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ORNL/TM-2010/7

Review of Sorghum Production Practices: Applications for Bioenergy

June 2010

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UT-BATTELLE

ORNL-27 (4-00)

ORNL/TM-2010/7

Environmental Sciences Division

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Date Published: June 2010

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831-6283
managed by
UT-BATTELLE, LLC
for the
U.S. DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

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PREFACE

The following exhaustive literature review of sorghum production practices was developed by researchers at Oak Ridge National Laboratory to document the current state of knowledge regarding sorghum production and, based on this, suggest areas of research needed to develop sorghum as a commercial bioenergy feedstock. This work began as part of the China Biofuels Project sponsored by the DOE Energy Efficiency and Renewable Energy Program to communicate technical information regarding bioenergy feedstocks to government and industry partners in China, but will be utilized in a variety of programs in which evaluation of sorghum for bioenergy is needed. This report can also be used as a basis for data (yield, water use, etc.) for US and international bioenergy feedstock supply modeling efforts.

SUMMARY

Sorghum has great potential as an annual energy crop. While primarily grown for its grain, sorghum can also be grown for animal feed and sugar. Sorghum is morphologically diverse, with grain sorghum being of relatively short stature and grown for grain, while forage and sweet sorghums are tall and grown primarily for their biomass. Under water-limited conditions sorghum is reliably more productive than corn. While a relatively minor crop in the United States (about 2% of planted cropland), sorghum is important in Africa and parts of Asia. While sorghum is a relatively efficient user of water, it biomass potential is limited by available moisture.

As a cellulosic feedstock for bioenergy, the sweet and forage types are of interest. Energy sorghum is forage sorghum bred for high biomass production. Dual purpose forage, sweet, and energy sorghums produce both biomass and grain. Related sorghums, sudangrass and sorghum x sudangrass, may also have a role as short growing season crops or crops allowing two cuttings in one growing season. At present about 1 x 10^9 L of ethanol are produced from grain sorghum in the United States. There is a small production of energy from sweet sorghums.

Grain sorghums have been bred for dwarf stature and stand 0.6-1.2 m (2-4') tall. The maximum potential biomass yield of the grain sorghum type is about 23 dry Mg ha^{-1}. In an FAO document (from the mid 1990s) on sorghum in China, grain sorghum water requirements are stated as 350 to 700 mm, depending on the length of the growing cycle (short-growth variety 90 days to long-growth variety 130 days). For optimum yields on good soil, short-growth, average-growth, and long growth varieties requires 500 to 600 (20 to 24), 650 to 800 (26 to 31), and 950 to 1100 (37 to 43) mm (inches) of well distributed rainfall, respectively (Natural Resources Institute, no date).

Sweet and forage sorghums have high yield potential, 20 to 40 dry Mg ha^{-1}. As an annual (instead of a perennial) crop, sorghum can be rotated with other annuals such as corn and soybeans or grown in multiple crop rotations, which can diversify production (reducing risk), improve soils and reduce weed and insect control requirements, making sorghum attractive to farmers (e.g. see Ngouajio, no date). In its breeding program for energy sorghum, Texas A&M University has a yield goal of 45 dry Mg ha^{-1} (20 dry tons $acre^{-1}$) (Schill, 2007). Reddy (2008) indicates that sweet sorghum is similar to grain sorghum, but requires 700+ mm of rainfall. Because both sweet and forage sorghums are thick stemmed, they are typically 60% to 70% moisture (wet basis) at harvest and handled as a silage crop, rather than as a hay crop. Sweet sorghum can have sugar contents similar to sugar cane and, like sugar cane, it must be processed quickly to avoid losses of sugars. It may be possible to field dry forage sorghum to lower moisture content if utilized for energy purposes, rather than as a forage crop where feed quality is important. If the desired storage method is ensiling and the moisture content is too low, it is difficult to store the crop as silage. Lower moisture content can lower transport costs.

Sorghum planting strategies are largely determined by site conditions (e.g. available moisture, length of growing season), requirements of the preceding and succeeding crop, and objective(s) in growing sorghum [whether solely for grain, solely for biomass (and sugar), or for both grain and biomass (and sugar)]. Forage sorghums have higher growing temperature requirements than corn (Roth, 1995). Minimum temperature for forage sorghum growth is about 15˚C (60˚F) and optimum growth occurs when mean temperatures are between 24˚C (75˚F) and 27˚C (80˚F). Planting should occur when soil temperatures have reached 18˚C (65˚F) at 5.1- to 10.2-cm (2- to 4-inch) depth.

There are both photoperiod sensitive and photoperiod insensitive sorghums. Photoperiod insensitive sorghums initiate reproductive growth after a set amount of time regardless of day length. Grain sorghum has been bred in temperate climates to do this. Photoperiod sensitive sorghum begins

reproductive growth (i.e. flowering) when day length reaches a certain threshold. This threshold depends on the particular genotype and ranges from 11.5 to 13.5 hours. If biomass is the desired product, sorghums with a photoperiod shorter than day length at the end of the growing season (first frost in temperate climates) allows the crop to maximize biomass production. However, disease and drought may limit how much of the growing season can be utilized and affect the timing of planting. In areas with longer growing seasons, it may be possible to grow a ratoon crop of sorghum (i.e. sorghum is harvested and then a second crop grows back from the roots). If a ratoon crop is desired, then sorghum with a longer photoperiod or photoperiod insensitive would be selected. Photoperiod sensitive sorghums generally do not set seed under Midwestern, USA conditions. Sorghums should be selected for an appropriate photoperiod for the region where they are grown, when they are planted, and the goal for which they are grown (biomass versus biomass plus grain).

Research at Purdue University (Cherney et al 1990, Johnson et al 1991) found that lodging resistance is critical for top yields. While two cuttings can reduce lodging, yield was greatly reduced. [Lodging is when plants fall over.] Varietal selection and agronomic practices may reduce lodging. Taller plants do not necessarily produce higher yields. Sorghum grown in monoculture had declining yields over time. Rye double cropped with sorghum can be a high yielding system.

Hybrids have a long history of use in sorghum production. Properly selected sorghum hybrids can help growers increase yields, use less water, reduce lodging losses, increase feed quality, and manage maturation (Bean et al 2004, Reddy et al 2008). Owens (2009) reported 20% higher biomass yield from sorghum hybrids in trial conducted in the United States in 2008. Hybrid energy sorghums are available from at least two American seed companies, Ceres and Edenspace, and research could further enhance traits desired for bioenergy.

There are approximately 168,000 sorghum accessions held at repositories around the world, with the two largest repositories being ICRISAT and USDA. The sorghum genome is the second major cereal crop to be sequenced. China has significant sorghum genetic resources and has exported germplasm to other countries. Many Chinese sorghum varieties are tall and offer a wide range in days to maturity (80 to 190 days). Stresses screened for include drought, cold, saline and alkali soils, and various diseases (e.g. head smut) and pests (e.g. sugar cane aphid and European corn borer). Cold tolerance is an important trait available in Chinese germplasm. For biomass, ICRISAT focuses on sweet sorghum with significant grain yield. In the United States Texas A&M focuses on high-yielding energy sorghum (i.e. for biomass and not grain). There are also brown midrib (BMR) sorghums that are lower in lignin. BMR sorghum was developed to improve feed quality (higher digestibility) and may also offer better characteristics than typical sorghum for bioconversion to ethanol.

One of the major challenges facing biomass crops, including sorghum, is logistics (harvest, transport, storage). Grain sorghum is harvested using equipment and systems common to other small grains, such as wheat. The logistics of grain sorghum (harvest, transport, storage) are well developed and similar to maize grain. Tall sorghums (forage, sweet, energy) are harvested with a forage or sugar cane harvester. High tonnages may require large self-propelled harvesters, which have a high capital cost. In areas where field and/or road conditions (combined with economics) limit the use of large-scale harvest equipment, smaller tractor-pulled forage harvesters are used (Pari et al, 2008). For cost-effective harvesting it is advantageous to have an extended harvest season or, in the case of an area also growing sugar cane, to have the sorghum harvest season from the sugar cane harvest season and be able to utilize sugar cane harvesters that would otherwise be idle.

Moisture content presents a challenge for utilizing forage, sweet, and energy sorghums. Generally, these sorghums are thick-stemmed and high in moisture content at harvest (60% to 70% on a wet basis), requiring either ensiling, or a cost-effective means of reducing moisture content below the point that permits dry storage methods (generally below 20%), or quick processing. The cost of biomass transport generally increases with moisture content since the amount of dry biomass carried by a given container (or truck) is reduced by the weight of embedded water. If the sorghum could be reduced to a moisture content of 40%, then the load could be increased, and costs may be reduced 40% under United States conditions. Road characteristics and local transport regulations limit the size and weight of transport equipment, but generally costs will be reduced as bulk load density and volume are increased to reach these limits.

Drying options and harvest logistics depend on use and storage plans. Due to the moisture content, sorghum for feed is generally handled as a silage crop (as opposed to a hay crop). To store the crop as silage (for feed), moisture content must be above 50%. And while sweet sorghum can produce sugar contents rivaling sugarcane, the sugars must be processed quickly (like sugarcane). Forage sorghum used exclusively for energy could be allowed to dry in the field, but field drying can compromise sorghum's value for feed, reducing marketing options.

The option of rapid, intermediate processing could involve small scale pyrolysis, pelletization or cubing, but any of these would demand significant drying (optimally, to a moisture content of about 10%). Pyrolysis would produce a liquid that might be more economically stored and transported.

Developing sorghum as an energy crop will need to be supported by an integrative research strategy that considers an entire cropping system (where sorghum may be one component) to sustainably and economically produce food, feed, fiber and fuels. Preliminary research questions that need to be explored include:

What sorghum products are desired?

- Both biomass (lignocellulose alone or lignocellulose and sugar) and grain?
- Primarily biomass (and grain produced, if any, is incidental)?
- Sugars (and possibly grain) with the bagasse as a secondary product?

What land will be used?

- Will sorghum replace current food and feed crops, or pasture?
- Will sorghum be integrated in crop rotations (potentially increasing long-term productivity of other crops)?
- Will sorghum be part of an expansion into marginal lands or part of recuperation of abandoned and degraded lands?

In addition to land use and product mix, productivity depends on intensity of production and constraining factors such as water. The feasibility of bioenergy from sorghum will depend on costs of required inputs, efficiency of operations, markets and prices for cropping system outputs and technologies available. For example, with today's conversion technologies, sweet sorghum for conventional ethanol may be the most viable bioenergy option, but in the future, lignocellulosic conversion technology may favor sorghum varieties with higher biomass yields per unit of input than sweet sorghum.

A question to research is whether one is better off utilizing sorghum that is specialized (e.g. energy sorghum for biomass and grain sorghum for grain) or sorghum that is multipurpose (e.g. sweet sorghum that produces both grain and biomass) instead? For example, if grain sorghum is grown on 1 unit of land and energy sorghum on 1 unit of land, will this produce more grain and biomass than dual purpose sorghum (a sorghum developed for both grain and biomass) grown on 2 units of land? The answer is likely to vary be location.

Storage is an issue with any bioenergy crop, particularly those with relatively short harvest seasons. To operate a conversion facility year round requires significant storage or diversification of feedstocks (e.g. woody crops, winter crops) to allow continuous harvest and delivery throughout the year. One means of reducing storage requirements is to extend the sorghum harvest season by staggering planting times, using varieties with differing maturities, and utilizing ratoon (multiple cutting) management.

Among potential annual bioenergy crops, sorghum may be advantageous where drought tolerance is important and it can enhance production of other crops (e.g. as seasonal cover crop or in rotations). Sorghum allows farmers flexibility in choice of crop from year to year. It has the potential for high yield (40+ dry Mg ha^{-1} yr^{-1}). Genetic mapping combined with a relatively fast breeding and field testing cycle facilitate further improvements for bioenergy once desired feedstock characteristics and site requirements are clearly defined. Acknowledging that improvements for bioenergy could potentially diverge from those for feed and food, the following research agenda is proposed:

1) Define traits important for bioenergy and characterize sorghum collections for these traits
2) Develop cost-effective means to stabilize sweet sorghum juice so it does not need immediate processing
3) Increase sugar yields of sweet sorghum for use in the near term as an ethanol feedstock (or to supplement sugar from sugarcane)
4) Increase grain yields for sweet and energy sorghums to explore multi-product potential
5) Develop varieties for high biomass yields (energy sorghum)
6) High and low lignin varieties (high lignin for thermochemical conversion such as gasification or pyrolysis and low lignin for ethanol feedstock)
7) Research cropping systems including
    - double cropping where sorghum supplements other grain production to increase overall output while reducing environmental impacts
    - cover crop and inter-crop sorghum that helps control weeds and pests for high-value crops (vegetables) while improving soils

While perennial biomass crops may be preferred for environmental benefits, annuals such as sorghum provide farmers with more agility to shift crop production in response to market signals. Both perennials and annuals can play important roles in an integrated system designed to minimize input requirements and maximize production of multiple food, feed, fiber and fuel products.

1. BACKGROUND

Sorghum [*Sorghum bicolor* (L.) Moench] has much potential as an annual energy crop. It is morphologically diverse, with grain sorghum being of relatively short stature and grown for grain, while forage/sweet sorghums are tall and grown primarily for their biomass. Sorghum is a more efficient user of water than corn under water-limited conditions and is well adapted to environments where water availability is a constraint.

Different sorghum types can be used as bioenergy feedstocks for a variety of conversion technologies (see Table 1). Sorghum grain can be utilized alongside corn grain in starch-to-ethanol facilities. In 2008, about 2.5 x 10^6 Mg (100 x 10^6 bushels) of grain sorghum was used to produce about 1.0 x 10^9 L (270 x 10^6 gallons) of ethanol in the United States. There is growing interest in using sweet sorghum juice to produce ethanol. For example, in 2008 Renergie, Inc. received a $1.5 million grant from the state of Florida to design and construct a facility to produce ethanol from sweet sorghum juice (News.mongabay.com, 2008). In India, in Andhra Pradesh State, Runsi Distilleries has a sweet sorghum to ethanol facility, and Tata Chemicals is, or has recently finished, constructing a sweet sorghum to ethanol facility in Maharashtra state (FBAE, 2008; Alibaba.com, 2008). In 2008, it was announced that Nigeria Global Biofuels would construct a 1.5 x 10^6 L per day ethanol facility (D-8 Secretariat, 2008) in Ondo State. According to the National Sorghum Producers, sweet sorghum is currently being used in India, South America, and the Philippines to produce ethanol (National Sorghum Producers, no date). Sweet sorghum juice is also of interest for on-farm ethanol production (Bennett and Anex, 2008).

Figure 1. Sorghum types and bioenergy applications: sorghum grain (left, photo courtesy of USDA ARS) can be utilized much like corn grain in starch-to-ethanol facilities while the biomass of forage, or energy, sorghum (right, photo courtesy of Dave Jordan, MacDon Industries, LLC) can be harvested as a cellulosic feedstock.

As a cellulosic feedstock, the sweet and forage types are of interest. Energy sorghum is forage sorghum bred for high biomass production. Dual purpose forage and energy sorghums produce both biomass and grain, and multipurpose sweet sorghums can produce biomass, sugar, and grain. Related sorghums, sudangrass, and sorghum x sudangrass may also have a role as short growing season crops or crops allowing two cuttings in one growing season.

Table 1. Sorghum types, conventional uses, and bioenergy applications for each

Sorghum type	Typical Purposes in US	Applications for Bioenergy and Some Current Examples
Grain sorghum	Grain harvested for livestock feed	Grain can be used in starch to ethanol conversion processes In 2008, 2.5x 10^6 Mg of grain sorghum used to produce about 1.0×10^9 L of ethanol in US Sorghum residue (stubble) can be used as feedstock for cellulosic ethanol conversion
Sweet sorghum	High-sugar content sorghum varieties – sugar harvested for molasses and/or biomass used as livestock feed	Sweet sorghum juice fermented to produce ethanol; on-farm conversion processes currently being explored In 2008, Renergie, Inc. received a grant from state of Florida to design and construct facility to produce ethanol from sweet sorghum juice In India, two sweet sorghum to ethanol facilities have been publicized by Runsi Distilleries and Tata Chemicals
Forage sorghum	Biomass harvested for livestock feed	Good candidate as annual crop for cellulosic ethanol conversion processes; forage sorghums being bred for high biomass yield for bioenergy applications DOE Regional Feedstock Partnership is currently conducting energy sorghum field trials in Iowa, Kansas, Kentucky, Mississippi, and North Carolina

Sorghums are thought to originate just north of the equator in Africa (in what today are Chad, Ethiopia, and Sudan). They are sensitive to day length or photoperiod and need consistent day length of up to 12 hours to trigger an internal mechanism to initiate reproductive growth, first flowers and later seeds. Sorghums have also long been cultivated in China, with records possibly dating back to the 3rd century A.D., and over time many landraces and varieties developed or were bred (Qingshan and Dahlberg, 2001).

In 2004, 59% of the land producing sorghum was in Africa, 25% in Asia, and 11% in North and Central America. In terms of production (tons produced), contributions were Asia 45%, Africa 25%, and North and Central America 21% (ICRISAT, 2009). Productivity in Africa and average productivity in Asia are held down by many factors: lack of improved seeds and technology, lack of markets and capital, and primarily the fact that most farmers are poor, lack irrigation, and use marginal rain fed lands where their best strategy is to reduce risk with low seeding rates and zero (or minimal) investment in other inputs (fertilizer, weed and pest control). In Asia, sorghum yields are lower in India, Pakistan, and Yemen. In China, average sorghum yield is around 4 Mg ha^{-1}, similar to yield observed in the United States.

Grain sorghums have been bred for dwarf stature and stand 0.6-1.2 m (2-4 ft) tall. In 2008, average grain sorghum yield in the United States was 3.51 dry Mg ha^{-1} (assuming 86% dry matter) (65.0 bu $acre^{-1}$). Assuming a grain:residue ratio of 1:1, 3.51 dry Mg ha^{-1} of residue was produced. Grain sorghum types will not be high yielding biomass crops. Under irrigation in California, yield was 6.59 Mg ha^{-1} (105 bu $acre^{-1}$) in 2006 for a total of biomass yield of 11.3 dry Mg ha^{-1} (assuming a 1:1 grain:residue ratio and 86% dry matter grain). The maximum yield of grain sorghum in 2009 in the Yield and Management Contest by the National Sorghum Producers was 13.6 Mg ha^{-1} (216 bu $acre^{-1}$) irrigated and 12.4 Mg ha^{-1} (197 bu $acre^{-1}$) rain fed, which would give total biomass yields of 23 and 21 dry Mg ha^{-1}(assuming 86% grain dry matter and grain:residue ratio of 1:1) (National Sorghum Producers 2009). Based on the results of the National Sorghum Producers Yield and Management Content, the current maximum potential biomass yield of the grain sorghum type is about 23 dry Mg ha^{-1}.

Sweet and forage sorghums have higher biomass yield potential (20 to 40 dry Mg ha^{-1}) than grain types. They are attractive to farmers as they can be grown as an annual (instead of a perennial) crop and be rotated with other annuals such as corn and soybeans. Sorghums for energy can also be grown as an annual energy crop alongside perennial crops to respond to quick shifting feedstock markets. Reddy (2008) indicates that sweet sorghum is similar to grain sorghum, but requires 700+ mm of rainfall. Because both sweet and forage sorghums are thick stemmed, the moisture contents at harvest are typically 60-70% (wet basis) and are generally handled as a silage crop rather than as a hay crop. Sweet sorghum can have sugar contents similar to sugar cane and like sugar cane requires quick processing to utilize the sugars and avoid degradation. It may be possible to field dry forage sorghum to lower moisture contents if utilized for energy purposes rather than as a forage crop where feed quality is important. If the desired storage method is ensiling and the moisture content is too low (below 50% on a wet basis), it is difficult to store the crop as silage. Reducing moisture content and handling as a dry crop (<20%) is desirable to reduce transportation and storage costs.

Forage sorghums have higher growing temperature requirements than corn (Roth, 1995). Minimum temperature for forage sorghum growth is about 15˚C (60˚F) and optimum growth occurs when mean temperatures are between 24˚C (75˚F) and 27˚C (80˚F). Planting should occur when soil temperatures have reached 18˚C (65˚F) at 5.1- to 10.2-cm (2- to 4-inch) depth. In Pennsylvania, Roth (1995) recommends a planting depth of 1.9 to 3.2 cm (0.75 to 1.25 inches). In Virginia, Teutsch (2006) recommends 2.5 to 3.8 cm (1.0 to 1.5 inches) (Table 1). The recommended planting depth for sorghum x sudangrass and sudangrass is shallower. Planting rates of 9 to 13 kg ha^{-1} (8 to 12 lb $acre^{-1}$) with 75% emergence results in plant populations of about 210,000 to 370,000 plants ha^{-1} (85,000 to 150,000 plants $acre^{-1}$). Excessive seeding rates can lead to lodging problems (Roth, 1995). [Lodging is when plants fall over. Lodged crops are difficult to mechanically harvest.] Planting too early and too deep are common reasons for poor sorghum stands (Teutsch, 2006). For its high biomass sorghum, Ceres (2009) recommends 185,000, 245,000, and 295,000 seeds ha^{-1} (75,000, 100,000, and 120,000 seeds $acre^{-1}$) for marginal nonirrigated, good nonirrigated, and irrigated land, respectively.

Yield can be affected by harvest timing, fertilization, and irrigation. Bolsen (2002) reviewed studies of the effect of maturity on yield of grain (his Table 1) and forage sorghums (his Table 2). He found that for the grain sorghum, total dry matter increased from the late milk to the late dough stage, but decreased from the late-dough to the hard-grain stage because leaf senescence and broken heads or stalks disconnected from the upper portion of the stalk caused whole-plant dry matter yields to decrease to the point where it was not greater (i.e. statistically significantly different) at the hard-grain stage than at the late-milk stage. For forage sorghums, dry matter increased from the late-milk to the late dough stage, and in some studies dry matter increased from the late-dough to the hard-grain stage, but in others decreased. For both grain and forage sorghum, whole-plant dry matter fraction increased with maturity. The fraction of moisture in the crop can affect transport costs and storage choices and losses.

There are a number of different strategies that can be followed when planting sorghum. These are, however, limited and influenced by site conditions (e.g. available moisture, length of growing season), requirements of the preceding and succeeding crop, and objective(s) in growing sorghum [whether solely for grain, solely for biomass (and sugar), or for both grain and biomass (and sugar)].

Table 2. Forage sorghum, sorghum x sudangrass, and sudangrass characteristics based on Virginia, USA conditions (Teutsch, 2006)

	Forage sorghum	Sorghum x sudangrass	Sudangrass
Soil drainage	Well drained to somewhat poorly drained		
Seeds per kg	29,000 to 44,000	44,000	121,000
Seeding date	1-2 weeks after corn, soil temperature at least 16˚C	2 weeks after corn, soil temperature at least 18˚C	
Seeding depth (cm)[a]	2.5 – 3.8	1.3 – 2.5	
Seeding rate (kg ha^{-1})	6 – 11 for wide rows 17 – 22 broadcast	22 – 34 drilled 34 – 45 broadcast	17 – 22 drilled 28 – 39 broadcast
Soil pH	Will grow at 5.5, optimum 6.0 - 6.5	Optimum 6.0 – 6.5	
Forage yield as silage (wet Mg ha^{-1})	34-67[b]	27-34 at 35% dry matter	

[a]For Virginia with its heavier soils
[b]No dry matter percent given

Photoperiod sensitive sorghums begin reproductive growth (i.e. flowering) when day length reaches a certain threshold (ranges from 11.5 to 13.5 hours). This threshold depends on the particular genotype. If biomass is the desired product, sorghums with a photoperiod shorter than day length at the end of the growing season (first frost in temperate climates) allows the crop to occupy the maximum amount of the growing season and maximize biomass production. In areas with longer growing seasons, it may be possible to grow a ratoon crop of sorghum (i.e. sorghum is harvested and then a second crop grows back from the roots). If a ratoon crop is desired, then a longer photoperiod would be selected. Photoperiod sensitive sorghums generally do not set seed under Midwestern, USA conditions. Sorghums should be selected for an appropriate photoperiod for the region where they are grown and the goal for which they are grown (biomass versus biomass plus grain). There are also photoperiod insensitive sorghums. Photoperiod insensitive sorghum will begin reproductive growth after a certain length of time, regardless of day length. Grain sorghum has been bred so they are photoperiod insensitive and will mature in a set number of days.

2. SORGHUM BIOMASS YIELD EXPERIMENTS

Purdue University (United States) carried out a biomass research project in Indiana, a part of which dealt with sorghum (Cherney et al., 1990; Johnson et al, 1991). Small plot studies were used in which plot size was designed to eliminate edge effects (yields are higher on the edge of a field exposed to additional sunlight and less competition. Yields were based on total above ground biomass. Note that yields from small plot research studies are generally higher than those obtained from actual operational scale farms. Fertilization for other than nitrogen was based on soil tests. They found the following results:

- When planting at two different densities (43,000 and 260,000 seeds ha^{-1}), there was no yield advantage to the higher density. [The authors do not indicate specifically whether this applied to both forage and sweet sorghum, but it presumably does.] There was less lodging at the lower density, but not for all varieties (Table 3).
- Two cuttings reduced lodging, but at too great a reduction in yield (Table 4).
- Lodging resistance is critical for top yields.
- There was evidence from Caravetta et al. (1990) that increasing within row spacing may reduce lodging. In addition to breeding for lodging resistance there may also be agronomic

management practices that may reduce lodging.

- Taller plants did not necessarily produce higher yields (Table 3).
- Sorghum double cropped with winter rye for four consecutive years had declining yields over time (Table 5).
- Sweet sorghum and sorghum x sudangrass interseeded into perennial grasses was not viable, yielding only 0.03 – 3.31 dry Mg ha^{-1}.

Table 3. Sorghum yields and lodging in Indiana, USA in 1990 (Johnson et al, 1991)

Genotype	Yield[a]		Height	Lodging	
				Population (plants ha^{-1})	
	Total	Grain		4.3 x 10^{-4}	2.6 x 10^{-5}
	Dry Mg ha^{-1}		m	1=flat, 5=erect	
Pioneer 931	24.7	2.02	4.64	4.92	4.83
Vartan 3192	24.1	0.10	4.37	4.50	4.17
NK Sucrosorgo 506	22.6	1.48	4.36	5.00	4.92
Grassl	21.7	0.28	3.69	4.22	3.08
Vartan 3	20.6	0.01	4.21	4.67	4.88
Funk's G 1990	19.7	0.00	3.74	5.00	4.92
Vartan 2319	19.7	0.01	5.08	4.00	4.17
Pioneer 811F	19.2	0.00	3.38	5.00	5.00
Golden Harvest H-58	18.6	3.07	3.32	3.83	3.67
Meridian 81E	18.3	1.11	3.68	4.22	3.67
Asgrow Titan R	17.8	5.30	2.78	3.00	2.00
Taylor-Evans Milkmaker	17.7	4.14	3.04	2.08	1.67
DekalbFS25E	17.5	4.09	3.00	4.33	2.42
Casterline Silo Plus	17.0	4.29	2.91	2.00	1.50
Taylor-Evans Silomaker	17.0	5.49	2.58	3.58	1.00
Garrison Seed Sile-All	16.5	4.78	2.96	2.08	1.50
NC^{+}965	16.5	2.68	3.29	3.58	3.17
PAG FS466	16.4	3.96	2.47	4.08	2.92
Tall corn hybrid (Dekalb 711)[b]	23.1	10.66			

[a]Crops were harvested on 3 and 12 October (at the end of the growing season) from 2 sites
[b]Corn hybrid for comparison

Table 4. Sorghum yields in Indiana, USA in 1989 (Cherney et al, 1990)

	One harvest	Two harvests (total)
	dry Mg ha^{-1}	
Dekalb-Pfizer FS25E	25.6	17.4
M-81E sweet sorghum	27.5	15.6
Vartan 2319	21.4	12.8
PAG FS-466	23.1	16.2
Funk's G 1990	31.4	15.2
Pioneer 931	30.5	19.0
NK Sucrosorgo 506	33.0	18.0

Timing of planting can greatly influence yield. In 1988, a severe drought year, sorghum planted in early May, when there was still adequate soil moisture yielded up to 33 dry Mg ha^{-1}, while sweet sorghum and sorghum x sudangrass planted in late May averaged only 8.6 dry Mg/ha. Corn planted at the same time as the sorghum in early May yielded only 4 – 5 dry Mg ha^{-1}. The combined yield of sweet sorghum double cropped with rye was up to 31 dry Mg ha^{-1}.

Table 5. Sorghum double cropped with winter rye for four years in Indiana, USA had declining yield[a] over time (Cherney et al, 1990)

Year	Sorghum x sudangrass	Sweet sorghum
	Dry Mg ha^{-1}	
1985	16.4	22.2
1986	12.6	19.1
1987	10.6	15.8
1988[a]	8.3	8.9

[a]Average over 4 nitrogen treatments (0, 50, 100, 150 kg N ha^{-1}), 4 replicates, 4 sites, 2 tillage treatments
[b]1988 was an extreme drought year

Monk et al (1984) report on sorghum improvement for energy. They found a significant correlation between height and biomass production, but note that lodging can be as serious issue with tall sorghums, especially those with significant grain production.

The Regional Feedstock Partnership Program sponsored by the U.S. Department of Energy is conducting field trials of a number of biomass crops, including sorghum (Owens, 2009). In 2008, sorghum was planted on 0.05 to 0.10 ha plots at 7 sites in Texas (2 sites), Iowa, Kansas, Kentucky, Mississippi, and North Carolina. Two photoperiod-sensitive energy sorghum hybrids (from Ceres and Edenspace), two photoperiod-sensitive forage sorghum hybrids, a sweet sorghum, and a grain sorghum (as a check) variety were planted and harvested in 2008. The Iowa site was not harvested in 2008. A single, end of season harvest was made. Nitrogen was applied as recommended for forage sorghum and no irrigation was applied. Grain sorghum, forage sorghum, and energy sorghum yielded 9, 27, and 27-34 dry Mg ha^{-1} (4, 12, and 12-15 dry tons acre^{-1}). [Experimental hybrids resulted in about a 20% yield gain over nonhybrids, a 4.5 to 6.7 to dry Mg ha^{-1} (2-3 dry tons acre^{-1} yield) increase]. In 2009, the grain sorghum was not planted and in addition to the two forage, two energy sorghum hybrids, and the sweet sorghum variety; a sweet sorghum hybrid was to be planted.

Oklahoma State University is looking into developing sweet sorghum as a crop for Oklahoma (Anon, 2008). At various locations the university is evaluating: yield of 4 varieties, staggered planting dates to develop a larger harvest window, nitrogen response, and effect of irrigation versus no irrigation.

3. SORGHUM HYBRIDS

One strategy for increasing sorghum yield is through the use of hybrids. As noted above, Owens (2009) reported 20% higher yield from experimental sorghum hybrids in 2008. Reddy et al (2006) report that sorghum grain yields in India and China increased by 50% and 47%, respectively, from 1960 to 1996. This corresponds to the period of adaption of hybrids in these countries, although other factors such as increased fertilization and better weed control may also have contributed to increased yields. According to Reddy et al (2008) hybrids are early maturing and need less water than varieties (i.e. sorghums that are not hybrids).

As of October 2009, commercial seeds for energy sorghum in the United States were available from Ceres (2009) (in cooperation with Texas A&M AgriLife Research) (referred to by Ceres as "high-biomass sorghum") and Edenspace. Ceres has two sorghum and two sorghum x sudangrass cultivars available. All four are photoperiod-sensitive, non-heading hybrids. The two sorghums are for single cuts, while the two sorghum x sudangrasses are suitable for multiple cuts in a growing season.

Edenspace refers to their hybrid seed product for cellulosic biofuels production as Energy Sorghum$_{tm}$, with Linebacker$_{tm}$ being the first available (National Sorghum Producers, 2008). It is a nontransgenic, photoperiod-sensitive forage sorghum.

4. WATER USE

In an FAO document (from the mid 1990s) on sorghum in China, sorghum water requirements are stated as 350 to 700 mm, depending on the length of the growing cycle (short-growth variety 90 days to long-growth variety 130 days). For optimum yields on good soil, short-growth, average-growth, and long-growth varieties requires 500 to 600 (20 to 24), 650 to 800 (26 to 31), and 950 to 1100 (37 to 43) mm (inches) of well distributed rainfall, respectively (Natural Resources Institute, no date).

Water use efficiency (WUE) is a measure of yield per unit of water consumed. Water use and WUE vary by site conditions. In western Kansas, grain sorghum requires 46 to 56 cm (18 to 22 inches), while in the eastern (more humid) part of the state 25 to 50 mm (1 to 2 inches) less is required (KSUAES&CES, 1998). One must be careful when utilizing the concept of WUE. A description of the complexities of utilizing WUE can be found in Jørgensen and Schelde (2001). One can find statements such as sorghum requires 1/3 less water than corn or sorghum requires only half the water of corn. The FAO document on China states that for sorghum, maize, and wheat the transpiration ratio is 141, 170, and 241 kg kg^{-1} plant material, respectively (Natural Resources Institute, no date). [Note: it is not stated in this reference whether plant material is total above ground biomass or just the grain fraction.] For grain sorghum grown in the North Plains of Texas over the 6-year period of 1998 to 2003, water consumption was 1060 and 842 kg water kg^{-1} grain for dryland and irrigated production, respectively (New, 2004). [The original units in New (2004) are 213 and 269 lb grain $acre^{-1}$ in^{-1} water for dryland and irrigated production, respectively.]

Conventional wisdom suggests that: under the driest conditions millet is preferred to (produces more than) sorghum and maize (corn), under semi-arid conditions sorghum is preferred to millet or sorghum, and with ample moisture corn performs best. Singh and Singh (1995) tested this belief for sorghum, maize, and millet in an experiment during the hot dry season (April-June) in North India in 1979 and 1980 at four irrigation levels that are described as: unstressed (S_0), mildly stressed (S_1), moderately stressed (S_2), and severely stressed (S_3). Results for dry matter production and WUE (based on total above ground biomass) are shown in Table 6. They found that maize and sorghum performed best at unstressed conditions. Just because a crop has a higher WUE does not mean it has a higher biomass yield. Different crops draw different amounts of water from different parts of the soil profile. Sorghum draws water from more of the soil profile than corn. In Table 6 below, at irrigation level S_1, maize has a higher WUE than sorghum, but it does not have a higher yield (they are equal).

Table 6. Biomass production, evapotranspiration, and water use efficiency for corn, sorghum, and millet in Northern India in 1979 and 1980 (Singh and Singh, 1995)

Irrigation level	Biomass (dry Mg ha^{-1})			Evapotranspiration (mm)			Water use efficiency (dry kg ha^{-1} mm^{-1})		
	Maize	Sorghum	Millet	Maize	Sorghum	Millet	Maize	Sorghum	Millet
S_1	9.0	9.0	8.3	567	582	568	15.9	15.4	14.6
S_2	5.2	7.1	5.9	403	432	429	12.8	16.4	13.8
S_3	4.7	6.1	5.4	342	329	331	13.7	18.5	16.3
S_4	3.0	4.1	4.0	276	288	224	11.0	14.4	17.9

Farré and Faci (2004) compared water use for sorghum and maize in Zaragoza, Spain, reporting total above ground biomass and grain yields, harvest index (grain fraction of total above ground biomass), and irrigation WUE for grain. Plant densities were 52,000 and 217,000 ha^{-1} for maize and sorghum, respectively. Reference evapotranspiration was 695 mm from sowing to maturity. Irrigation water was applied such that for 6 treatments water applied decreased from T-1 to T-6, with T-1 receiving the full amount of water required. Consistent with Singh and Singh (1995), they found sorghum extracted more water from the deeper soil layers and maize from the upper soil layers. Yields, harvest index, and irrigation WUE for the six water treatments are in Table 7.

Table 7. Yields, harvest index, and irrigation water use efficiency (WUE) for maize and sorghum at Zaragoza, Spain in 1995 (Farré and Faci, 2004)

Treatment	Biomass (dry Mg ha^{-1})		Grain (dry Mg ha^{-1})		Harvest index		Irrigation WUE (g grain m^{-2} mm^{-1})	
	Maize	Sorghum	Maize	Sorghum	Maize	Sorghum	Maize	Sorghum
T-1	21.4	18.4	10.8	8.54	0.51	0.49	1.95	1.65
T-2	17.4	16.4	8.79	7.42	0.50	0.47	1.85	1.70
T-3	11.0	13.0	4.80	6.30	0.43	0.46	1.25	1.75
T-4	7.00	10.7	1.95	4.88	0.28	0.46	0.75	2.05
T-5	4.85	7.28	0.558	2.65	0.12	0.37	0.30	1.50
T-6	3.57	5.22	0.095	0.643	0.03	0.13	0.10	0.65

McCorkle et al (2007) report that in the Panhandle region of Texas, where the availability of irrigation water is becoming a bigger issue, in field trials over the period 2001 to 2003, comparing sorghum silage to maize silage, yields ranged from 43.0 to 60.3 Mg ha^{-1} (19.2 to 26.9 tons $acre^{-1}$) for sorghum silage and 53.3 to 57.1 Mg ha^{-1} (23.8 to 25.5 tons $acre^{-1}$) for maize, but to grow sorghum silage required 40 to 53 percent less water than maize silage.

One practice in semi-arid areas (e.g. western Great Plains and High Plains in the United States) is to fallow (a year in which no crop is planted), such as in wheat-fallow or sorghum-fallow (one crop in 2 years), or wheat-sorghum-fallow (2 crops in 3 years) rotations. The fallow year allows moisture to accumulated in the soil and be available for a crop the next year. Although the fallow year allows yields in succeeding years to be greater, over the rotation cycle total yield may not increase by using a fallow year in the rotation (Table 8, e.g. compare over 2 years continuous sorghum 4.37 Mg ha^{-1} versus sorghum-fallow 4.21 Mg ha^{-1}, or over 6 years where continuous sorghum gives a greater yield than any of the rotations utilizing fallow).

Table 8. Dryland sorghum and winter wheat yields (Mg ha-1) in continuous and fallow rotations 1973-1987 at Tribune, Kansas, USA (Norwood et al 1990)

Rotation	**Continuous wheat**	**Wheat-sorghum-fallow**		**Wheat-fallow**		**Continuous sorghum**	**Sorghum-fallow**
Tillage	Conventional[1]	Conventional[1]	Reduced	Conventional[1]	Reduced	Conventional[1]	Conventional[1]
Wheat	1.14[c]	2.28[b]	2.66[a]	2.38[ab]	2.68[a]		
Sorghum		2.40[c]	3.29[b]			2.18[c]	4.21[a]
2 year yield	2.27			2.38	2.68	4.37	4.21
3 year yield	3.41	4.69	5.96			6.55	
6 year yield	6.82	9.38	11.92	7.14	8.03	13.10	12.63

[1]stubble mulch (leaving residue on the surface while farming) was the conventional tillage practice used

Water is a limiting factor of production in many areas. One wants to match an appropriate crop and genotype or hybrid with available soil moisture. There is no advantage to planting a high yielding crop if the water is not available to support the high biomass yield. According to Koch (no date), sorghum can produce a ton of forage with 6 to 8 cm (2.5 to 3 inches) of [total] water. Sorghums are known for their ability to extract soil moisture.

5. HARVEST AND STORAGE SYSTEMS

Grain sorghum is harvested in a similar fashion as are other small grains, such as wheat. In modern agriculture, grain sorghums have been bred for uniform height so they may be efficiently harvested with a combine. The logistics of grain sorghum (harvest, transport, storage) are well developed and similar to maize grain. Sorghum grain is usually dried to a moisture content of 10% to 12% and has a bulk density of 520 to 720 kg m^{-3} (32 to 45 lb ft^{-3}) which allows for storage and efficient transport (Natural Resources Institute, No date).

Tall sorghums (forage, sweet, energy) are harvested with a forage or sugar cane harvester (see Figure 2). High tonnages require large self-propelled harvesters, which have high capital costs. However, field and road conditions may not permit, either physically or economically, use of large-scale harvest equipment and it may make sense to us a tractor-pulled forage harvester (Pari et al, 2008). Pari et al (2008) report on European efforts to develop a sweet sorghum harvester appropriately scaled to European conditions.

Figure 2. Energy sorghum harvested as a cellulosic bioenergy feedstock with a forage harvester (photo courtesy of Dave Jordan, MacDon Industries, LLC).

For cost-effective harvesting, it is advantageous to have an extended harvest season or, in the case of an area also growing sugar cane, to have the sorghum harvest season offset from the sugar cane harvest season and be able to utilize sugar cane harvesters that would otherwise be idle. Sweet sorghum is similar to sugar cane in that the juice (sugar) in the stalk needs to be processed fairly rapidly; otherwise sugars in the stalk are lost. Reddy et al (2008) show data on how the amount of sugar decreases over the course of four days (Table 9). Given that the sugar in sweet sorghum, like in sugar cane, needs to be processed rapidly, technologies need to be developed to stabilize the juice and maintain the sugar for later processing so that the processing season for the sugar could be extended. At Oklahoma State University, USA, Anon (2008) refers to a process that includes a newly designed field harvester that can press and collect juice from sweet sorghum in a single pass and utilization of large bladders for on farm fermentation. Grassi (no date) refers to a "first commercial innovative mechanical drying and compaction technology" for stabilization of "humid" lignocellulosic residues that can produce pellets (with neither predrying nor a binder) at a processing cost of about 35 Mg^{-1} and a bulk density of about 600 kg m^{-3}. The moisture content of the pellets is not given. [The Grassi reference is from 2005 or later as it references prices from November 2005 in its third slide.]

Table 9. How sweet sorghum sugar content is affected by delay in crushing (Reddy et al, 2008)

Crushing (days after harvest)	Juice extraction (L x 10^3 ha^{-1})	Brix reading	Sugar yield (Mg ha^{-1})	Sugar reduction from harvest day (%)
0	42.4	18.5	2.62	-
1	40.6	19.2	2.47	5.7
2	35.0	20.9	2.18	16.8
3	37.6	21.4	2.20	16.0

An additional question with sweet sorghum (and other high tonnage sorghums) is whether the whole plant should be processed or whether the leaves should be discarded. For sweet sorghum, should only the stalk be processed and both the grain and leaves be discarded? For sweet sorghum with little grain, this is not an issue, but if sweet sorghum is developed for both its sugar and grain, appropriate harvesting technology must be developed to harvest both the stalk and grain.

Moisture content presents a challenge for utilizing non-grain sorghum. Generally, sorghums grown for biomass will be high in moisture content at harvest (60% to 70% on a wet basis), although when grown for biomass, as opposed to for animal feed, it may be possible to field dry to a lower moisture content. High moisture content may limit the amount of dry matter that can be carried in a truck load. For example, in the United States the typical maximum load that can be carried by a truck is about 22.7 Mg (50,000 lb) and the largest volume a trailer can have is about 140 m^3 (5,000 ft^3). At 60% moisture content, the maximum dry matter content of the load is 9.1 dry Mg (20,000 dry lb). In this largest sized trailer, this load is achieved with a density of 64 dry kg m^{-3} (4.0 dry lb ft^{-3}). Chopped sorghum has a density of between about 70 and 120 dry kg m^{-3} (4.4 and 7.5 dry lb ft^{-3}), which is much lower than grain sorghum. At this high moisture content the load is limited by the weight, and the volume would not be fully utilized. If the sorghum could be reduced to a moisture content of 40%, then the load could be 13.6 dry Mg (30,000 dry lb) and the maximum weight allowable would be achieved by a density of 96 dry kg m^{-3} (6.0 dry lb ft^{-3}). Transport options are limited by moisture. It may also be that road characteristics limit the size of trailer, and a higher bulk density may be desirable, if highway conditions support the higher load weight.

Texas A&M is working to design a collection system similar to a cotton module for packaging sorghum for transport and storage. [A cotton module is built in a module builder (about 9 meters long, 4 meters high, and 3 meters wide) by dumping a number of loads of harvested cotton into the module builder and compressing each load (as a garbage truck does with garbage) until the module is built and discharged. It is shaped similar to a giant bread loaf and weights about 10 Mg (Cotton.org, 2010 Wikipedia, 2010).] This most likely will require modification of the cotton module technology. After harvest the sorghum is transferred to the module builder using a silage wagon. The biomass is then compressed into a module and surrounded with a protective cover. The high moisture content of sorghum is a challenge in compressing the material into a module (Fannin, 2009). High moisture contents may necessitate the use of ensiling for storing sorghum, or a cost effective means of reducing sorghum moisture content below 20% so that a dry storage method such as baling could be used.

Another option is some type of distributed intermediate processing. For example, a pyrolysis unit could be used to process the sorghum into a liquid that would be far denser than the sorghum biomass itself. The liquid can be stored and more economically transported. In the case of pyrolysis the optimal feedstock moisture content is around 10%. Pelletization and cubing are other options, but again optimal moisture content is around 10%.

Storage is an issue with biomass crops and sorghum is no exception. The seasonality of production and the desire to operate a conversion facility year round may necessitate storage of biomass. One means of minimizing storage is to pursue strategies for expanding the sorghum harvest season (e.g. planting varieties with differing maturities or utilizing multiple cuttings on some sorghum fields). Another is to utilize multiple feedstocks with differing harvest seasons along with sorghum (e.g. winter rye or trees).

6. SORGHUM AND SUGAR CANE

While sweet sorghum can give sugar yields comparable to sugar cane, it is not used for refined sugar production because its high sugar content interferes with sucrose crystallization and hastens the inversion of sucrose to glucose and fructose (Tew et al, 2008).

One proposed use of sweet sorghum is to plant it at times when sugar cane lands are fallow. Sugar cane is a hybrid with multiple parents. Sugar cane is vegetatively propagated because the seed produced does not breed true (i.e., it could express any of the parents and would not produce a uniform field or product). Under normal Florida conditions, for example, the seed produced will not germinate. Sugar cane, though a perennial, needs to be replanted about every two to five years in the United States. [In other parts of the world, replanting may occur less frequently, every 7+ years.] In the continental United States, sugar cane fields are replanted in Louisiana from August through October, usually in September (Tew et al, 2008) and in Florida from late August through January (Baucum et al, 2006). Part of existing sugar cane production fields are used to take vegetative material and replant fields. The later one waits to replant the sugar cane field, the less area one has to sacrifice to seed cane, as the per unit area production of sugar cane increases from August through September. However, research in Louisiana has found that planting in August leads to higher subsequent sugar yields in three out of five hybrids that occupy 99% of sugar cane acreage in Louisiana (Viator et al, 2005). In the continental US, sugar cane is harvested for sugar in November through March. If sugar cane fields that need to be replanted are replanted by January, then there is no fallow period. However, if a sugar cane field is not replanted by January, then one has to wait until the subsequent August-January period to replant and those fields will be fallow from after harvest until replanting (i.e. during a summer growing season). Sweet sorghum could be planted instead of fallowing the land (Baucum et al, 2006). Another possible crop to grow in this potentially fallow period is soybeans.

For sorghum to be grown during fallow on sugar cane lands, it would need to be harvested not later than mid-August, to allow optimum replanting of sugar cane. In an experiment near Schriever, LA, USA in 2003 and 2004, Tew et al (2008) evaluated how sorghum yield (five sweet sorghum varieties and two sorghum x sudangrass varieties) and total ethanol produced are affected by harvest date (Table 9). (Only the highest yielding varieties are reported in Table 10.) Planting occurred on 29 April 2003 and 6 May 2004. Stalks were stripped of leaves and seed heads to simulate what would likely occur if the sorghum were harvested with a sugar cane harvester. A mid-April planting and mid-August harvest would allow approximately a 120 day growing season. Note that in 2003 and 2004, 26 August and 2 September were 119 days after planting, respectively. In 2004 16 August was 101 days after planting. A mid-April planting might result in a lower yield than indicated in Table 10 (at equal days after planting) because of less growing degree days.

According to information presented by Reddy et al (2008), sweet sorghum needs less water than sugar cane. A sweet sorghum crop growing in India needed 4,000 m^3 for a 4-month period versus 36,000 m^3 of water for a sugar cane crop growing over 12 months. It is possible under Indian conditions to grow two sweet sorghum crops while a single sugar cane crop is growing. The two sweet sorghum crops would require 8,000 m^3 of water. They report that the sugar in the stalk of two sweet sorghum crops and one sugar cane crop would produce 2800 and 5600 l ha^{-1}, respectively. In addition the sweet sorghum can produce 2.0 to 2.5 Mg ha^{-1} grain. [The original source for the sweet sorghum water use is Soltani and Almodares (1994).]

Table 10. How harvest timing (days after planting) affect sorghum yield and total ethanol from sorghum in Louisiana (Tew et al, 2008)

Days after planting	MMR 33/47[a]	Theis[b]	M81-E[b]	MMR 33/47	Theis	M81-E	MMR 33/47	Theis	M81-E
	Hexose sugars (Mg ha^{-1})			Fiber (Mg ha^{-1})			Ethanol[c] (L ha^{-1})		
85	3.2	5.0	4.7	10.0	14.2	11.0	5,670	8,300	6,930
101	5.0	8.1	6.6	14.2	14.2	12.8	8,330	10,220	8,800
119	6.4	9.8	8.0	20.2	15.3	13.4	11,450	11,620	9,860
138	8.3	10.1	9.5	23.4	16.6	15.5	13,840	12,340	11,570

[a]Sorghum X sudangrass hybrid
[b]Sweet sorghum
[c]Estimated theoretical ethanol, based on assuming 1.7 and 2.65 kg hexose sugar and fiber per L ethanol, respectively

7. CROP IMPROVEMENT EFFORTS

Klein et al (2008) identify five distinct phases for grain sorghum improvement efforts in the United States:

1) introduction of a limited number of cultivars (1878-1908),
2) selection of early maturing plants of short stature from heterogeneous populations (1904-1936),
3) breeding of improved cultivars (short stature, photoperiod insensitive) that are combine harvestable (1930s-1940s),
4) hybrid seed production (1946-present), and
5) conversion of tropical sorghums (tall, photoperiod sensitive) to sorghum usable in temperate climates (short, photoperiod insensitive) and the use of diverse sorghum germplasm for breeding (1963-present)

Starting in 1963, a cooperative effort, now known as the Sorghum Conversion Program, between USDA and Texas A&M University was begun to convert tropical photoperiod sensitive sorghum into sorghums that would flower and set seed within 50 to 75 days after planting and be ready for harvest within 120 days after planting. These traits would make sorghum a useful crop in the temperate latitudes for grain production. Tropical sorghums are converted by crossing the photoperiod insensitive tropical sorghums with a variety that is insensitive to day length. During the winter, the crossed plants are grown at the Tropical Agricultural Research Station in Mayaguez, Puerto Rico and seed from these are collected and sent to Chillicothe, Texas to be grown during the summer, and display genetic variability for height and maturity. Seeds from short plants with early maturity are sent back to Mayaguez for further crossing. The crossing process continues for 5 to 7 years, until the plants are converted. In addition to height and maturity, breeders incorporate insect and disease resistance, drought tolerance, and improved grain quality (Adams, 1995). According to Klein et al (2008): "The conversion program was designed to move recessive dwarfing and photoperiod insensitive genes from a four-dwarf temperate zone variety into the genomes of exotic lines. Through this program over 840 converted and partially converted lines have been developed thereby providing new diverse germplasm that now provides an important source of germplasm used in sorghum improvement programs throughout the world."

During the 1960s through 1990s, four sweet sorghum varieties were developed by the USDA Sugar Crops Field Station in Meridian, MS; the Mississippi Agricultural and Forestry Experiment Station; and other experiment stations in the southeastern United States (msucare.com, 2009). Four varieties were released (date of release in parentheses): Dale (1970), 115 day maturity; Theis (1974), 130 day maturity; M81-E (1981), 130 day maturity; and Topper 76-6 (1994), 120 day maturity.

The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) has engaged in research to develop sorghum hybrid parents and from these parents hybrids adapted to Asia, Africa, and the Americas. ICRISAT was established in 1972 in Patancheru, Andhra Pradesh, India with a directive to improve the productivity of sorghum in the semi-arid tropics of Asia, sub-Saharan Africa, and Latin America. Research on hybrid parents began at Patancheru, India in 1978, Sotuba, Mali in 1982, Bulawayo, Zimbabwe in 1985, and Nairobi, Kenya in the early 1990s. Work on hybrid parents done at ICRISAT is documented in Reddy et al (2006). They divide the research into 3 phases, 1978-1988, 1989-1998, and 1999 onwards. ICRISAT has developed hybrid parents for grain and forage yields. In addition it has worked on resistance to major biotic (e.g. grain mold, shootfly resistance) and abiotic (e.g. moisture) stresses, developed lines with increased high sugar content in the stalks of sweet sorghum, increased forage yield, and developed hybrids adapted to postrainy (or nonrainy) season conditions (for climates such as India). Hybrids are developed on a regional basis.

Research began in 1980 to identify sweet sorghum lines with high sugar content stalks (high Brix values) from the world sorghum germplasm collection at ICRISAT. Two cultivars were selected. In addition, several high Brix sweet sorghum lines from Nigeria, Zimbabwe and from within advanced breeding progeny at ICRISAT were selected. Sweet sorghum research was discontinued at ICRISAT in the late 1990s, but restarted in 2002. By 2005, ICRISAT had released a few varieties (e.g. SSV 84 and SSV 74 and is developing hybrids.

ICRISAT is interested in sorghums that provide both grain and biomass. This is consistent with work in China, where the sweet sorghum hybrid Shennong No. 2 was developed (FAO, 1994).

Reddy et al (2008) presented data for India showing that hybrids of sweet sorghum gave much higher yields of grain and slightly lower sugar yields than [nonhybrid] sweet sorghum varieties tested during both the rainy and nonrainy seasons. Sweet sorghum varieties are more photoperiod sensitive than hybrids studied. Hybrids are earlier maturing and need less water than "pure-line" varieties (Reddy et al, 2005). Reddy et al (2007, 2008) also compared two hybrids to a control variety and report days to 50% flowering was 6 to 9 days less with the hybrids (Table 11). The days to flowering gives an indication of the rate of development of sorghum. They compared hybrids during the rainy and nonrainy season and found that if one wants sugar then one should breed separately for the rainy and post rainy seasons (Table 12).

Table 11. Hybrids relative to variety in India (Reddy et al; 2007, 2008)

	Days to 50% flowering	Brix[a]	Juice (kl ha^{-1})	Sugar (Mg ha^{-1})	Grain (Mg ha^{-1})
ICSA749 x SSV74 (hybrid)	85	18.0	27.2	9.15	3.28
ICSA511 x SSV74 (hybrid)	88	18.0	22.7	7.84	5.79
SSV84 (variety – control)	94	16.6	16.8	4.98	2.67

[a]Reddy et al list no units for Brix. Typically Brix is as Degrees Brix (°Bx), a measure of dissolved sugar to water. A 25°Bx solution would be 25 g of sugar and 75 g of water.

Table 12. How rankings for sugar and grain change between rainy and nonrainy season over 2 years (Reddy et al, 2008)

	Brix (%)[a]		Sugar (Mg ha^{-1})				Grain (Mg ha^{-1})			
Hybrid	Rainy	Nonrainy	Rainy	Rank	Nonrainy	Rank[b]	Rainy	Rank	Nonrainy	Rank[b]
ICSA675 x SSV74	16.6	10.3	6.3	1	1.1	9	6.7	8	7.1	8
ICSA675 x SPV422	17.3	11.7	6.1	2	0.9	14	6.6	9	6.7	10
ICSA324 x SSV422	16.5	16.1	4.8	13	1.7	2	4.9	17	3.9	20
ICSA474 x E36-1	13.5	14.3	4.8	14	1.7	3	6.3	14	6.2	15
NSSH104 (check)	18.5	19.8	5.9	3	1.2	8	4.2	18	7.2	3

[a]Reddy et al list the units as %. Typically Brix is as Degrees Brix (°Bx), a measure of dissolved sugar to water. A 25°Bx solution would be 25 g of sugar and 75 g of water.
[b]There were a total of 20 sorghum hybrids grown. Only selected sorghum hybrids are shown

The research in progress at ICRISAT for sweet sorghum identified several promising varieties and several hybrid seed parents and restorers, developed hybrids that are relatively less photoperiod and thermo sensitive and earlier maturing than varieties, and identified several sweet-stalked hybrids that are higher yielding than the best control hybrid (ICRISAT, 2007). Three sweet sorghum varieties had days to 50% flowering ranging from 69 to 96, while two hybrids had days to 50%flowering of 65 to 74, depending on the month of planting during November to March. The hybrids (days to 50%flowering) were much less affected by month of planting and varying day length than the varieties (Reddy et al, 2008).

ICRISAT is cooperating with the Bureau of Agricultural Research (BAR) and the University of Los Baños in the Philippines on production and development of sweet sorghum hybrids (Hernandez, 2009). After the 2008 growing season six hybrids were identified for seed production and characterization.

Texas A&M University is currently conducting sorghum research on both high biomass and sweet sorghum, and is cooperating with Ceres on research on and commercialization of biomass sorghum. For biomass sorghum, they are developing parental lines with maternal lines that are short to facilitate seed collection and hybrids to produce tall high-biomass plants. These hybrids are photoperiod sensitive do not initiate flowering until day length is less than 12 hours, thereby maximizing the length of growing season and biomass produced. Breeding for a thick stalk helps prevent lodging. In 2007, the forage sorghums used in the breeding program grew to 3.0 to 3.7 m (10 to 12 feet) tall and yielded 25 to 29 dry Mg ha^{-1} (11 to 13 dry tons $acre^{-1}$). The yield goal is 34 to 38 dry Mg ha^{-1} (15 to 17 dry tons $acre^{-1}$) in the next few years and 45 dry Mg ha^{-1} (20 dry tons $acre^{-1}$) within the next decade, based on conventional breeding. No transgenic breeding is planned because sorghum easily hybridizes with johnsongrass [*Sorghum halepense* (L.) Pers.], an aggressive weedy species. For sweet sorghum, seed is also an issue because the plant puts much of its sugar into the stalk and not seed and the plant is tall, making it mechanically difficult to harvest seed. Texas A&M is breeding the maternal line short to aid in seed collection. The program seeks to exploit hybrid vigor in sweet sorghum (Schill, 2007).

Qingshan and Dahlberg (2001) describe Chinese efforts in sorghum improvement. Comprehensive and systematic Chinese research on sorghum began in 1951 after the establishment of the People's Republic. From 1956 to 1984 germplasm was collected throughout China, preserving the germplasm resources and laying the foundation for improving sorghum.   Most varieties were grain sorghum, but some fodder and sugar varieties were collected. Traits have been identified, including agronomic and nutrition characteristics and screenings for resistance to biotic and abiotic stresses. There is wide variation in days to maturity, from 80 to 190 days. Most local varieties are photoperiod and thermo insensitive. Many accessions are tall, with the tallest being 4.5 m (15'). Stresses screened for include drought, cold, saline and alkali soils, and various diseases such as head smut, and pests such as the sugar cane aphid and European corn borer. Starting in the late 1950s, improved sorghum varieties began to be released. Chinese sorghum germplasm has been exported to other countries, including the United States, the former USSR, and Australia. Cold tolerance is an important trait available in Chinese germplasm.

As of 2008, there were approximately 168,000 sorghum accessions held at repositories around the world, with the two largest repositories being ICRISAT and USDA. However these collections have not been adequately explored for traits important to the biofuels industry. While the sorghum genome is the second major cereal crop to be sequenced, genetic improvement is difficult without clear targets. At the International Conference on Sorghum for Biofuels in 2008, the feedstock development group stated that for rapid genetic improvements, traits important to the biofuels industry must be defined. They noted that critical traits must take account of cultures and conditions in individual countries and regions. Until other criteria are defined, yield is the most important trait on which to concentrate. Because sorghum is a diploid, compared to other biofuel crops, it is relatively genetically simple and allows for multiple breeding cycles per year (Pederson and Dahlberg, 2008).

There are also sorghums that are lower in lignin content; brown midrib (BMR) mutant lines. The brown midrib trait was identified in sorghum in 1978. The brown midrib trait is available in forage sorghum and sorghum x sudangrass. Standability is an issue with brown midrib sorghum. Forage analysis (e.g. in vitro dry matter digestibility) and animal feeding trials have shown improved digestibility (Burmood, 2003). The lower lignin content may lead to better conversion into ethanol. ICRISAT has been breeding brown midrib sorghums (Reddy et al, no date).

8. ADAPTATION OF MODERN SORGHUM VARIETIES AND HYBRIDS IN DEVELOPING COUNTRIES

Tannins can limit the nutritional value of grains, including sorghum. Some tannins form complexes with proteins and proteases in the alimentary tract, reducing protein digestibility. However, the tannins impart bird and insect resistance, and in some cases in traditional foods the phenolics found in red sorghum give desired color and flavor. (Grain sorghum comes in a number of colors, including white, brown, pink, red, and yellow. White sorghum is generally preferred for food products.) (Phenolics are naturally organic compounds and can give foods tastes and smells.) Traditional varieties are generally taller than the dwarf varieties bred for mechanical harvest. However, traditional varieties are open pollinated and farmers can retain seed at harvest for the next planting season. Modern hybrids are generally higher yielding, but only make economic sense when grown with the required inputs of fertilizer, weed control, pest control, and water management. Hybrid seed is more expensive and cannot be retained for the next planting season. Varieties with resistance to disease, insects, birds, drought, and acceptable yields of both grain and fodder are preferred by resource-limited farmers (Natural Resources Institute, no date).

9. HOW TO APPROACH SORGHUM RESEARCH

Developing sorghum as an energy crop will need to be supported by an integrative research strategy that considers an entire cropping system (where sorghum may be one component) to sustainably and economically produce food, feed, fiber and fuels. Preliminary research questions that need to be explored include:

What sorghum products are desired?

- Both biomass (lignocellulose alone or lignocellulose and sugar) and grain?
- Primarily biomass (and grain produced, if any, is incidental)?
- Sugars (and possibly grain) with the bagasse as a secondary product?

What land will be used?

- Will sorghum replace current food and feed crops, or pasture?
- Will sorghum be integrated in crop rotations (potentially increasing long-term productivity of other crops)?
- Will sorghum be part of an expansion into marginal lands or part of recuperation of abandoned and degraded lands?

In addition to land use and product mix, productivity depends on intensity of production and constraining factors such as water. The feasibility of bioenergy from sorghum will depend on costs of required inputs, efficiency of operations, markets and prices for cropping system outputs and technologies available. For example, with today's conversion technologies, sweet sorghum for conventional ethanol may be the most viable bioenergy option, but in the future, lignocellulosic conversion technology may favor sorghum varieties with higher biomass yields per unit of input than sweet sorghum.

A question to research is whether one is better off utilizing sorghum that is specialized (e.g. energy sorghum for biomass and grain sorghum for grain) or sorghum that is multipurpose (e.g. sweet sorghum that produces both grain and biomass) instead? For example, if grain sorghum is grown on 1 unit of land and energy sorghum on 1 unit of land, will this produce more grain and biomass than a dual purpose sorghum (a sorghum developed for both grain and biomass) grown on 2 units of land? The answer is likely to vary be location.

Another issue to consider is what conversion technologies are available. This will affect the choice of crops grown. For example, sweet sorghum is high in sugar that can be converted into ethanol using currently available technology, whereas conversion of lignocellulose to ethanol is still in the developmental stage. The choice of type of sorghum today would likely be sweet sorghum, but in the future with improvements in lignocellulosic conversion technology it would likely be an energy sorghum that would yield more biomass per unit land area than sweet sorghum.

10. WHY SORGHUM AS AN ENERGY CROP AND NEEDED IMPROVEMENTS

Among potential annual bioenergy crops, sorghum may be advantageous where drought tolerance is important and it can enhance production of other crops (e.g. as seasonal cover crop or in rotations). Sorghum allows farmers flexibility in choice of crop from year to year. It has the potential for high yields (40+ dry Mg ha^{-1} yr^{-1}). Genetic mapping combined with a relatively fast breeding and field testing cycle facilitate further improvements for bioenergy once desired feedstock characteristics and site requirements are clearly defined. Acknowledging that improvements for bioenergy could potentially diverge from those for feed and food, the following research agenda is proposed:

1) Define traits important for bioenergy and characterize sorghum collections for these traits
2) Develop cost-effective means to stabilize sweet sorghum juice so it does not need immediate processing
3) Increase sugar yields of sweet sorghum for use in the near term as an ethanol feedstock (or to supplement sugar from sugarcane)
4) Increase grain yields for sweet and energy sorghums to explore multi-product potential
5) Develop varieties for high biomass yields (energy sorghum)
6) High and low lignin varieties (high lignin for thermochemical conversion such as gasification or pyrolysis and low lignin for ethanol feedstock)
7) Research cropping systems including
    - double cropping where sorghum supplements other grain production to increase overall output while reducing environmental impacts
    - cover crop and inter-crop sorghum that helps control weeds and pests for high-value crops (vegetables) while improving soils

While perennial biomass crops may be preferred for environmental benefits (e.g. lower soil erosion, lower fertilizer requirements), annuals such as sorghum provide farmers with more agility to shift crop production in response to market signals. Sorghum's fast breeding cycle, compared to perennials, can help increase bioenergy feedstock production while perennials are being developed. Both perennials and annuals can play important roles in an integrated system designed to minimize input requirements and maximize production of multiple food, feed, fiber and fuel products.

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