweet sorghum, deliver the juice to a bio-refinery and process it to fuel-grade ethanol. We also evaluated the bagasse for suitability as a livestock feed and as a fuel. In addition to these objectives we evaluated methods of juice preservation, ligno-cellulosic conversion of the bagasse to fermentable sugars and alternative methods of juice extraction.

In the process of pursuing these objectives, we evaluated five sweet sorghum cultivars for suitability as a fuel crop for Arizona. We identified two “day-neutral” varieties, Advanta Sugar –T and HP1010 which could be used for multiple planting and harvest dates. We also evaluated the irrigation water requirements for sweet sorghum in Southern Arizona and determined that the day-neutral varieties required 500-900mm of water per season while the photo-sensitive (short-day) varieties required 700-1000mm per season, depending on planting date. The day-neutral varieties also produced more ethanol per unit of water applied than the photo-sensitive varieties.

Although we successfully modified a forage chopper to harvest sweet sorghum in 10-20cm billets, we found that a sugar cane harvester (cane combine) produced cleaner billets and had significantly greater capacity.

We were unable to find a roller mill for crushing the sorghum stalks with a capacity of more than 2 tons per hour of fresh cane and this capacity became the limiting factor in our ability to produce juice in sufficient quantities to supply 10,000 gallons per day.

We determined that the best method of juice preservation was the addition of sodium metabisulfite at a rate of 51.5g/liter at the time of juice expression. This dosage preserved the juice for up to 80 hours at temperatures of up to 36 degrees C.

The bagasse resulting from processing the cane for juice proved to be a palatable animal feed with a relative feed value of 98.72. The bagasse has good fuel potential with an average of 19,770 kJ/kg dry weight which is similar to that of wood.

We are continuing to evaluate the use of filamentous fungi for the conversion of cellulose to fermentable sugars and are also evaluating a counter flow diffusion extraction system for removal of sugar from the cane stalks.

Introduction:

The overall objective of this project was to develop pilot-scale equipment and procedures to grow, harvest and field-process sweet sorghum to separate juice from bagasse, deliver juice to a fermentation facility and process sweet sorghum juice to fuel grade ethanol in central Arizona. Secondary research and development (R&D) objectives are to evaluate methods of juice sterilization and preservation and to evaluate methods for saccrification of sweet sorghum bagasse after juice removal. In addition, we will pursue alternative uses of sweet sorghum bagasse for biomass fuel. The specific objectives are to:

1. Plant a minimum of 30 acres of a sweet sorghum variety that is adapted to the southern Arizona climate, and grow the crop to maximum sugar content maturity.
2. Modify a previously developed forage harvester for efficient harvesting of sweet sorghum and harvest the crop at a minimum rate of 100 tons per day (bulk biomass at approximately 70% juice/moisture content).
3. Design, assemble, test and utilize a fully portable, pilot-scale roller-mill juicing system mounted on a trailer, which can be used for “in-field” juicing of the harvested sorghum stalks.
4. Develop methods of juice preservation for transport to an ethanol refinery located up to 60 miles from the growing site and test these methods under field conditions.
5. Construct two 10,000 gallon fermenters (pilot-scale) specifically for sweet sorghum juice to ferment it to maximum possible ethanol levels.
6. Distill the fermentation broth to produce 95% ethanol, and de-water completely to produce fuel grade ethanol.
7. Evaluate the utilization of sweet sorghum bagasse for fuel.
8. Evaluate the economics of fuel ethanol production from sweet sorghum.
9. Concurrently investigate alternative methods for extracting juice from sorghum stalks and evaluate ligno-cellulosic conversion processes.

The project was initiated in August 2010, however, since the growing season for sweet sorghum is from March through November, the first cropping season under this project was 2011. In addition to the technical objectives of the project, the project served to provide research opportunities for four MS students and one Ph.D. student. Three MS theses have been completed and the fourth is awaiting scheduling of the defense. The Ph.D. dissertation will be defended in December 2013.

Project Approach:

The project objectives were approached in different ways since all are not “research” objectives, per se. The specific research questions addressed in the course of the project were: a) Determination of the maturation of different varieties of sweet sorghum as a function of planting dates including heat-units required for maturity. b) Irrigation water requirements for sweet sorghum grown in Arizona and the production of sugar (and ethanol) per unit of water. c)

Preservation of sweet sorghum juice for sufficient time to allow transport to a fermentation/distillation facility d) Evaluation of diffusion methods for extraction of sugar from the sweet sorghum stalks e) Use of filamentous fungi to convert cellulose in the sweet sorghum stalks to fermentable sugars.

The project objectives which were more “developmental” in nature included modification of a forage harvester for harvesting sweet sorghum for juicing, evaluation of a sugar cane harvester for sweet sorghum harvesting, evaluation of a sugar cane type roller mill for juice extraction and fabrication of cone bottom fermenters for juice fermentation at an existing corn ethanol plant.

Project Outcomes:

Objective 1 Sweet Sorghum Production Trial:

2010 Growing Season. Thirty acres of sweet sorghum (cv M81E) were planted on April 19, 2010 and another ten planted on June 1, 2010. On September 21, the crop was in the “hard dough” stage with average Brix of 13.9. The crop was well managed throughout the season and was ready to harvest by October 1. However, since we had no milling equipment, we left the crop in the field and continued to monitor. As the crop continued to mature and senesce, the sugar content increased. On November 9, the average Brix was 20.7. We continued to monitor the crop, even though we could not harvest and process due to problems explained below. Below freezing temperatures were experienced on several nights in late December. Although we had not yet received our milling equipment, we did a “plot harvest” on December 23rd, after two freezing nights. The results showed that the juice was still viable and had an average Brix of 12.7. The biomass yield was 37.6 T/A with a corresponding juice yield of 2895 gal/A. While the levels are below what we might expect in late October or early November, we have shown that the juice remains viable after several freezes in the field and can still yield reasonable levels of juice with sugar contents not much different than that from early October.

2011 Growing Season: We obtained seeds from Advanta Seeds for what they believed to be three new short-season, day-neutral, hybrid sweet sorghum varieties. We anticipated that the day neutral varieties would allow us to plant several times during the summer and achieve crop maturity after adequate heat unit accumulation rather than as a function of day-length which is the characteristic of the M81E. The varieties were: SugarT; 23402 which is a sterile male hybrid with no seed heads and 28702. We planted five acres of each of these varieties at the Red Rock Agricultural Center on May 2, 2011 and another five acres of each on June 15, 2011. We also plant five acres of M81E on each of these dates for comparison. This gave us 40 acres of sorghum with first harvests estimated to begin from mid to late August. We also planted about 1-1/2 acres of experimental plots of each of the varieties at our Campus Agricultural Center on the same dates to develop heat-unit based crop coefficients and determine water requirements for each variety. Based on results of some previous plant density research at our campus agricultural center, we planted half of each variety on 40 inch rows and half on 80 inch rows. We also planted 24 plots of the four varieties at our campus agricultural center on May 2 (each of the four varieties at two different water depletion levels and three replications) and another 12 plots on June 15 (each of the four varieties at only one water depletion level replicated three times). The study at the campus agricultural center was funded from a different source than the DOE Grant and is the MS thesis project for a Biosystems Engineering graduate student.

The photoperiodicy (dependence of flowering on day length) was evaluated in the experiments at the campus agricultural center. The minimum daily mean temperature for growth of sweet sorghum is 8^0C and the maximum is 35^0C. Table I shows a comparison of heat until accumulation from planting to "flag leaf" and flowering for the four varieties. It can be seen from table I that for HP1010 and Sugar T the accumulated heat units to flag leaf and flowering are almost equal regardless of planting date. This is a strong indication that these varieties are "day neutral". On the other hand, there is more than a 200 heat unit difference to flag leaf and flowering between the May and June plantings for M81E and almost a 600 unit difference between the May and June plantings for both flag leaf and flowering for the 28702 variety. This is a strong indication that these varieties are short-day varieties dependent on day length to initiate flowering and maturity. This information can be used to predict harvest dates for various planting dates for various locations. For example table II shows the projected harvest dates for various planting dates starting March 1 at the RRAC for two years, 1991 and 2011. 1991 had the coldest average temperatures for the past 20 years and 2011 was an average year. As shown in the table, in the cold year, maturity could not be achieved for planting dates of June 15 or later. A similar table can be used to compare crop maturity at two different locations.

Table I. Heat Unit Accumulation and Physiological Development for four Sweet Sorghum Varieties.

VARIETY	Planting Date	Heat Units to Flag Leaf	Heat Units to Flowering
HP1010	May 5, 2011	1577	1800
HP1010	June 15 2011	1502	1717
Sugar T	May 5, 2011	2030	2232
Sugar T	June 15 2011	1979	2220
M81E	May 5, 2011	2463	2729
M81E	June 15 2011	2235	2496
28702	May 5, 2011	3075	3244
28702	June 15 2011	2496	2590

Table II. Heat Unit Maturity Comparison SugarT at Red Rock Ag. Center, 1991 and 2011.

Planting Date	Projected Harvest Dates	
	1991	2011
March 1	September 5	August 11
March 15	September 8	August 16
April 1	September 11	August 24
April 15	September 19	August 31
May 1	September 28	September 8
May 15	October 8	September 16
June 1	October 25	October 2
June 15	Not maturing	October 21

We initiated harvest on October 11, 2011 beginning with the early planted (5/3/2011) Sugar T variety in 80 inch rows. We expected both the early planted Sugar T and the Sterile Male hybrid (Advanta variety HP 1010) to be at their maximum sugar levels at this time. We spent quite a bit of time adjusting the mill tolerances and feed rate trying to find a balance between production rate and extraction percentage. We found that the mill could only handle an average of about 1.2 to 1.5 tons per hour of sorghum billets and gave us an extraction rate of just 30% that first day (that is 30% of the wet weight of the billets extracted as juice). The sweet sorghum billets had a wet moisture content averaging 73% so extraction of 30% juice means that we were removing only about 40% of the juice. We spent a great deal of time adjusting the mill to try and improve the extraction rate but the overall average for all varieties ended up at 33% (45% of the juice) with a high of 37% for the Sugar T and a low of 29% for the M81E. Table AI of Appendix A provides a summary of harvest results for all varieties. We were disappointed in both the yield (in terms of tons per acre of billets) and the sugar content of the juice, although the harvested juice for the Sugar T early planted crop was 15 which is about what we measured on September 29 prior to harvest. Figure A1 shows the sorghum yields in tons of billets per acre. This clearly shows that Sugar T had much better yields than any of the other varieties. Row spacing had only a slight effect on the yield of Sugar T and no effect on 28702 but greatly affected the yield of the Sterile Male hybrid (HP 1010) and somewhat affected M81E. Figure A2 shows the yields in gallons per acre and Figure A3 shows yield in gallons per ton. Obviously both are related to billet yield per acre. Although the yield in gallons per ton is not greatly variable between varieties the reduced tonnage of billets for the M81E variety leads to much less yield of juice per acre.

2012 Growing Season: For the 2012 growing season we decided to plant Sugar T again as it seemed to provide the best yields and, since it is day-neutral, we could achieve a range of harvest dates by varying the planting dates. The 28702 variety proved to be photo sensitive and did not mature well in the 2011 season so we decided not to pursue it any further. The HP1010 (sterile male hybrid) variety had high sugar content and proved to be a day-neutral variety but the biomass yields were much lower than that of Sugar T and M81E so we also decided to discontinue our work with that variety. We decided to also plant Dale for the 2012 season. It is an "old" well tested syrup variety which, in previous small plot tests in Arizona did well and showed some day-neutral characteristics.

We planted the SugarT variety on March 30, April 16, May 1, May 14 and May 30, 2012 (two acres each planting). We planted the Dale variety on April 16, May 1, May 14 and May 30, 2012 (two acres each planting). All plantings were done at the Red Rock Agricultural Center. We did not get the Dale variety planted on March 30 as we had incorrect plate sizes in the planter. The seed was much finer than the SugarT seed and was not going through the plates. We monitored the soil moisture just prior to each irrigation to ensure that irrigation levels were adequate this season. We irrigated weekly and the plants seemed very healthy. The heat units did not accumulating as quickly as we anticipated. By June 30 we had accumulated 1784 heat units for the March 30 planting.

We also evaluated germination of SugarT and Sterile Male seeds at 12 degrees C. We did this because our agronomist had told us the seed would not germinate until soil temperatures reached 18 degrees C (65 degrees F). We got 100% germination within 7 days for the Sterile Male and 87% germination within 7 days for the SugarT which justified our early (March 30) planting.

We tracked heat units from planting using weather data from an automated weather station at the Red Rock Agricultural Center (RRAC). Flag leaf and flowering followed the heat unit model very closely for the SugarT variety for all planting dates with 100% of flag leaf emergence occurring at about 2005 heat units and 100% flowering at about 2226 heat units. Although the Dale variety was assumed to be a short-day variety (i.e. photo sensitive) it did not appear to show that characteristic nearly as strongly as M81E and actually began flowering at about the same time as SugarT. In fact, maturation of the Dale variety seemed to follow very closely that of SugarT. We did a trial harvest of the March 30th planting of SugarT on August 1 when it had accumulated 2515 heat units. We knew this was a little pre-mature but we needed to test our field equipment and recorded the data anyway. The results looked quite promising, except for low brix and the crop appeared to be reaching maturity so we did our "planned" harvest the following week on August 7. Unfortunately, Pinal Energy, our bio-refinery partner, had ceased ethanol production on July 1 due to the high cost of importing corn from the mid-West and since their plant was shut down, they were not able to process our sweet sorghum juice. We therefore, decided to harvest only four rows of each variety at each planting since we had to dump the harvested juice. Accumulated heat units at the time of this first harvest were 2663. We harvested only SugarT at this time as we had no March 30th planting of Dale for reasons explained in the previous report. We harvested the April 16 planting of both varieties on August 23 when they had accumulated 2854 heat units. This was very close to the "optimal" 2800 that we had determined for SugarT in the 2011 research. The May 1 planting was harvested on August 31 at a heat unit accumulation of 2784. Sugar content as determined by Brix readings was about the same for the August 23 and August 31 harvests of SugarT at 10.0 and 10.5 respectively. The Dale variety had higher brix for both harvest increasing from 11.1 to 13.8. The May 15th plantings were harvested on September 27th at heat unit accumulation of 3053. Brix of both varieties were greater at this point at 11.8 for SugarT and 17.3 for Dale.

The final harvest of the May 30th planting was done on October 4 at a heat unit accumulation of 2813. The SugarT at this harvest had brix of 9.8 and 11.5 and the Dale a brix of 16.5. Table A2 in Appendix A summarizes the results of this cropping season. We were disappointed that our improved irrigation timing and amounts, in terms of soil moisture depletion, did not appear to increase or improve our yields as compared to 2011. Both billet yields and juice yields on a per acre basis were similar for 2011 and 2012 and both were much lower than we had obtained in plot experiments at the Campus Agricultural Center in Tucson (refer to Martinez, et al., 2012 for a description of those results). Although the Dale variety produced higher brix its juice and biomass yields were both lower than that of SugarT resulting in approximately the same production of fermentable sugars per acre.

The 2012 cropping season completed the sweet sorghum production aspect of this project. We are continuing to evaluate the Dale variety and some hybrids from Monsanto during the 2013 season utilizing funding from other sources.

Objective 2 Develop/modify harvesting equipment:

During the 2010 growing season, we modified a two-row, Hesston model 7155 forage chopper by removing all of the chopping blades but one and rebalanced the knife reel. This machine then chopped the standing sorghum into billets between 4 and 8 inches in length. The modified chopper could easily produce 5 tons per hour of billets, although we could only chop one row per pass. However, we were unable to obtain clean billets as much of the leaf material remained after chopping. We did add two fans, one at the exit chute of chopper and another on the wagon that we were chopping in to. This removed some leaves but still left us with “dirty” billets. With some additional modifications, we may have been able to obtain cleaner billets. However, we decided to purchase a used sugar cane combine which performed much better, had a higher capacity (up to ten tons per hour) and produced clean, 6-10 inch billets. We used the cane combine for the 2011 and 2012 seasons. Figure B1 in appendix B shows the modified forage chopper in operation and figure B2 shows the cane combine in operation.

Objective 3. Milling equipment development:

We completed specifications for a mill capable of handling 10 tons of wet sorghum per hour and put out for bid. We received a low bid from Manufacturera de Implementos in Veracruz, Mexico (MIM) and obtained permission from the University and DOE to make this purchase. We submitted a purchase order to them on September 15, 2010 and were given a delivery date of November 24, 2010. We also ordered a smaller mill for plot work from a firm in India (because we could not find such equipment in the US). We did receive the plot mill from India in September and used it for some plot work at the campus agricultural center (CAC).

MIM informed us in mid-November that they would not be able to deliver the mill until mid-January which was well past maturity for the sweet sorghum planted in 2010. They did deliver a “loaner” mill to us on January 6, 2011. This was a single set of 4-rollers, 13-1/2 inches in diameter by 18 inches long. The mill included a feed conveyor, hammer mill prior to the rollers and a bagasse discharge conveyor. A photo of the mill is included as figure C1 in appendix C of this report. Representatives from MIM came to Tucson to help us set up the mill and work through problems of initial operations. We had trouble with clogging and we were unable to obtain much juice yield which was probably aggravated by the extremely dry state of our sorghum stalks. MIM had told us we could expect this mill to have a capacity of about 7 tons per hour. We were unable to get more than two tons per hour on our best day and managed to produce only about 150 gallons of juice after six hours of mill operation. The juice that we did obtain had a brix of about 11.2 which corresponded quite well to the brix readings from our sample harvests a few days before. It soon became apparent that we were not going to be able to produce sufficient juice in a one-day operation to deliver a minimum of 1,200 gallons of juice to Pinal Energy for fermentation and after numerous attempts to do so; we discontinued harvest and juicing operations on January 19, 2011. We delivered two loads of bagasse to a local feed lot following our two day-long harvest and juicing trials. The bagasse was very palatable and readily eaten by the cattle. The feeder was quite interested in obtaining more and offered to pay us for future deliveries. However, since our main objective was to deliver juice to the bio-refinery, we abandoned our field operations for the season and shredded and plowed-under the remaining standing crop.

After their experience with this mill under our field conditions, MIM returned to Mexico and re-evaluated the larger mill (four rollers 18x24 inches) and concluded that even that mill would have a maximum capacity of no more than 7tons per hour. Since our hand harvest and juicing trials in late December and early January indicated an average juice yield of about 75 gallons per ton this would give us only 4,200 gallons of juice per day or a little less than one-half of the 9,000+ gallons needed to fill one of the 10,000 gallon cone-bottom fermenters. They were unwilling to lower their price because of reduced capacity nor were they willing to lease the mill to us for trial. Since their mill would not meet the specifications as they bid it, we cancelled the order in early February 2011.

We found a small mill with a sugar cane processor in Louisiana who was willing to lease the mill to us.. We leased a mill with two sets of three-roll mills and one two-roll feed roller set. The mill required a considerable amount of servicing and repair but we made good progress in getting it in shape and ran some test runs at the Campus Ag. Center with some of the crop there. We had to install a new motor on the hydraulic pump and replace some bearings on the rollers but all-in-all these expenses came to less than $5,000. Figure C2 shows the initial setup of the juicing machinery at the Red Rock Agricultural Center (RRAC) and figure C3 shows the mill in operation.

During the 2011 harvest season we utilized this mill with harvest and juicing commencing on October 11, 2011. Based on pre-harvest monitoring of the crop, we decided to begin harvesting the early plantings of Sugar T, followed by early planted HP 1010 (Sterile Male), Advanta 28702 and M81E. We were not able to achieve a desired extraction rate of 50-55%, achieving an overall average of only 33% across all varieties and planting dates. In addition, we were only able to achieve a milling rate of about 1.2-1.5 tons per hour which greatly limited how much juice we could produce each day. The result was that the most juice we sent to Pinal Energy in a single day was about 900 gallons, much less than the 5,000 gallons desired. The maximum we were able to achieve was 2 tons per hour and that for only short periods of time. Our average productivity was 1.2 tons per hour. This meant that we were unable to harvest the full 2.5 acres of each plot, each day and, in fact, were able to produce much less juice than desired. The juice production was also limited by the relatively low extraction rate of the mill, of only 33%. We tried numerous adjustments of the rollers with little or no increase in extraction rate. We did add warm water to the billets as they were fed into the system and this did seem to improve the overall extraction with no dilution of brix.

We continued to use this mill during the 2012 harvest season with essentially the same extraction rates and milling capacities as for 2011. Our experiences with the two mills (the MIM mill and the Louisiana mill) have led us to the conclusion that we cannot easily obtain a mill which is field portable, will have high capacity (10 tons/hr) and a reasonably high extraction rate. Thus milling seems to be a major bottleneck in production of sweet sorghum juice for ethanol.

In prior work, in 2008, we utilized a 21" diameter screw press and were able to produce 1,200 gallons of juice in six hours of operation with an extraction rate of about 55%. Based on our cumulative experience, we would recommend a screw press of 36". Since capacity varies as the square of the diameter, such a mill should be able to process about 4,000 gallons of juice in an eight hour day and a 42 inch diameter screw press should be able to process about 6,000 gallons per day. If we have the opportunity and funding to do so, we will further investigate this method.

Objective 4. Juice preservation:

Sweet sorghum juice has a notoriously short shelf life and, if untreated, may begin to spoil or "self-ferment" within one hour after juicing. We evaluated two methods of preservation, lowering the pH by addition of acid just after juicing and addition of sodium metabisulfite. The research (Marquez, 2011) found that lowering the pH extended the shelf life by several hours at temperatures in the neighborhood of 25 degrees C. However, ambient temperatures at harvest times in Arizona (August – October) are actually in the range of 35-40 degrees C and, at these temperatures, lowering the pH actually accelerated spoilage. On the other hand addition of a small amount of sodium metabisulfite immediately after juicing preserved the juice for up to 80 hours at temperatures of 36 degrees C. The optimal dosage found in this research is 51.5mg/l or 19mg/100 gallons. Sodium metabisulfite in these quantities is quite inexpensive and starting with our fall 2011 harvest we used this method of preservation very successfully for the duration of the project, never experiencing spoilage.

Objectives 5 and 6. Construct two 10,000 gallon fermenters for sweet sorghum fermentation, distill the broth to 95% ethanol and dewater to fuel grade ethanol:

Work on achievement of this objective was undertaken by our industrial partner, Pinal Energy, LLC of Maricopa, Arizona. The fermenters were completed in November 2010 but since we were unable to harvest and provide juice, they were not utilized until the 2011 harvest season. In that season, we delivered juice to Pinal Energy from each of the 16 "plots" harvested in

October and November. The juice was fermented in the fermenters as planned, although at much lower volumes than originally intended. Volumes ranged from 250 gallons to 1000 gallons. All juice fermented within 24 hours with an average time of 15 hours. The average ethanol yield (eth/glucose) was 0.61 which is slightly above the theoretical average and is likely due to other sugars present (Pinal only measured glucose). The fermented broth was then sent directly to the distilling columns and distilled to 95% ethanol and dewatered to fuel grade ethanol and mixed with the product from the corn stream. No problems were encountered in either the fermentation or distillation process. Unfortunately, Pinal Energy ceased operation of their ethanol plant in July, 2012 so we were unable to deliver and ferment juice during the 2012 season. Figure D1 in appendix D shows these two fermenters.

Objective 7. Evaluate the utilization of sweet sorghum bagasse for fuel and animal feed:

Sweet sorghum bagasse samples were taken from the field milling operation during the 2011 harvest and send to a lab in Chandler, Arizona for analysis as animal feed. Results of that analysis showed the bagasse to have the following characteristics: Neutral detergent fiber = 57.289%; Acid detergent fiber = 36.072% and a Relative Feed Value = 98.72. However the crude protein was only 3.147%. While the RFV is a good value, a ration utilizing sweet sorghum bagasse would need to have additional protein added to the ration. In actual operations for 2010, 2011 and 2012 harvests, we delivered the bagasse to a feedlot close to the sweet sorghum fields and the feed lot operator found the steers readily ate the bagasse indicating a high level of palatability.

Similarly, we evaluated the fuel value of the bagasse and found it contained an average of 19,770 kJ/kg dry weight. This is approximately the same as dry wood, which is not surprising since the bagasse is primarily lignin and cellulose.

Objective 8. Evaluate the economics of fuel ethanol production from sweet sorghum:

We are finalizing the economic analysis which will be detailed in the upcoming publication, “Sweet Sorghum to Ethanol in Arizona: A Guidance Manual for the Grower”. The summary analysis indicates that the cost to grow the crop in Arizona varies with the distance from Pinal Energy, the only ethanol plant in Arizona and with water costs. The two main options for growing sweet sorghum is within the Maricopa Irrigation and Drainage District and within the Gila River Indian Nation, both are within Pinal County. The total cost to grow the crop ($618/ac) within the Gila River, extract the juice ($289/ac), and make the ethanol ($175/ac) is $1,082 per acre. Income is derived from the ethanol and selling the bagasse. The potential net income for the entire process is $137 per acre, when selling the ethanol for $2.20 per gallon and the bagasse for $40 per ton. The breakeven price per gallon of ethanol is $1.54. (Livingston, et al., 2013)

Objective 9. Investigate alternative methods for extracting juice from sorghum stalks and evaluate ligno-cellulosic conversion processes:

Laboratory experiments by Fei (2011) showed that the diffusion extraction method resulted in more than twice as much sugar released from the stalk as compared to stalk crushing. However, the resulting solution has brix of only 5% indicating that some significant concentration of the liquor would need to take place before it could be efficiently fermented in a bio-refinery. We have constructed a larger scale diffusion extractor which we will use to extract sugar from sweet sorghum stalks harvested with a forage chopper from the 2013 season.

A Ph.D. student has been evaluating the use of filamentous fungi to break down cellulose and convert it to sugars. She has utilized two known strains, *N. crassa* and *T. atroviride*, with limited success and has isolated a third strain from sorghum stalks in the field. She is currently conducting laboratory experiments with all three strains and will complete her dissertation by December, 2013.

Publications resulting from this project:

MS Theses:

Jia, Fei. 2011. Development of an Efficient Method of Sugar Extraction from Sweet Sorghum. MS Thesis submitted in partial fulfillment of the requirements for an MS degree in Agricultural and Biosystems Engineering. University of Arizona, Graduate College. 90p.

Marquez, Mario. 2011. Ethanol From Sweet Sorghum. MS Thesis submitted in partial fulfillment of the requirements for an MS degree in Chemical and Environmental Engineering. University of Arizona, Graduate College. 57p.

Martinez-Cruz, Tania, E. 2012. The Water Use of Sweet Sorghum and Development of Crop Coefficients. MS Thesis submitted in partial fulfillment of the requirements for an MS degree in Agricultural and Biosystems Engineering. University of Arizona, Graduate College. 86p.

Reports:

Bliss, A. and J.E. de Steiguer. 2012. Estimating the Cost of Sweet Sorghum Ethanol Feedstock: Empirical Results from a Pilot Study in Southern Arizona. School of Natural Resources and the Environment. The University of Arizona. 32p.

Livingston, P.A., T. Teegerstrom and D. Slack. 2013. Sweet Sorghum Ethanol in Arizona: A Guidance Manual for the Grower. University of Arizona, Departments of Agricultural and Resource Economics and Agricultural and Biosystems Engineering. In draft form… to be completed by September 30, 2013.

Journal Articles:

Martinez-Cruz, Tania, E, D.C. Slack, K. Ogden and M. Ottman.. 2013. The Water Use of Sweet Sorghum and Development of Crop Coefficients. Irrigation and Drainage (ICID). Accepted for publication, manuscript under revision.

Papers Presented at Professional Meetings:

Martinez-Cruz, Tania E., Donald C. Slack, Kimberly Ogden and Michael Ottman. 2011. Methodology to Determine the Effect of Water Stress on Sweet Sorghum (Sorghum bicolor (L.) Moench), a Bioethanol Crop and the Development of Crop Coefficients. Paper presented at the XVI National Irrigation Congress of Mexico. Culican, Sinaloa, Mexico. September 6-9, 2011.

Slack, D.C., T.E. Martinez-Cruz, K.L. Ogden and M.Ottman. 2012. Sweet Sorghum as an Energy Crop.Invited Presentation at the 4th KKU International Engineering Conference. KhonKaen, Thailand. May 10-12, 2012. Published in the Conference Proceedings. 6p.

Martínez-Cruz, T. E., D. C. Slack, K. L. Ogden and M.Ottman. 2012. The Effect of Water Stress on Sweet Sorghum (Sorghum bicolor (L.) Moench) and the Development of Crop Coefficients. Paper Presented at the 4th KKU International Engineering Conference. KhonKaen, Thailand. May 10-12, 2012. Published in the Conference Proceedings. 9p.

Rojas, I., D.C. Slack, M.R. Riley and M. Orbach. 2012. Bioconversion of Lignocellulosic Components of Sweet Sorghum Stalks to Ethanol Utilizing Fungi and Yeast. Paper Presented at the 4th KKU International Engineering Conference. KhonKaen, Thailand. May 10-12, 2012. Published in the Conference Proceedings. 4p.

Slack, D.C., P. Espinoza, S. Husman and P. Livingston. 2013. A Continuous Growing and Harvesting Cycle for Sweet Sorghum for Ethanol Production. Proceedings of the 6th TSAE International Conference. Thai Society of Agricultural Engineer. Hua Hin, Thailand. April 1-3, 2013. Pp. 13-16.

Yanes, M., K. Currier, T. Lau, D. Slack and P. Livingston. 2013. Pilot-Scale Continuous Conveyor Diffusion Extraction System for Sweet Sorghum. Proceedings of the 6th TSAE International Conference. Thai Society of Agricultural Engineers. Hua Hin, Thailand. April 1-3., 2013. Pp. 103-105.

Other Presentations:

M.R. Riley. “Sustainable production of transportation fuels in semi-arid environments”, ICOSSEE (International Congress on Sustainability Science and Engineering) Tucson, AZ 1/12/11.

M.R. Riley. “Production of ethanol from sweet sorghum grown in semi-arid environments”, SWIAA (Southwest Indian Agriculture Association) 2011, Laughlin, NV, 1/18/11/.

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Video:

A short video produced by Arizona Public Media can be seen at: http://www.arizona.edu/features/sweet-sorghum-fields-fuel

Appendix A: Sweet Sorghum Production Trials Results.
Table A1: Summary of Harvest Results at Red Rock Agricultural Center - 2011

		Red Rock Agricultural Center 2011 Sweet Sorghum Results						
Summaries by variety and planting date:								
					Gallons/	Juice		Harvest
Variety	Planting	Row	Billet Yield	Extraction	Ton	Yield	Brix	Date
	Date	Spacing, in	Tons/A	%		Gal/A		
Sugar T	5/5/2011	80	29.50	30.51	71.79	2117.70	15	10/11/2011
Sugar T	5/5/2011	40	36.76	45.54	107.14	3938.92	13.75	10/12/2011
Sugar T	5/5/2011	40	33.81	39.04	91.86	3105.96	13.7	10/27/2011
Sugar T	6/15/2011	80	30.90	34.95	82.23	2541.24	12.5	11/1/2011
Sugar T	6/15/2011	40	27.66	35.48	83.49	2309.13	12	11/1/2011
Mean early			33.36		90.26	3054.19	13.39	
Mean late			29.28		82.86	2425.19		
Mean 40"			32.74		94.16	3118.00		
Mean 80"			30.20		77.01	2329.47		
Overall mean			31.73	37.10	87.30	2802.59		
Sterile Male	5/5/2011	80	11.96	32.93	77.48	926.49	15	10/13/2011
Sterile Male	5/5/2011	40	22.67	25.93	61.02	1383.56	15	10/14/2011
Sterile Male	6/15/2012	80	8.38	37.26	87.67	734.97	12.25	10/18/2011
Sterile Male	6/15/2012	40	18.89	35.73	84.08	1588.27	14	10/24/2011
Mean early			17.32		69.25	1155.03	14.1	
Mean late			13.64		85.87	1161.62		
Mean 40"			20.78		72.55	1485.92		
Mean 80"			10.17		82.57	830.73		
Overall mean			15.48	33.79	77.56	1158.32		
Advanta 4[1]	5/5/2011	80	11.94	35.70	83.99	1003.12	10.5	10/17/2011
Advanta 4	5/5/2011	40	16.72	29.91	70.37	1176.50	12.5	10/31/2011
Advanta 4	6/15/2011	40	17.07	28.54	67.15	1146.05	12.5	11/4/2011
Advanta 4	6/15/2011	80	11.89	26.80	63.06	750.02	14	11/4/2011
Mean early			14.33		77.18	1089.81	12.4	
Mean late			14.48		65.10	948.03		
Mean 40"			14.31		66.71	963.26		
Mean 80"			14.50		75.57	1074.58		
Overall mean			14.41	30.95	71.14	1018.92		
M81E	5/5/2011	80	18.04	29.62	69.70	1257.38	13.75	10/28/2011
M81E	5/5/2011	40	26.65	28.15	66.23	1764.75	16	11/8/2011
M81E	6/15/2011	80	15.95	29.97	70.52	1124.98	14	11/9/2011
M81E	6/15/2011	40	18.50	29.43	69.24	1281.21	12.5	11/9/2011
Mean early			22.34		67.96	1511.07	14.1	
Mean late			17.23		69.88	1203.09		
Mean 40"			22.58		67.73	1522.98		
Mean 80"			17.00		70.11	1191.18		
Overall mean			19.79	29.62	68.92	1357.08		
[1]Note: "Advanta 4" is a name we gave to Advanta variety 28702								
Data Collected by Ed DeSteiguer, Andrew Bliss and Don Slack. This analysis is by Don Slack								

Figure A1. Sorghum Yield T/A
Red Rock Ag. Center U of AZ 2011

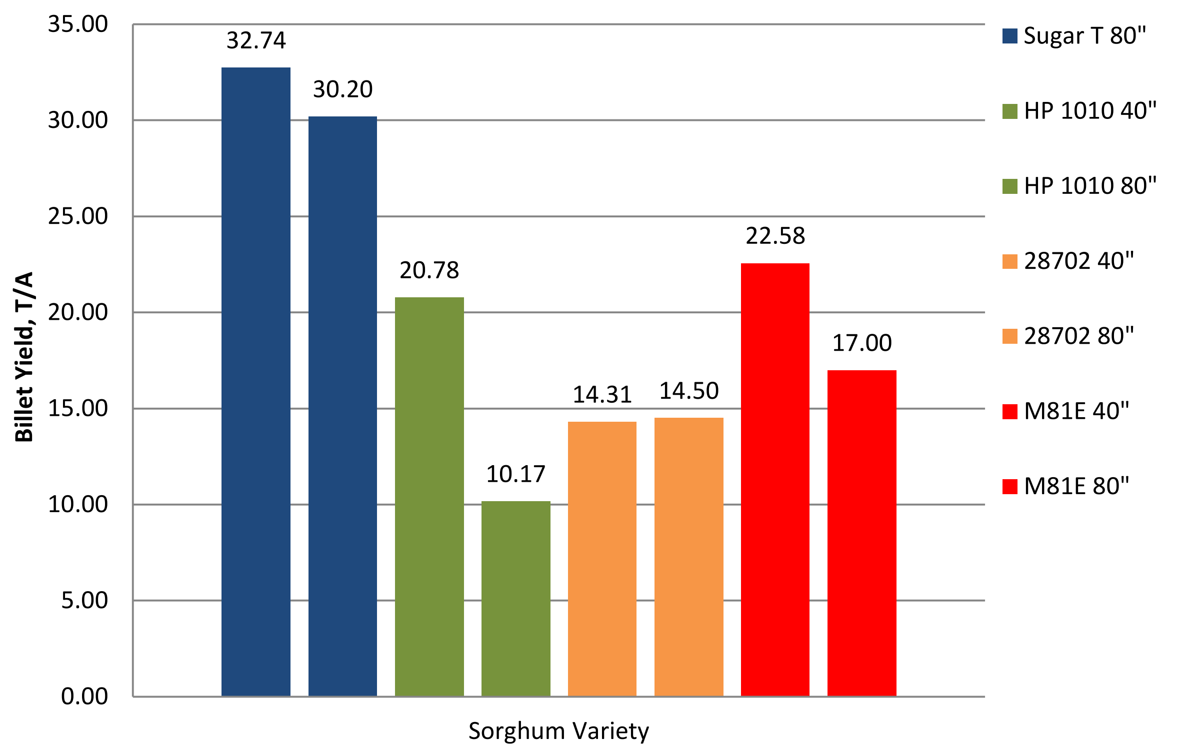
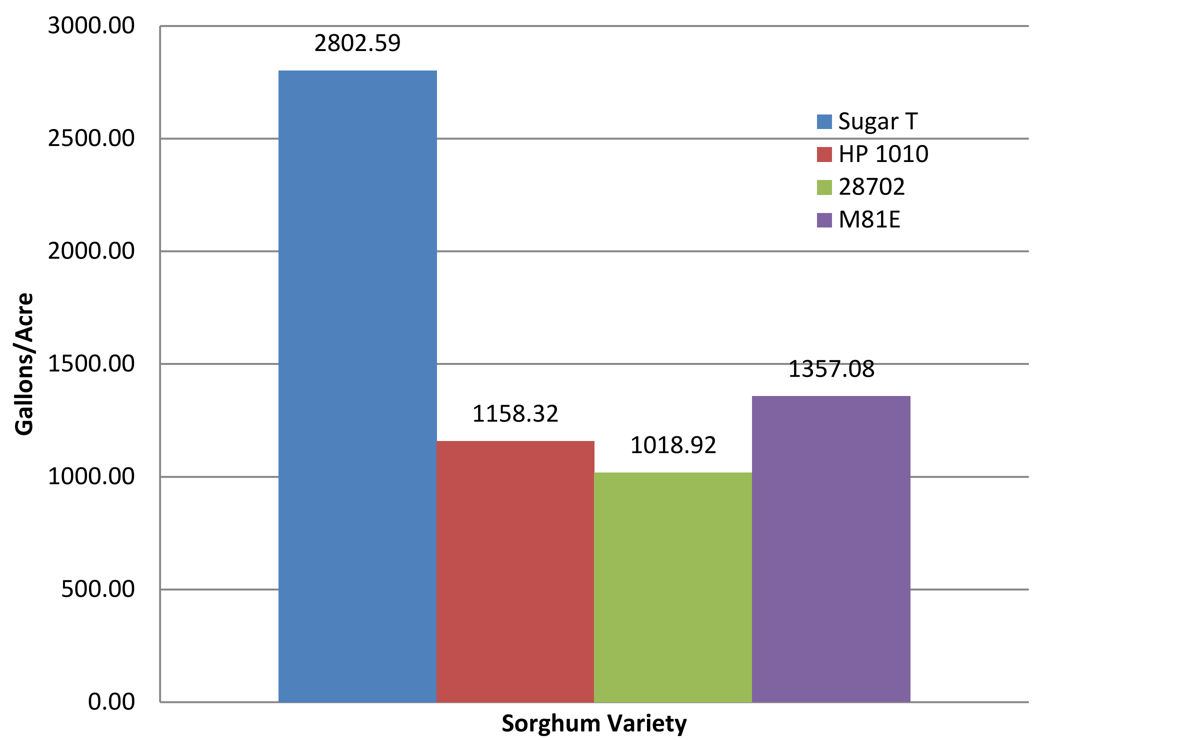


Figure A2. Juice Yield - Red Rock Ag. Center
2011 Season



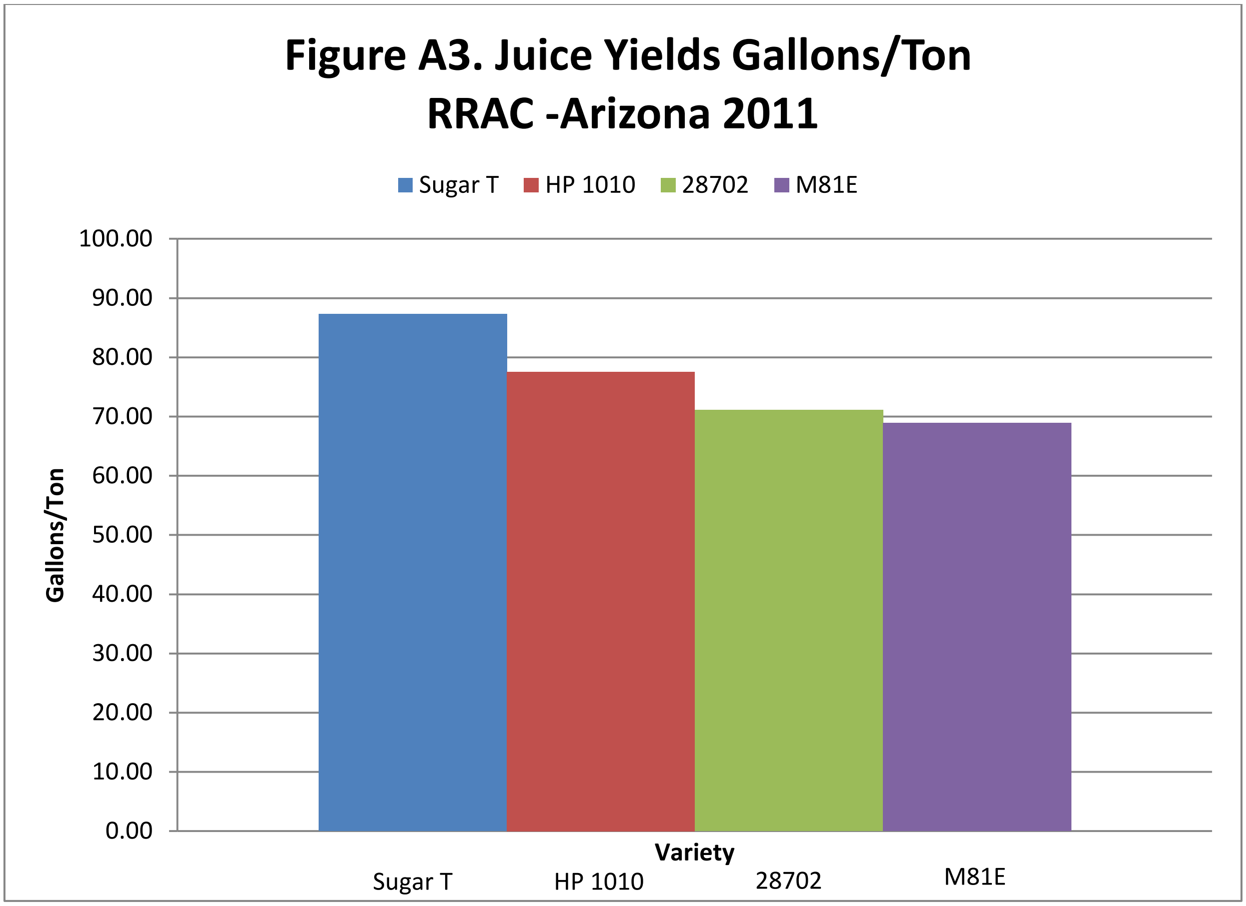


Table A2: Summary of Harvest Results at Red Rock Agricultural Center - 2012

		RED ROCK AGRICULTURAL CENTER 2012 SWEET SORGHUM RESULTS							
Summaries by Variety and Planting Date									
Variety	Planting Date	Harvest Date	Row Spacing, in	Billet Yield Tons/A	Extraction %	Gallons/ Ton	Juice Yield Gal/A	Brix	Heat Units at harvest
Sugar T	3/30/2012	8/1/2012	40	29.53	47.30	111.29	3286.62	7.7	2515
Sugar T	3/30/2012	8/7/2012	40	19.43	37.03	87.14	1693.24	7.5	2663
Sugar T	4/16/2012	8/23/2012	40	25.01	32.89	77.38	1935.06	10.0	2854
Sugar T	5/1/2012	8/31/2012	40	16.88	23.24	54.67	922.87	10.5	2784
Sugar T	5/15/2012	9/27/2012	40	19.53	27.21	64.02	1250.35	11.8	3053
Sugar T	5/30/2011	10/4/2012	40	23.34	32.53	76.53	1786.21	11.5	2813
Mean values				22.29	33.37	78.51	1812.39	9.8	
Dale	4/16/2012	8/23/2012	40	25.07	27.76	65.32	1637.36	11.1	2854
Dale	5/1/2012	8/31/2012	40	13.40	44.39	104.44	1399.20	13.8	2784
Dale	5/15/2012	9/27/2012	40	13.72	33.19	78.09	1071.72	17.3	3053
Dale	5/30/2011	10/4/2012	40	13.52	29.96	70.48	952.64	16.5	2813
Mean values				16.43	33.82		1265.23	14.7	
Note: Optimal heat unit accumulation was determined in 2011 to be between 2500 and 2800 for SugarT									

Appendix B: Harvesting Equipment.

Figure B1. Modified forage chopper harvesting sweet sorghum.

Figure B2: Sugar Cane Combine harvesting sweet sorghum RRAC 2012

Appendix C: In-field milling equipment.

Figure C1. Mill from MIM, Mexico, January 2011.

Figure C2. Leased mill set up at Red Rock Agricultural Center September, 2011

Figure C3. Leased mill in operation showing three sets of rollers.

Appendix D: Cone-bottom fermenters for sweet sorghum juice.

Figure D1. 10,000 cone bottom fermenters for sweet sorghum juice at Pinal Energy, LLC.