

MASTER

SORGHUMS AS ENERGY CROPS

BY

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E. S. Lipinsky and S. Kresovich

INTRODUCTION

Sorghum ranks fifth in production area of the cereal crops of the world. In the tropical regions, sorghum grain is a major source of food. In the United States, sorghum grain is a major source of animal feed, being produced on approximately six million hectares. Despite these impressive credentials, sorghum is one of the least understood of the leading world crops among Europeans and North Americans. Like corn, sorghum is a multi-use crop. Currently, sorghum is a source of food and feed; however, with efficient processing, sorghum may also become a leading source of fuel and fiber in the United States.

Within the genus Sorghum tremendous diversity exists. In fact, there are approximately 17,000 accessions in the World Collection. As sorghums became domesticated, the plants were continually selected for their value in different aspects of utilization. This continual selection led to the development of four major groups of sorghum. These were classified by Poehlman as follows:

1. Grain sorghums: This group is characterized by its relatively large grains and is grown principally for feed and food uses.
2. Sorgos (sweet sorghums): This group has tall, juicy, sweet stalks and usually smaller kernels than the grain type. Sweet sorghum is grown primarily for syrup production, but may also be grown for fodder, hay, or silage.
3. Grass sorghums: This group has slender stems, narrow leaves, numerous tillers, and small spikelets and seeds, as compared with the grain and sweet sorghums. In the United States, the

grass sorghums are produced for pasture, hay, and silage.

4. Broomcorn: This group is characterized by inflorescences with long lateral branches and is used for making brooms.

A fifth group of sorghum is also now emerging and is known as "high energy" sorghums (or sweet-stemmed grain sorghums). This type combines the sugary stalk of the sweet sorghum with the large kernel production of the grain sorghum. Although this group is currently in the experimental stage, it will show future potential as a source of energy and/or food.

Botanical, Physiological, and Agronomic Characteristics of Sorghum

Tremendous diversity exists within the genus Sorghum. However, basic structural and developmental patterns are substantially the same among all the types. The sorghum plant is a large-stemmed grass which can be grown as either a single stem or a single stem with a number of secondary tillers, as determined by both cultivar and/or plant population. The plant ranges from 0.5 to 5.0 meters in height.

The stems are solid, but the central part becomes pithy. Stem thickness, like height, varies greatly with the basal diameter mostly lying within the range from 5 mm to 3 cm. The leaves are two-ranked as in other grasses, alternating on opposite sides. The number of leaves at maturity varies with cultivar, roughly from 10 to 30. Buds at the nodes of the stem often give rise to side branches.

The root system is fibrous with a single seminal root that grows vertically downward, giving off laterals throughout its length. The permanent roots are adventitious, extending several feet away from the plant, and can mainly be found in the top 1-1.5 m of soil. Many cultivars of sorghum develop buttress roots from the above-ground nodes.

The sorghum inflorescence, or "head", is a somewhat loose to compact panicle. The primary branches of the panicle contain a pair of

spikelets; one is perfect and fertile, while the other is either sterile or staminate. A well developed panicle may contain as many as 1,000-2,000 seeds. Seed weights range from approximately 7 to over 70 grams per 1,000 mature seeds.

The sorghum plant--whether grain, sweet, forage, broomcorn, sudangrass, or johnsongrass--has a number of distinctive physiological and agronomic characteristics which increase its potential as a viable source of food, feed, fiber, and fuel over a wide geographic range. Firstly, sorghum exhibits the C_4 (Hatch-Slack) photosynthetic pathway and is therefore quite efficient in assimilating carbon dioxide. Also, sorghum lacks the process of photorespiration; therefore, it is highly productive, achieving maximum short-term crop growth rates of approximately $51 \text{ g m}^{-2} \text{ ground day}^{-1}$.

Secondly, sorghum utilizes water efficiently. The root system is fibrous and extensive. Ponnaiya demonstrated the existence of heavy silica deposits in the endodermis of the root, forming a complete silica cylinder in the mature root. This mechanical strength is of great importance in preventing collapse of the system during drought stress. A waxy cuticle covers the above-ground structure to retard drying. Unlike corn, sorghum has the ability to remain dormant during a drought period and then to become active rapidly following moisture reintroduction. The water requirement to produce one kilogram of sorghum dry matter ranges from 250-350 kilograms, whereas the requirement for wheat and soybean is approximately 500 and 700, respectively.

The nutrient requirements for sorghum are also low. Experiments in Texas have shown that the grain in a sorghum crop yielding $6,175 \text{ kg ha}^{-1}$ removes about 110 kg of nitrogen and 16 kg of phosphorus and potassium. For sweet sorghum in the southeastern United States, the normal recommendation is approximately 45, 20, and 45 kg ha^{-1} of nitrogen, phosphorus, and potassium, respectively.

Crop production is a system for harvesting energy from the sun, as food, feed, fiber, and fuel and, therefore, efficiency should be assessed in terms of converting solar radiation into useful end-products.

Recent yield increases in agriculture have become a function of higher inputs of energy from fossil fuels. Sorghum provides a highly efficient plant resource for production of useful end-products under many different types of cropping systems in many different climatic regions.

Energy Crop Systems

The use of agricultural and silvicultural crops for energy use is as old as civilization. However, the crops previously have been grown for their food, fiber, or other industrial uses, with energy production of a by-product output. Serious modern consideration of crops exclusively for energy use began with the classic study of Inman and Alich. Since then, dozens of systems studies have been conducted, but relatively little quantitative field data relating to energy crops have been presented. A project team involving universities, farm bureaus, and the U.S. Department of Agriculture was brought together by Battelle Columbus Division under a contract with the U.S. Department of Energy's Biomass Energy Systems Program to develop new energy crops (Figure 1). This project team, which is evolving as the Department of Energy reorganizes and transfers biomass production responsibilities to the U.S. Department of Agriculture, brought together plant breeders, biochemists, soil chemists, agronomists, plant physiologists, agricultural economists, engineers, and commercial farmers for the purpose of developing sorghums as energy crops. A companion program on processing and converting sweet sorghum to fuel ethanol also was initiated by the Department of Energy. Individual Battelle team members and the principal investigators for the subcontractors and co-contractors are given the recognition that they richly deserve in Table 1. The authors of this paper are the spokesmen for this fully integrated project team.

TIME: THE ENEMY OF ENERGY CROPS

Candidate energy crops include the lignocellulosic crops (e.g., poplar, eucalyptus, and pines) starch crops (e.g., maize, grain sorghum,

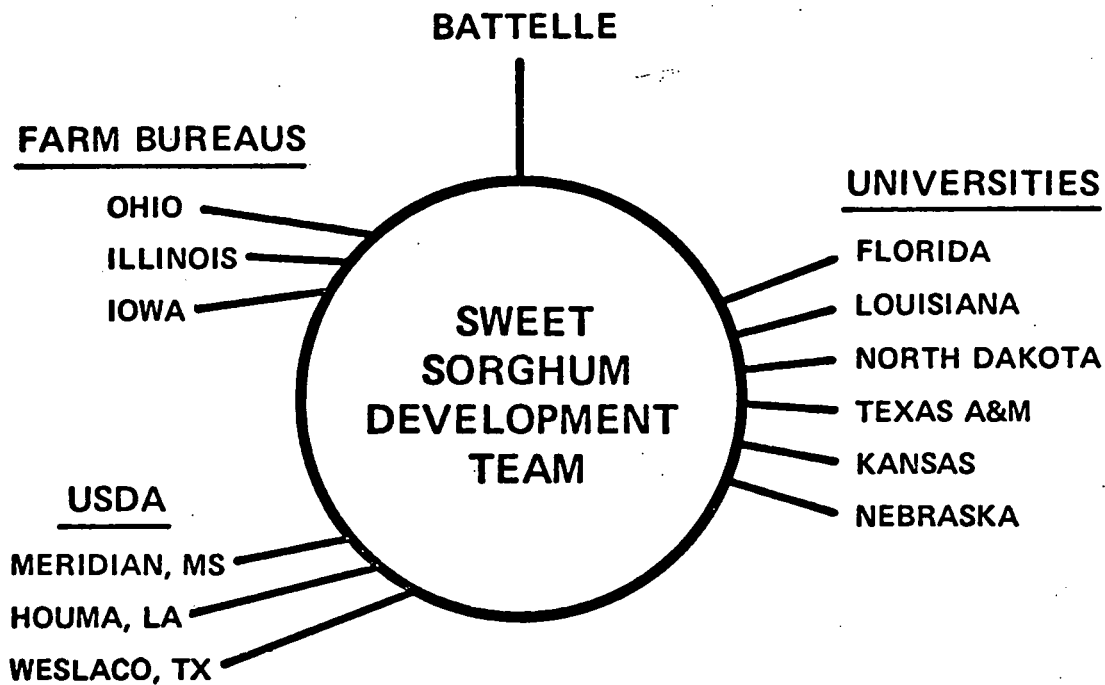


FIGURE 1. SORGHUM DEVELOPMENT TEAM

TABLE 1. KEY INVESTIGATORS IN DOE FUELS FROM SUGAR CROPS PROGRAM

Organization	Investigator	Role
Battelle Columbus Division	M. Arthur	West Jefferson Field Tests
	M. Davis	Analytical Chemistry Task Leader
	D. Jackson	Agricultural Task Leader
	S. Kresovich	Agronomy and Plant Physiology
	W. Lawhon	Agricultural Advisor
	E. Lipinsky	Biomass Research Leader
	T. McClure	Project Leader
	M. Price	Plant Chemistry Advisor
	A. Scantland	Farm Bureau Coordinator
University of Nebraska	J. Maranville	
	M. Clegg	
Kansas State University	G. Posler	
North Dakota State University	D. Meyer	
Ohio Farm Bureau	J. Hill	
Illinois Agricultural Association	M. Yates	
Iowa Farm Bureau	R. McClain	
Louisiana State University	R. Ricaud	Sweet sorghum studies
	B. Cochran	
Texas A&M University	C. Connolly	Sweet sorghum studies
	S. Reeves	
	F. Creelman	
	F. Miller	
University of Florida	G. Gascho	Sugarcane and sweet sorghum studies
	T. Shih	
USDA Houma Sugarcane Field Laboratory	J. Irvine	Sugarcane studies
	R. Breaux	

TABLE 1. (Continued)

Organization	Investigator	Role
USDA Food Crops Utilization Research Laboratory at Weslaco, Texas	A. Smith	Sweet sorghum processing and sugar crop analyses
USDA Sugar Crops Field Station, Meridian, Mississippi	K. Freeman D. Broadhead N. Zummo	Sweet sorghum studies

and potatoes), and sugar crops (e.g., sugarcane, sweet sorghum, and sugar beets). This list is not exhaustive, because non-commercial candidates (e.g., aquatic plants and emergent plants) could be added.

Successful exploitation of energy crops is a battle against time. Although time is always the enemy, it adversely affects different energy crops in different ways. For the type of silvicultural plantations investigated by Salo, et al, the problem is that one plants a crop with heavy expenditures of funds for labor, fertilizer, and other cultural inputs and must wait many years to collect the reward for this effort. Discounted cash flow analysis (DCF) treats such investments very harshly!

For perishable sugar crops, such as sweet sorghum, time acts as the enemy in several ways:

- (1) The harvesting season is limited to a matter of weeks except in the warmest areas of the United States
- (2) The perishable sugars must be promptly processed by methods that are currently energy intensive to prevent serious deterioration
- (3) The product is so unstable that there is reluctance to treat it as a commodity.

The perishability of sweet sorghum results in an economic disadvantage that is difficult to overcome, except by integrating the agricultural production, processing, and conversion of such sugar crops into systems involving other, more stable crops. Thus the DCF disadvantages cited for trees are avoided, but at a very high price.

The difference in production costs that arise from different season lengths can be seen in Figure 2. When a large investment is made in sugar milling, transportation, and distillation facilities, it is worthwhile to use these as many hours per year as possible.

Some crops fare better than do trees and sweet sorghum. Grain crops are highly storable and yield a return the same year in which they are planted. Therefore, the time disadvantages for trees and sweet sorghum are avoided.

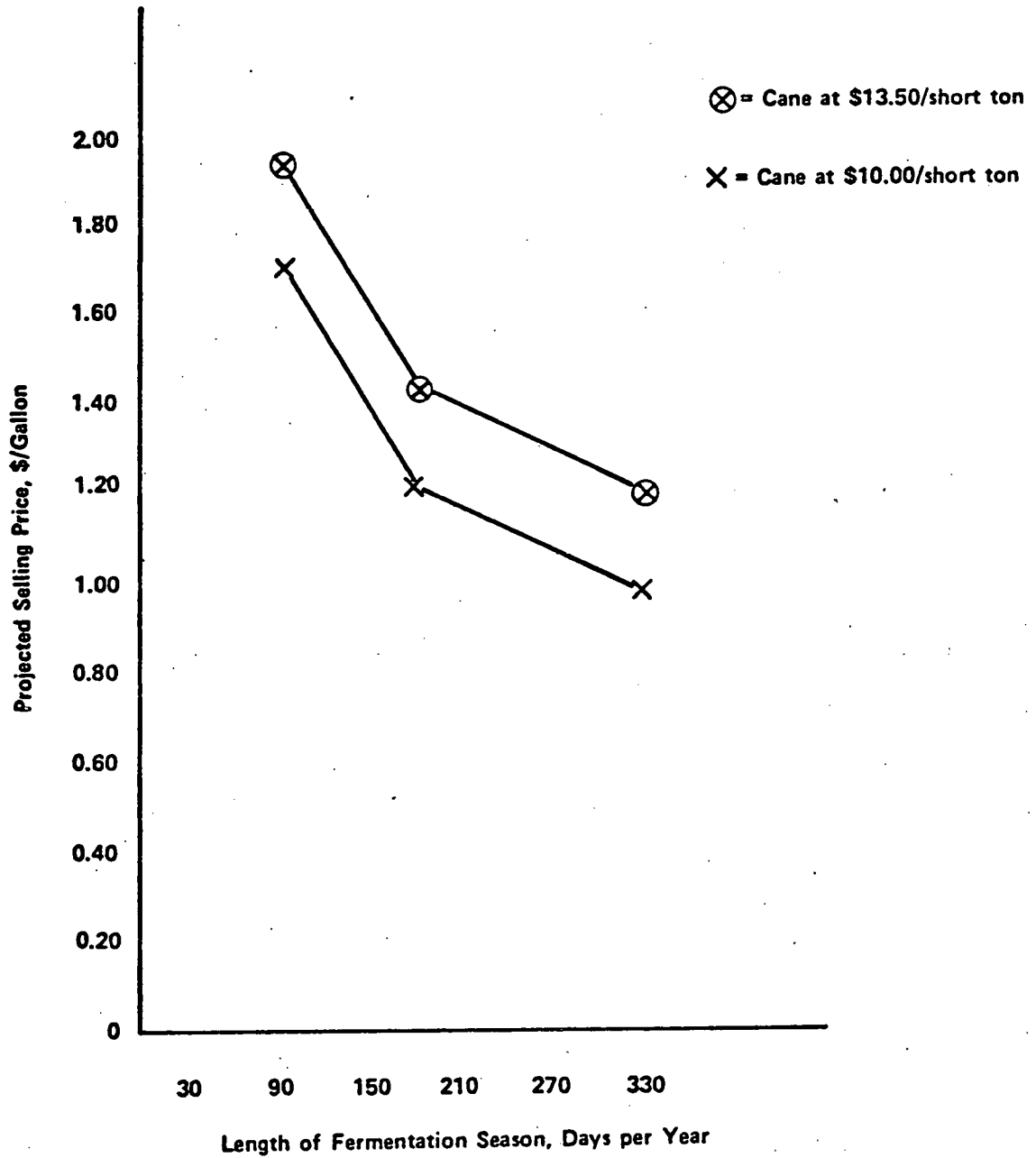


FIGURE 2. INFLUENCE OF FERMENTATION SEASON LENGTH AND CANE COST ON PROJECTED ETHANOL SELLING PRICE

Multiyear crops that begin to pay rewards the first year that they are grown are highly advantageous from a time viewpoint. Sugarcane is an example of such a crop. After a 9 to 15 month growing period, the plant can be harvested annually for from 2 to 5 or 6 years. This agonomic advantage for sugarcane offsets to some extent its processing seasonality disadvantage.

INTEGRATION TO IMPROVE SORGHUM PROSPECTS

Because time is the enemy of sweet sorghum, integrated systems need to be developed. These integration concepts can be categorized as follows:

- (1) Multiple sweet sorghum crops each year
- (2) Integration for sugarcane
- (3) Integration with sugar beets
- (4) Integration with starch crops
- (5) Sweet stemmed grain sorghum
- (6) Integration with lignocellulosic crops.

Each of these alternatives has its advantages and its drawbacks. As shown in Figures 3 and 4, these approaches span a broad spectrum of possibilities.

Multiple Sweet Sorghum Crops

As shown in Figure 5, only a few areas of the United States have a long enough frost-free season to permit multiple cropping of sweet sorghum. The multiple crops must be multiple plantings now, because cultivars that ratoon well enough for commercial practice have not been developed. In the United States, there does not seem to be a great opportunity for multiple cropping of sweet sorghum, because climatological areas with sufficient growing season for this type of multiple cropping are quite limited.

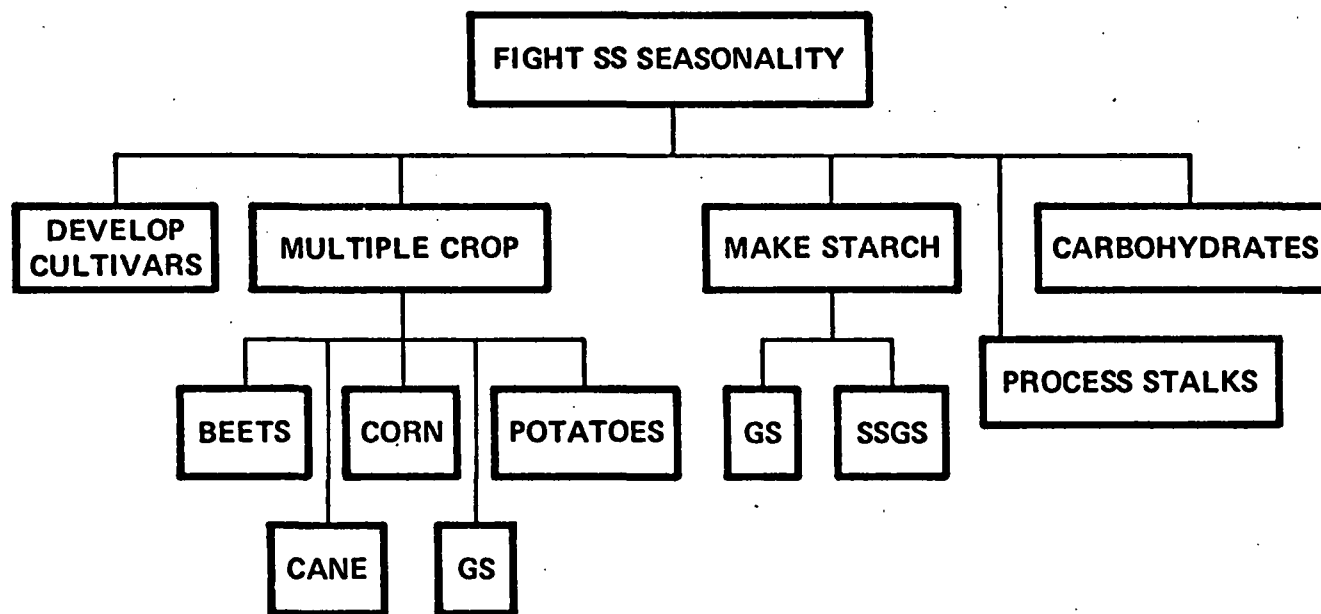


FIGURE 3. ALTERNATIVE APPROACHES TO FIGHTING SWEET SORGHUM SEASONALITY PROBLEMS

SS = Sweet Sorghum
 GS = Grain Sorghum
 SSGS = Sweet-Stemmed Grain Sorghum

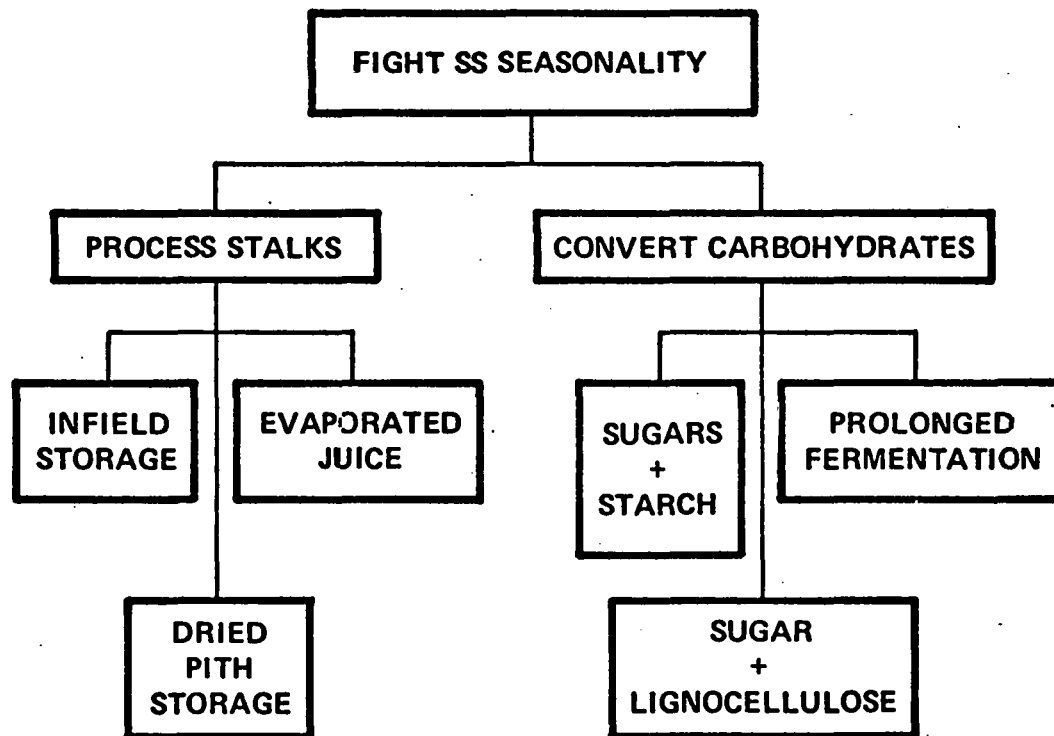


FIGURE 4. PROCESSING AND CONVERSION ALTERNATIVES TO FIGHT SWEET SORGHUM SEASONALITY

SS = Sweet Sorghum

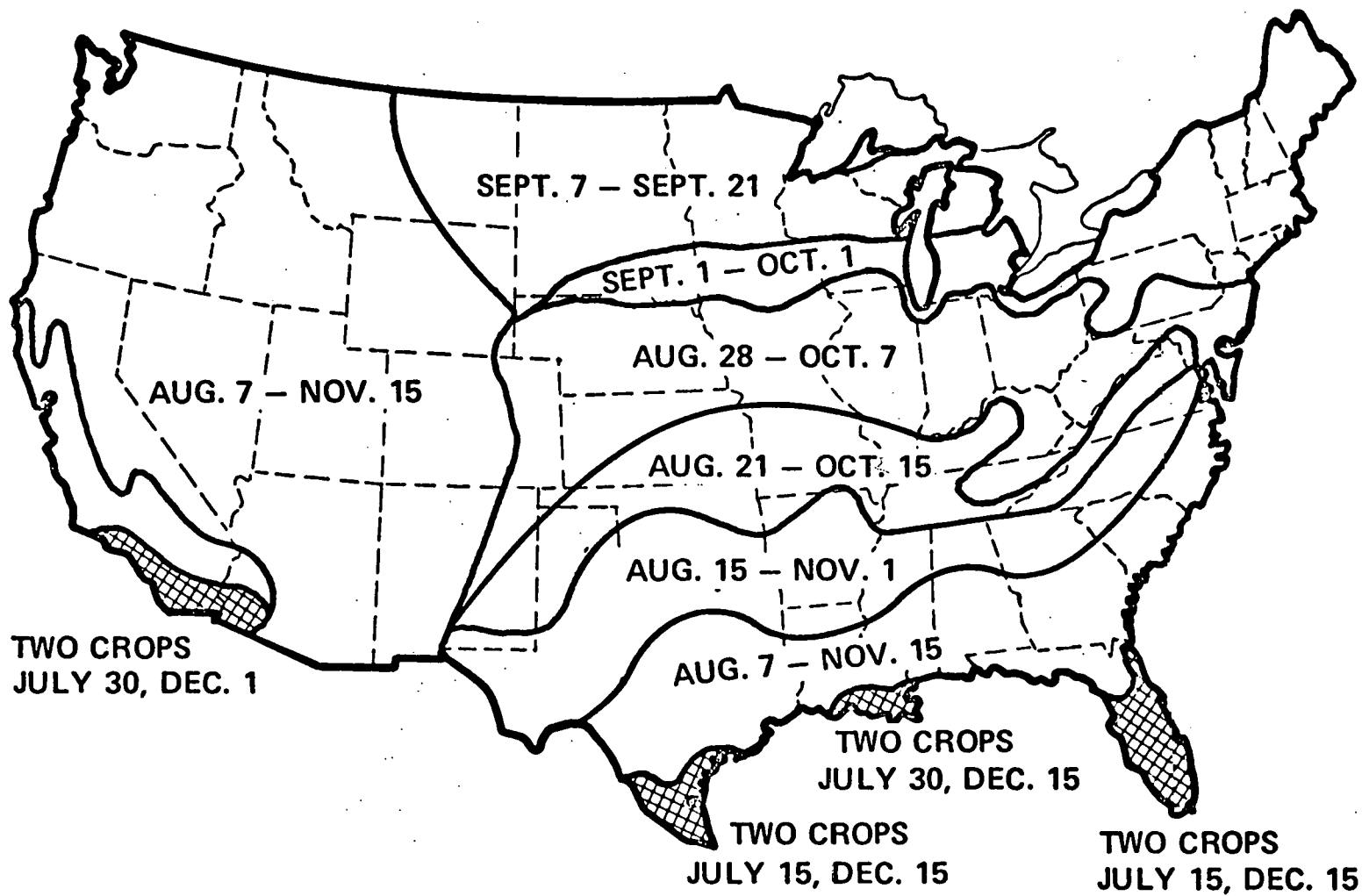


FIGURE 5. LIKELY SWEET SORGHUM HARVESTING SEASONS, BY CLIMATOLOGICAL AREA

In the South, the harvesting season and the processing season for sweet sorghum can be expanded by variety or cultivar development, so that some parts of land serving a central processing facility can begin harvesting early while other parts of land are planted in cultivars that mature late in the season.

Integration with Sugarcane

The season right for sugarcane processing ranges from about 70 days per year in Louisiana to 330 days per year in Hawaii. Sugarcane for fuel ethanol use can have a somewhat longer season, because inversion of sucrose that occurs after the season is over adversely affects food marketability but not fuel marketability.

Integration of sweet sorghum with sugarcane appears relatively easy to do and has been demonstrated by Louisiana State University and Texas A&M. In Louisiana, sweet sorghum is ready for harvest during the time immediately before the sugarcane is ready for harvest. In Texas, sweet sorghum could be planted before and/or after the sugarcane. Similar opportunities exist in Florida.

Integration of sweet sorghum with sugarcane also can occur by use of "fallow" land that occurs between sugarcane crops. For example, in Florida the land is usually plowed up after the last ratoon crop in early spring and replanted in new sugarcane in the following fall. Instead, sweet sorghum could be planted in this fallow season which would increase the yield per acre per year substantially.

Integration with Sugar Beets

Sugar beets are substantially more storable than is sugarcane or sweet sorghum. The early sugar beets must be harvested before they have stored all the sugar that they could store. Therefore, it is desirable to have an early season sugar crop such as sweet sorghum in the North and West of the United States, to that the processing and conversion

facility can start up early and so that the sugar beets can be retained in the ground until maximum sugar concentration has been obtained.

The excellent prospects that sugar beets would otherwise have are marred by their susceptibility to nematodes and numerous diseases. The standard method to control these problems is to rotate sugar beets with other crops. Sweet sorghum and other sorghums need to be explored as rotation crops that continue to keep the sugar and ethanol facilities in operation.

Integration with Starch Crops

With rare exceptions, neither sugar beets nor sugarcane can be combined with sweet sorghum to provide year-around operation for an alcohol facility in the United States. Integration of sweet sorghum with maize, grain sorghum, wheat, potatoes, or other starch crops does make such a prospect possible.

One way of integrating sweet sorghum with a starch crop-to-alcohol process is to use the sugar crop during its relatively short harvesting season. At that time, the starch cooking operation could be shut down, because sweet sorghum does not require cooking and enzymatic hydrolysis to be prepared for fermentation. There would be savings in energy, because 25 to 50 percent of ethanol facility's energy consumption comes from the cooking operation. On the other hand, the owners of the facility would have to acquire sweet sorghum processing equipment and go to the trouble of working up contracts with numerous sweet sorghum growers who would need to supply this crop on a scheduled basis.

Another approach to integration of sweet sorghum with starch crops has been under development at Battelle Columbus Division. In this process, sweet sorghum juice is employed instead of hot water to cook the starch. The sweet sorghum's sugars remain in the solution after starch hydrolysis and add to the quantity of sugars fermented by the facility. This technique allows the sorghum sugars to be fermented at a higher concentration than would be possible otherwise. This process has been demonstrated in the laboratory.

When sweet sorghum is employed as a source of sugars in either of the above schemes, the stalks that remain after the sugars are used for fermentation can be used as fuel. This is by no means a negligible bonus.

Sweet-Stemmed Grain Sorghum

Grain sorghums have heavy grain heads and virtually no sugars in the stalks. Sweet sorghum cultivars have been bred to have relatively small grain heads and to concentrate sugars in their stalks. Hybrid sweet sorghums or crosses of sweet sorghum with grain sorghum has yielded sorghum plants with a large grain head and sugar in their stalks. Such plants are called sweet-stemmed grain sorghums. The harvested plant contains a rapidly fermentable sugar requiring no cooking, an easily stored grain for extended processing, and an energy rich stalk that can be used for fuel or producing the steam to conduct the cooking and distillation operations. Truly, this is a high-energy sorghum.

High-energy sorghum can be marketed and contracted for on a basis that involves a percentage of the selling price of the alcohol. This method of marketing is similar to that by which sugar beets are sold for table sugar production.

Integration with Lignocellulosic Crops

As the technology for direct conversion of lignocellulose into ethanol develops, it becomes possible to consider extending the sweet sorghum season by processing cellulosic raw materials into alcohol when the sweet sorghum juice is not being processed to alcohol. The first candidate with lignocellulosic raw material could be the sweet sorghum or sweet-stemmed grain sorghum stalks. Other options include trees or even waste paper.

Another opportunity exists with the potential utilization of the stalk of brown midrib mutants of sorghum as a feedstock for alcohol. These mutants, originally designed for use as a high quality feed

(silage), contain a relatively small amount of lignin and, therefore, could become a prime candidate for cellulosic conversion.

CONCLUSION

The sorghums present many opportunities for energy crop system development--perhaps too many. Selection of the appropriate system for development in each major climatological region is a complex task. The sorghums do not represent an easy road to cheap ethanol. In time, it will be recognized that none of the other crops do, either. The problem is one of obtaining availability at prices we can tolerate.

An intensive sorghum development program involving plant breeding, improvements in cultural practices, new harvesting hardware, innovative juice processing and conversion, and solution of the sweet sorghum stillage problem would be required to obtain large quantities of ethanol at reasonable cost from this resource when we need it. Will the United States choose to accept the challenge? If the United States chooses to meet the challenge, will a sustained effort be forthcoming at a high enough level to achieve success? Who will decide whether the challenge should be accepted? If it is not accepted, what resources will be used to achieve the goals that the sorghums might have achieved?

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NOTE: This is a preliminary text without bibliography and some illustrative materials. The complete text will appear in the Proceedings of this conference.