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A Systems Analysis of Sweet Sorghum Harvest for a Piedmont Ethanol Industry

by

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(ABSTRACT)

The Piedmont System is a collection of equipment for efficiently removing the juice from sweet sorghum stalks for the production of ethanol. The concept is to separate the whole stalks into pith and rind-leaf fractions, pass only the pith fraction through a screw press, and thus achieve an improvement in juice expression efficiency and press capacity. The operation of three alternative harvesting/processing systems were modeled and compared using computer simulation to determine which system could produce sweet sorghum juice and deliver it to a central plant at the lowest cost per liter of potential ethanol produced. In addition, an energy analysis was done to determine the net energy gain.

System A cut the sorghum stalks and hauled them to a crossroads site where they could be stored up to 30 days before juice expression. System B separated the pith and rind-leaf fractions in the field, and juice expression was accomplished at a nearby site. No storage was possible for System B. System C cut the stalks like System A, but then a mobile processor moved through the field to separate the pith and rind-leaf fractions.

It was found that the cost of producing feedstock with System C ($0.87/L) was significantly higher than either System A ($0.56/L) or System B ($0.63/L). While the System A cost was slightly lower than that of System B, it is recommended that both Systems A and B should be studied further since small adjustments to the model could eliminate the advantage of System A over System B.

Increases in whole-stalk yield and juice sugar level would lower the cost of all three systems by as much as 43%.

As the price of energy rises, sweet sorghum is expected to gain an economic advantage over corn as a feedstock for ethanol, because of its higher energy ratio. If the by-products are used to produce ethanol through cellulose conversion, the overall energy ratio for sweet sorghum was calculated to be 1.1 compared to 0.8 for corn. The energy ratio if only liquid fuels are considered was 7.9 for sweet sorghum compared to 4.5 for corn.

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1.0 Introduction

1.1 Background

Sweet sorghum has been used for the production of edible syrup in the United States for over 100 years. Production peaked around 1920 at approximately 190 million liters (Swope, 1975). Present production has dropped below 4 million liters per year. Due to this relatively small production, a limited amount of work has been done toward improving production, harvesting, and processing of this crop. Sweet sorghum has tremendous potential as a feedstock for the production of ethanol; consequently, there is accelerating interest in development of means to realize that potential.

The Eastern U.S. Piedmont (Figure 1) is a physiographic region covering 170 counties in seven states (Cundiff and Vaughan, 1986). The area is characterized by relatively poor, drought-prone soils, and few row crops can be grown competitively. Sweet sorghum with its drought resistant characteristic grows well in the Piedmont, and has produced more carbohydrates per hectare than corn (Parrish et al., 1985). The challenge is to collect these carbohydrates, concentrate them into a storable form, and economically convert them into a product with high demand.

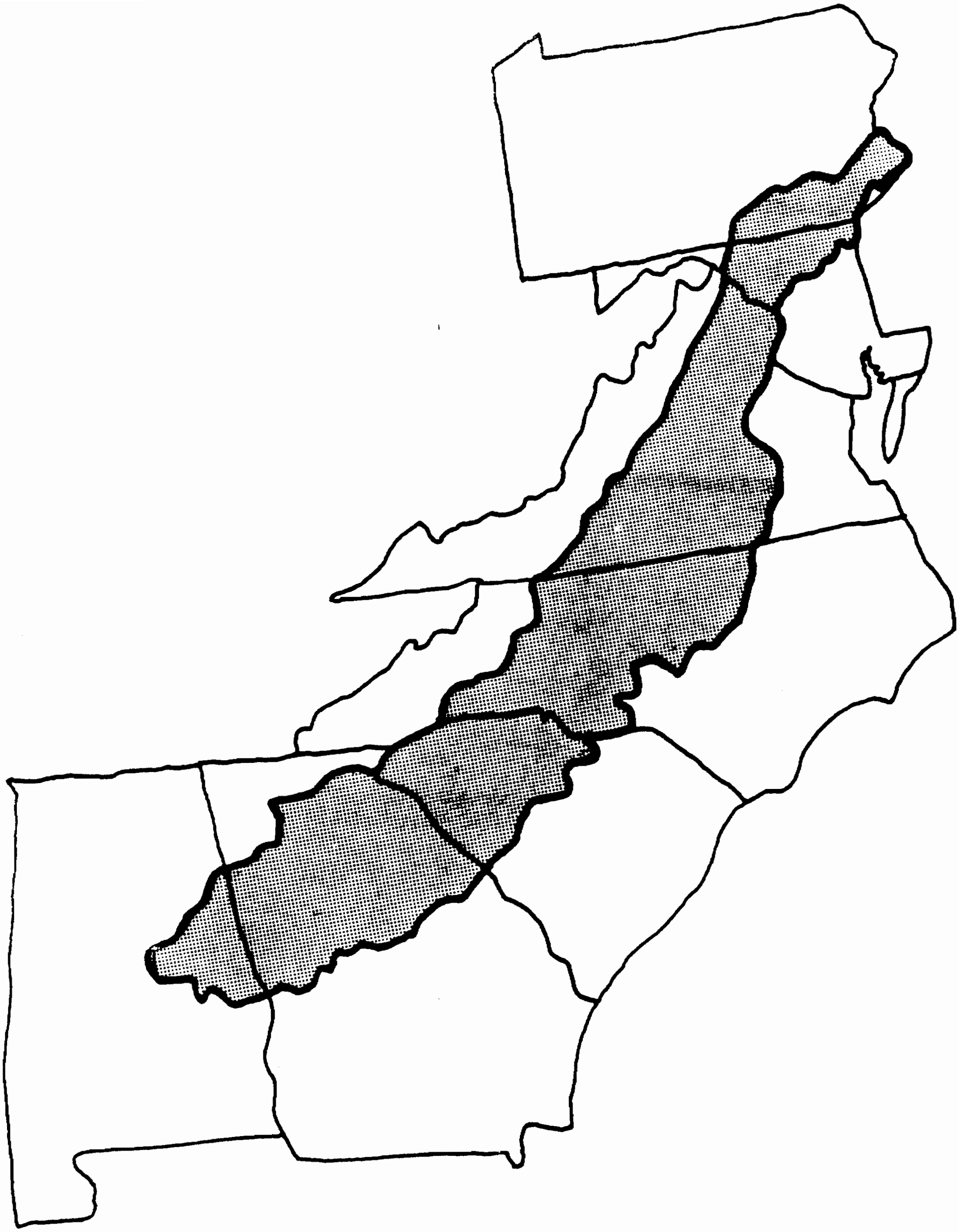

Figure 1. Map of the Eastern United States Piedmont Region

Ethanol is blended with gasoline as an octane enhancer in approximately 8% of the current U.S. gasoline supply (Grinell, 1990), and could provide the market for a large expansion of sweet sorghum production in the Piedmont, as well as other areas of the country. This increase in demand would justify increased research in production and processing techniques which could greatly improve the competitive position of sweet sorghum relative to corn as an ethanol feedstock. An efficient, mechanized means of harvesting and processing large quantities of sweet sorghum cane is a necessary step in the development of a successful sweet-sorghum-for-ethanol industry.

1.2 Sweet-Sorghum-for-Ethanol Industry

Sweet sorghum can be processed using existing sugar cane technology; however, the whole-stalk must be transported to a central mill. On the other end of the technological scale is the hand-fed roller mill, the method most often used today to mill sweet sorghum cane for edible syrup. This method relies heavily on hand labor and is much too slow for consideration as a practical method of sugar extraction for ethanol production. The system being proposed (hereafter referred to as the Piedmont System) would process the cane in or near the field, and thus only the juice would have to be transported over long distances. The Piedmont System separates the stalk material into two fractions; the pith fraction, which contains most of the juice and sugars, and the rind-leaf fraction, which contains most of the fiber. The pith fraction is squeezed to remove the juice, which can be directly fermented to ethanol, or can be concentrated to syrup for storage and later fermentation. The remainder of the pith fraction, the pith presscake, can be ensiled and fed to cattle or possibly used as a feedstock for ethanol if the technology for converting cellulose to sugar becomes economical. The rind-leaf fraction can be ensiled or left on the field, where it can be either reincorporated into the soil or dried and baled as hay.

The Piedmont is characterized by a large number of small farms with small fields. Very few, if any, farmers in the Piedmont would be able to supply enough sweet sorghum to support an efficient ethanol industry. One suggestion for organizing an industry is a central mill owned by a company or perhaps a cooperative. This mill would contract with farmers to grow a certain number of hectares of sweet sorghum. The farmers would be paid based on the whole-stalk yield and the sugar content (Brix). The division of responsibilities would be agreed upon in the contract. Perhaps harvesting, processing, and juice transportation would be the responsibility of the mill, and ensiling of the residue would be the responsibility of the farmer. He may feed the silage, or he may sell it as a feedstock for cellulose conversion, in which case he would deliver it to a central mill. This contractual arrangement is believed to be one that will provide an opportunity for a large number of farmers to participate in the enterprise. If small farmers, perhaps with as little as 10 hectares, can participate, then the distribution of production plots would be more uniform, and the transportation cost to accumulate a given quantity of product at a central point would be minimized. Unlike the sugar cane production areas in Louisiana and Florida, there are few potential mill locations in the Piedmont where a high density of the cropland can be planted in sorghum.

Many factors must be considered in order to make a sweet-sorghum-for-ethanol industry operate as efficiently as possible. One of the main factors is the organization of the harvesting and processing of the sweet sorghum stalks. The principle of separating stalks into juice, pith presscake, and rind-leaf material has been shown to improve efficiency over squeezing the juice from the whole-stalk (Crandell et al., 1989), but several options exist for the application of this principle. The whole stalks might be harvested and transported to a nearby processor for separation and juice removal. This method would allow the stalks to be stored between harvest and processing, which would effectively extend the harvest season, but would require a relatively large investment in equipment and labor. Alternatively, the separation into the pith and rind leaf fractions might be accomplished in the field by the harvester. In-field processing would eliminate the need for several expensive machines and some labor, but it would also reduce the harvest season by eliminating the possibility of storing harvested material. An additional alternative is to harvest the stalks, store them in the field, and later bring a field processor to the stalks, rather than hauling the stalks to the processor. All three systems have advantages and disadvantages, and it is impossible to determine which would be the most efficient system without a complete analysis that includes as many of the relevant variables as possible.

1.3 Computer Simulation of Harvesting/Processing Systems

In order to optimize research time and money, it would be helpful to determine which, if any, harvesting/processing system would be more efficient than the others, so that efforts can be concentrated on developing the machines necessary for that system. Computer simulation is one way to predict the outcome without actually building and testing all of the possible systems. By modeling each system as closely as possible and simulating the operation of each system for a large number of years, the probability distribution of the feedstock cost for one unit of ethanol can be predicted and compared.

This research details the development of computer simulation models which were used to simulate the operation of three harvesting/processing systems and compare the cost of producing sweet sorghum juice for fermentation. A weather generating submodel and a soil trafficability submodel were used to predict which days during the season would be suitable for operating the various pieces of equipment in the different systems. The number of hectares which could be efficiently harvested by one unit of each system was determined and that number of hectares was assumed to be planted for that unit.

The goal of this research was to compare the cost of producing and transporting to a central plant enough sweet sorghum juice to produce one liter of ethanol using each of the three systems. If this cost figure is significantly lower for one system, then efforts to develop and improve equipment design should obviously be concentrated on the machines for the lower cost system.

1.4 Objectives

1. To compare, using computer simulation, the economics of three alternative options for harvesting and processing sweet sorghum to produce ethanol in the Piedmont.
    - Develop SLAM-II based submodels to simulate the harvesting and processing operations for each alternative system. These submodels will use output generated by a weather generation model and a soil trafficability model.
    - Develop economic models to predict the feedstock cost per liter of ethanol including production, harvesting, processing, and transportation of juice to a central evaporation plant.
2. To estimate the energy balance expected for the production of ethanol from sweet sorghum and compare it to that expected when corn is used as a feedstock.

2.0 Literature Review

2.1 Agricultural Feedstocks For Ethanol

Several agricultural crops have been considered as good candidates for an ethanol feedstock. Among these are starch crops such as corn, grain sorghum, and potatoes; and sugar crops such as sugar cane, sugar beets, Jerusalem artichokes, fruit crops, and sweet sorghum (SERI,1980; 1981). Starch crops tend to concentrate the carbohydrates into a compact, storable package such as a kernel of corn, but the carbohydrates are starches which must be saccharified (converted to sugars) before fermentation to ethanol. The sugar crops have the advantage of their carbohydrates already being in a fermentable form, but the sugars are distributed throughout the plant and thus are harder to separate from the plant fibers and concentrate into a storable form.

Nathan (1978) pointed out that the United States consumed approximately 74 quads of energy in 1976 and may consume 130 quads by the year 2000. A quad is equivalent to 0.5 million barrels of oil per day for one year. Sweet sorghum, or any other farm crop, is not a total replacement for oil, but can make a significant contribution to an overall energy program. Even in the current market, with adequate supplies of crude oil, ethanol has found a market niche as an octane enhancer for gasoline. Over 3.2 billion liters (850 million gallons) of fuel ethanol were produced in the United States in 1989. Approximately 8% of our total gasoline was an ethanol blend (Grinnell, 1990). Corn was the feedstock for 86% of this ethanol, produced primarily as a by-product of the wet milling industry. Donna Fitzpatrick, DOE Assistant Secretary for Conservation and Renewable Energy, testified before three House Subcommittees that when U.S. ethanol production reaches 7.5 to 15 billion liters (2 to 4 billion gallons) annually, corn prices will be at a level that will make ethanol production uneconomical unless ethanol or oil prices increase. To avoid such an occurance, DOE is involved in research to develop ethanol from feedstocks, such as sweet sorghum, that do not have to compete in food markets.

Nathan (1978) stated that sweet sorghum has the greatest long range potential for ethanol production of the three main sugar crops (sugar cane, sweet sorghum, and sugar beets) because it can be grown over a much larger geographic region than sugar cane. He also indicated that while the amount of research that has been done on this crop is small, it has responded well and with proper funding, could produce dramatic increases in yields such as have been achieved with corn, sugar cane, and other crops. Nathan further pointed out that harvesting methods for sweet sorghum are at a primitive developmental stage compared with those for major U.S. crops. The only known commercial-scale production of sweet sorghum syrup as an ethanol feedstock was conducted in Louisiana. In 1986, Agrifuels Refining Corporation contracted with farmers surrounding New Iberia, Louisiana to grow 750 ha (2,000 acres) of sweet sorghum (Agrifuels, 1986). The growers cut the sweet sorghum in mid-August with soldier-type sugar cane harvesters, and transported it using available sugar cane equipment. The company processed 38,065 Mg in a rented sugar mill and produced 2,337,000 liters of 76° Brix syrup. Since the sugar cane season does not start until mid-October, they were able to take advantage of the vacant mill to conduct the experiment. Agrifuels built a 132 million liter per year ethanol plant with the expectation of using 70% sweet sorghum syrup and 30% black-strap molasses, a by-product of sugar production, as the feedstock. The plant has never been operated because of financial difficulties in the parent company.

2.2 Piedmont System

Cundiff (1987) developed a process to efficiently separate sweet sorghum stalks into a pith fraction containing most of the sugar and juice, and a rind-leaf fraction containing most of the fiber. Separation was accomplished by first striking the stalks with a dull knife at short (1 cm) intervals, thus breaking the pith into short pieces. Since the rind and leaves are tougher than the pith and tend to remain in much longer sections, the chopped material can then be fed into a separation device where the two fractions are separated. The juice is then removed from the pith fraction using a screw press. The removal of much of the fiber from the material to be pressed makes the operation of the press (the most expensive part of the system) much more efficient. Cundiff and Vaughan (1986) explored the possibility of using this concept to establish a sweet sorghum for ethanol industry that would allow the agricultural sector of the Piedmont region to be self sufficient in energy. They concluded that this industry could probably produce enough energy to supply half the on-farm energy needs in the Piedmont.

Weitzel et al. (1989) studied several parameters for the pith separation process and found that if approximately 65% of the mass of the stalk is separated into the pith fraction, then approximately 70% of the whole stalk sugar can be recovered in the juice when the pith fraction is run through a screw press. The amount of juice extracted was approximately 45% of the total plant mass. In contrast, Monroe et al. (1984) were able to extract approximately 45% of the stripped stalk mass as juice using a roller mill, the method most commonly used to remove juice for edible syrup production. (Stripped stalks are stalks that have had the leaves and seedheads removed.) Leaves and seedheads account for approximately 30% of the total plant mass (Nathan, 1978). The method reported by Weitzel et al. (1989) actually extracted more juice from the pith fraction than the roller mill used by Monroe et al. (1984) extracted from the whole stalks. In addition, Monroe only reported extracting approximately 45% of the available sugar in the juice while Weitzel reported extracting 70%. Bryan et al. (1985) were able to improve juice expression slightly to around 50%

of stalk mass by shredding the stalks before introducing them into the roller mill, but did not report sugar expression efficiency. Since the same material was being pressed, one might assume that the sugar expression efficiency was improved by approximately the same amount as the juice expression efficiency.

Sloane and Hashimoto (1980) hand peeled samples of sugar cane to separate the rind from the core (pith). In this case the leaves were not included. They found that approximately 58% of the fiber was in the rind and approximately 12% of the sugar was included in the pure rind. These results imply that if the separation of the pith fraction were perfect, the expected loss in the rind-leaf fraction would be 10 to 15% of the sugar in the whole plant. If the sugar is divided similarly between plant parts in sugar cane and sweet sorghum, the results reported by Weitzel et al. (1989) are questioned. They indicated that 95% of the sugar could be retained in the pith fraction. Weitzel et al. based their 95% figure on a total nonstructural carbohydrates (TNC) analysis of the pith and whole stalk samples. They did not analyze the rind-leaf fraction to determine if the amount of sugar found in the two fractions totalled to the amount found in the whole stalks. If the value estimated for sugar in the whole stalks was underestimated, then the percent of sugar separated into the pith fraction would have been overestimated. However, based on the work by Sloane and Hashimoto (1980), it would be reasonable to expect a separation of 80 to 85% of the sugar into the pith fraction if the separation device perfectly separated the pith and rind.

Worley and Cundiff (1988) repeated Weitzel's tests (with some additions) using commercial scale equipment and found similar results. They found that if 70% of the stalk mass were separated into the pith category, approximately 45% to 50% of the stalk mass could be expected to be removed by the screw press in the form of juice. Crude filtering removed another 2% of the stalk mass from the juice. Thus, the process leaves approximately 30% of the stalk mass in the rind-leaf fraction, 20% to 25% in the pith presscake (the pith fraction after juice removal), 2% in the filtercake, and 43% to 48% in the juice. A 40.6-cm diameter screw press was used in these tests and a feed rate of 6 Mg/h of pith material was demonstrated. They felt that the capacity of the press could easily be increased to 10 Mg/h. It is important to note that a press capacity of 10 Mg/h of pith material is equivalent to a capacity of 14.3 Mg/h of whole stalks per hour since the rind-leaf fraction (30% of the mass) does not have to be pressed.

Crandell and Worley (1988) developed and tested a vibrating screen to separate the pith from the rind-leaf in chopped whole-stalk sweet sorghum. The device achieved the desired separations of 60% to 75% of stalk mass in the pith fraction, but was able to operate at only 3 to 4 Mg/h. The desired throughput was at least 5 Mg/h.

Crandell et al. (1989) improved the design of the separation device tested in 1988 and achieved the desired separation at feed rates as high as 8.4 Mg/h. Juice expression was somewhat lower than the previous year (approximately 40% of whole stalk mass). The pith presscake and the rind-leaf fractions contained approximately 30% each of the whole stalk mass. The screw press produced pith presscake at approximately 60% m.c. both years, so the reduction in juice yield was apparently due to the lower moisture content of the stalks. The capacity of the 40.6-cm diameter screw press was increased by a better feeding mechanism to as high as 9.5 Mg/h of pith material, equivalent to 12.7 Mg/h of whole stalks.

2.3 Possible Uses of By-Products

The by-products of the Piedmont System process (rind-leaf fraction, pith presscake, and filtercake) may be used for a number of applications. Since these fractions have some similarities with the by-products of the sugar milling industry, experiences of this industry may suggest similar uses of these products. A discussion of some of the possible applications follows.

2.3.1 Pulp and Paper

Sugar cane bagasse has been used for the manufacture of paper since 1838 (Paturau, 1969) and a number of plants are in operation throughout the world today. Removal of most of the pith from the bagasse is necessary to produce a high quality paper. Tensile strength is improved, while the amount of bleach necessary for processing the pulp is reduced significantly if most of the pith (25 to 30% of the bagasse) is removed. In the Piedmont System, approximately 50% of the dry matter in the plant is removed in the pith fraction so that the rind-leaf portion should be an excellent candidate for a pulp feedstock. It could be improved even more if a method were developed to remove the leaves since leaf material lowers the quality of the pulp. Paturau (1969) estimated the value of sugar cane bagasse at $54 per Mg of dry matter when used for pulp production.

Rind-leaf material has a low density compared to wood and would therefore incur a larger freight cost. In addition, wood can be cut year-round and stored outside with no significant losses while rind-leaf material is only processed for two months in the fall. The rind-leaf material would probably be air dried in the field, baled in large (0.5 to 1 Mg) bales and hauled to the pulp mill in this form. One significant advantage of the rind-leaf fraction would be energy savings in the chipping and preparation of wood for pulp.

Another similar product presently being developed for pulp production is Kenaf. The USDA (1988) indicates that a $400 million Kenaf newsprint mill in South Texas is scheduled for operation within two years. Moore et al. (1976) compared the economic potential of Kenaf with other established crops in the southeast and Kenaf compared favorably with corn, cotton and soybeans. The value assigned to Kenaf in this study was $36 to $49 per Mg of dry matter based on the price range of pulpwood delivered to the mills in 1974. Rind-leaf fraction should be worth this much or more at the mill due to projected energy savings in production.

2.3.2 Particle Board/Fiber Board

Particle board and fiber board require much the same raw material properties as paper pulp. The economics would be very similar to paper pulp although the value might be slightly lower (Paturau, 1969).

2.3.3 Hay

The rind-leaf fraction could be fed as hay. It would contain some seed and some sugar, and SERI(1980) pointed that the leaves and fibrous residue of sweet sorghum is high in protein. It would also be a good source of roughage. The hay would probably be stored in large round bales. Coble and Egg (1986) stored baled whole stalk sorghum hay for five and one-half months with losses of approximately 21% of the original dry matter for bales stored outside. The authors also reported production losses of 51% of dry matter. Production losses were high primarily due to the fact that they were trying to harvest whole stalks of sweet sorghum. A good crop of whole sweet sorghum stalks simply has too much mass per unit land area for effective field drying. As a comparison, Verma and Nelson (1983) reported losses ranging from 26 to 35% from large round bales of ryegrass stored outside for seven months. Martin (1980) stated that production losses of hay crops could vary from 10% to 71%.

2.3.4 Silage

The pith presscake contains 15 to 20% of the sugar and some of the seedhead. The rind-leaf fraction contains another 15 to 20% of the sugar and the remainder of the seedhead. Both fractions can be ensiled to produce a moderate-value silage. A high protein supplement could be added to improve the quality of the silage. If locally available, broiler chicken litter (another waste by-product) might be ensiled with the sorghum by-products or added later as a supplement. Otherwise, soybean meal or other high protein supplements could be used. The filtercake is rich in sugar and can easily be added to the other fractions to add more value to the silage. Paturau (1969) stated that sugar cane filter mud (filtercake) has value as an animal feed but that the main problem with its use was economically drying the product. Drying would not be necessary if the product could be added on-site to the presscake before ensiling.

2.3.5 Biofuel

Audubon Sugar Institute (1984) tested sweet sorghum bagasse to determine the available heat energy, and found heat of combustion values of between 14,000 and 16,000 kJ/kg for sweet sorghum, which is slightly less than the value for sugar cane bagasse (approximately 19,000 kJ/kg). Sweet sorghum was also harder to burn than sugar cane, apparently because of the high ash content in sweet sorghum. Part of the problem they experienced was due to a high soil content. The harvesters that were used tended to pull up the stalks with the roots rather than cut them off, resulting in high soil levels in the stalk material.

Jenkins and Ebeling (1985) tested 62 biomass fuels for heat content and found most forest residues to contain approximately 19,000 kJ/dry kg of material. The authors did not test sweet sorghum bagasse, but found a value of 17,330 kJ/dry kg for sugar cane bagasse. This value is slightly lower than the value found by Audubon Sugar Institute (1984). Using the Jenkins and Ebeling data, the value of sorghum bagasse (or rind-leaf material) could be reasonably estimated to be 80% of the value of wood residue when used for fuel.

2.3.6 Cellulose Conversion to Ethanol

USDA (1988) predicted that "cellulose conversion and processing of renewable resources into oxygenated fuels and chemicals will be the next major development in agriculture". Dekker and Wallis (1983) used an auto hydrolysis-steam explosion process to saccharify (convert to sugar) 80% of the cellulose in sugar cane bagasse. All of the by-products of the Piedmont System would be excellent candidates as feedstocks for conversion of cellulose to sugar for the subsequent production of ethanol. Herbaceous plants are generally easier to break down than woody materials because of their relatively low lignin content. The disadvantages of herbaceous material are high transportation cost due to the bulkiness of the material and the fact that long-term storage is impossible without first drying or ensiling the material. Wright (1988) indicated that the technology for economical conversion of cellulose to ethanol by enzymatic hydrolysis may not be far away. He proposed the use of a "Simultaneous Saccharification and Fermentation" (SSF) process to greatly improve efficiency in both cost and energy. In his analysis, he used a feedstock cost of $44.10/dry Mg for wood and equated this feedstock cost to $.036/kg ($.03/lb) of sugar. These figures imply that the expected yield of sugar is approximately 2/3 of the dry solids in the feedstock.

2.4 Energy Balance Considerations

The debate continues as to whether or not ethanol production has a positive net energy flow. Nathan (1978) observed that the energy ratio (energy output/ energy input) is so near to 1.0 that it can be made greater than or less than 1.0 depending on what assumptions the researcher makes. Most of the effort to identify an energy balance is based on ethanol production from corn. Scheller and Mohr (1976) showed a positive net energy flow while Reilly (1978) projected a negative energy flow. The main difference between these studies was the assumption by Scheller and Mohr that the corn crop residue will be used as an energy source. Chambers et al. (1979) explored the different assumptions which may be made in an energy analysis and explains how these assumptions may affect the results of the analysis. One of the most important parameters is the energy value of a unit of ethanol. It is well known that the energy content of ethanol is about two-thirds that of gasoline. However, a strong argument can be made that ethanol, especially in the form of gasohol (90% gasoline and 10% ethanol) may deliver mileage equal to or greater than pure gasoline. Chambers et al. (1979) stated that dynamometer tests showed a slight decrease in mileage with gasohol, but some road tests indicated an increase in mileage. Also, indoline was used in most of the dynamometer tests rather than commercially available gasoline. Fuel efficiency is dependent on technology and can change as new engines are developed. Chambers et al. (1979) asserted that carefully controlled laboratory tests are less useful in determining expected field performance than carefully monitored road tests. The premise that fuel efficiency for gasohol is approximately equal to that of gasoline was also supported by Nathan (1978).

Regardless of the outcome of the above described analyses, the fact remains that much of the energy used to make ethanol is in the fermentation and distillation phases and can be supplied by coal, biomass, or other forms of energy not suitable for use in transportation. SERI (1981) suggested that the "energy crisis", which was experienced in the late 1970's and could resurface at any time, was actually a "liquid fuels crisis", since solid fuels are much more abundant, especially in this country. Therefore, probably the biggest advantage of ethanol is that it uses a low value fuel to produce a high grade fuel. (High grade here refers to the desirable characteristics of being highly portable and useable in existing engines with little or no modifications.) Nathan (1978) supported the above argument by showing that the energy ratio (energy output divided by energy input) is much higher for ethanol production if only liquid fuel inputs are considered.

2.5 *Economic Considerations*

Several factors must be considered in order to conduct a valid economic analysis. They include estimation of the cost of producing sweet sorghum, determination of the expected yield of ethanol per unit of sugar, and the methods used to estimate the cost of owning and operating equipment. Production practices for the production of sweet sorghum have been established for several years, although much potential exists for research to improve agronomic practices and varieties. Maxey et al. (1989a) estimated the cost of producing and harvesting no-till forage sorghum in southwest Virginia at \$613/ha, including \$367/ha for production and \$246/ha for harvesting. Yield estimates vary greatly depending on variety, location, and weather, but Nathan (1978) reported that the national average experimental whole-stalk yield was approximately 67 Mg/ha. The average for the Piedmont area is considerably below the national average due to the short growing season and poor soils.

The yield of ethanol is directly related to the amount of sugar harvested and retained in the juice. The theoretical yield from 1 kg of sugar is 0.64 L of ethanol. Meade and Chen (1985) indicated that modern fermentation and distilling methods will produce about 90% of the theoretical yield or 0.576 L/kg sugar.

Expected service life and projected lifetime maintenance costs for various kinds of farm equipment were given in ASAE Standard D230.4 (1988). These figures were used to estimate the cost of depreciation, repairs, and maintenance of equipment used in this systems study.

Boehlje and Eidman (1984) pointed out that if present value of equipment, rather than replacement cost, is used in an economic analysis, then a real interest rate should also be used, rather than nominal, or charged, interest rate. Real interest is defined as the real profit that a lender receives for lending money, or the difference between the nominal interest rate and inflation. They reasoned that the use of present value in an analysis rather than replacement cost ignores the effect of inflation, and therefore inflation should also be ignored in calculating the interest cost. The authors calculated real interest as follows:

$$(1+i) = \frac{(1+r)}{(1+f)}, \qquad [2.1]$$

where i = real interest rate,

r = nominal interest rate, and

f = inflation rate.

Boehlje and Eidman (1984) also stated that the "capital recovery" method for calculating depreciation and interest cost gives a more accurate estimate of the cost of owning a piece of machinery than does estimating the cost of depreciation and interest separately. Capitol recovery cost is calculated by

$$ACRC = [(p - s) \times CRF] + (s \times i), \qquad [2.2]$$

where ACRC = annual capital recovery cost,

p = purchase price of equipment,

s = salvage value of equipment,

CRF = capital recovery factor, and

i = interest rate.

The capital recovery factor can be calculated by

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1}, \qquad [2.3]$$

where n = expected life (y) of equipment, and

i = interest rate.

2.6 Models

2.6.1 Soil Trafficability Models

The terms tractability and trafficability are often used interchangeably. Trafficability technically refers to the ability of a soil to support the weight of a piece of equipment while tractability refers to the ability of a tractor to pull a piece of equipment through the field without excessive wheel slippage due to high soil moisture (McFarland and Beach, 1981). Trafficability is the term which best describes the condition of interest in this study and will be used exclusively in this discussion. If the soil is trafficable on a given day, then the day is considered an available day for harvesting.

Many soil water models have been developed and used for various purposes including estimation of irrigation requirements, input for plant growth models, and estimation of available work days in the spring or fall. De Jong (1981) described most of the soil water models existing at that time. He outlined two basic philosophies used to develop these models:

1. Physical models are based on Darcy's law and describe water movement through the soil in response to a potential gradient. These models work well if enough information is known about the soil type, the plants being grown and their stage of maturity, and the thicknesses of the layers of soil. In field conditions, these models become very complicated since soil types vary throughout most fields and initial and boundary conditions are not ordinarily constant. De Jong cited 22 models based on this philosophy.

2. Soil water budget models use an empirical approach to forecasting soil moisture levels. These models use past histories of standard meteorological data to predict the flow of water into and out of soil layers. Two important concepts used in these models are field capacity and permanent wilting point. Field capacity is defined as "the amount of water remaining in soil two

or three days after the soil has been saturated and free drainage has practically ceased." Permanent wilting point is defined as "the water content of a soil at which plants, specifically sunflower plants, wilt and fail to recover their turgidity when placed in a dark humid atmosphere." These concepts are used by all of the soil moisture budget models. Among the 11 models cited by De Jong in his review was a "Versatile Soil Moisture Budget", developed by Baier and Robertson (1966) and revised and updated by Baier et al. (1979) and Dyer and Mack (1984).

Dyer and Baier (1979) suggested that the Versatile Soil Moisture Budget works well for estimating available work days in the spring when the field is usually at or near field capacity because (1) little or no ground cover exists, (2) little or no root withdrawal is taking place, and (3) therefore, evaporation is the critical factor in determining field trafficability. However, a much simpler model can be used for estimating available work days in the fall. The model is based on the assumption that, "In the fall, trafficability is more dependent on the drainage rate of excess water (above field capacity) through the top layers of soil than on evaporation, although both factors must be considered". The ground is usually covered with heavy foliage which reduces evaporation and plants are usually entering the senescent stage resulting in minimal water removal by roots. Unlike the Versatile Budget, this model allows each layer of soil to contain gravity water (moisture level above field capacity) for short periods of time. This feature is important when the objective is to determine field trafficability since the assumption made is that a field is trafficable if it is at or below field capacity. On the other hand, crop growth models are primarily concerned with moisture levels below field capacity and thus require accuracy only at these levels. The main problem with validating any trafficability model seems to be a lack of records for any location concerning which days a field was or was not workable. According to limited, subjective records available to Dyer and Baier (1979), their model was able to correctly predict approximately 75 to 80% of the workdays for two locations in Canada. The only meteorological data needed for this model was rainfall and daily maximum and minimum temperatures (available for many locations) and radiation at the top of the atmosphere, which is available from standard meteorological charts (Smithsonian, 1971).

Coefficients predicting the flow of moisture between, into, and out of the soil layers were derived empirically.

Bardovsky (1978) used soil moisture levels in combination with rainfall on a given day to predict whether or not that day would be suitable for a given field operation. He recognized that even though a heavy rain might not raise the average moisture level of the top layer (15 cm) of soil to a high level, the soil surface conditions might still be unsuitable for some operations. He used the following set of criteria to predict the soil moisture level suitable for the indicated field operations:

Field Operation	**% Field Capacity**
Light Equipment (Sprayer, Fertilizer Applicator)	90
Heavy Equipment (Combine)	85
Light soil disturbance (Planting, Disking)	80
Heavy soil disturbance (Moldboard Plowing)	75

Bardovsky's model was based on the soil moisture balance of Ritchie (1972) and required inputs of rainfall, leaf area index of the crop, and parameters of air temperature, net radiation, and vapor pressure to calculate evaporation using the Priestly-Taylor method (Priestly and Taylor, 1972). He validated the model with data from two locations in Texas and found that it slightly overestimated workdays at one location and slightly underestimated them at the other location, but the errors were considered small enough so that the results were acceptable. As mentioned earlier, field capacity is a somewhat nebulous concept. It is very difficult to say that a particularly field was at 100% of field capacity at a specific time. Because of the empirical nature of the models, an equally good fit might have been achieved if the moisture levels had ranged from 85 to 100% instead of 75 to 90% of field capacity. However, the important implication of Bardovsky's research is that the difference in requirements between a light machine, such as a sprayer, and a heavy machine, such as a combine, is approximately 5% of field capacity.

McFarland and Beach (1981) used a model based on anticedant precipitation index (API) to estimate the number of days delay caused by a given amount of rainfall. The soil moisture conditions on any given day were estimated by the API index. When the expected delay was less than 0.5 days, the day was considered a workday. The model used a survey of farmers by Reinschmiedt (1973) which estimated the number of days delay caused by varying amounts of rain, given the rainfall history for the 14 days preceding the rain. The authors fitted this data along with meteorological records of rainfall to estimate a recession factor to be used in the model. The model only required daily rainfall data to run if the recession factor could be determined for the region of interest. Testing of the model was largely subjective due to a lack of trafficability records.

2.6.2 Weather Generation Models

Several models have been developed in recent years which have attempted to simulate weather parameters for a given location using probabilistic methods. The choice of which model is the best for a given application depends upon which output parameters are needed, the accuracy of the model, and the data required as inputs to the model. For instance, if the model requires a ten year history of solar radiation values, it cannot be used in many locations since this value is only available for a few locations in each state.

Most models first predict whether a given day will be wet or dry since this has a large influence on temperatures and radiation. This prediction is usually made using a Markov chain which simply recognizes that the probability that a given day will be wet is affected by whether or not the previous day(s) was (were) wet (Hunter, 1983). A first-order Markov chain assumes that this probability is only affected by the previous day. A second-order chain assumes that the previous two days have some effect on the probability for the day in question. Roldan and Woolhiser (1982) compared the Markov process with an alternating renewal process which uses probabilistic theories to generate wet and dry series of days. They found no improvement using the alternating renewal process and it required more computer time than the first order Markov process. Once the model predicts that a day is wet, it then predicts how much rain will occur on that day using a random variate generator. The type of distribution used to generate rainfall amount varies from model to model. Once the rainfall data has been generated, data for other parameters, including temperature and solar radiation can be generated, predicated on whether or not the day is wet. Of course, these values are also correlated to the values on the previous day(s) (serial correlation) and to each other (cross correlation). Care must be exercised to preserve as closely as possible the serial and cross correlations between these parameters. Analyzing data from 31 stations in the United States, Richardson (1982) found that maximum and minimum temperature and solar radiation are serially and cross correlated, and that the correlations vary with season and location.

Woolhiser et al. (1985) developed a microcomputer program for the simulation of daily precipitation, maximum and minimum temperature, and solar radiation. The model used a first order Markov chain to determine the occurence of wet days and a mixed exponential distribution to estimate the amount of rain on a wet day. The other parameters were modeled based on the work done by Richardson and Wright (1984). The serial correlations and correlations between these variables are preserved by this model. Seasonal variations in both rainfall generation parameters and temperature generation parameters is approximated using Fourier series. The model was developed specifically for South Dakota, but can be adapted to other locations if the data necessary for deriving the parameters is available.

Richardson and Wright (1984) developed a weather generator called WGEN which also used a first order Markov chain to predict wet days, but this model used a two parameter gamma distribution to generate the amount of rainfall. WGEN then used the method described by Richardson (1981) to generate maximum and minimum temperatures and solar radiation based on histories of these data. Seasonal variations in rainfall were accounted for by using monthly values for the generation parameters. These values were estimated using recorded data values for each month over a 20-year period. Seasonal variations in temperature and solar radiation were estimated using Fourier series as in Woolhiser et al. (1985). Inputs to the model can be taken from a data bank consisting of parameters derived for 139 locations throughout the United States and interpolations between these locations. However, the accuracy of the model can be enhanced by supplying data, if available, for monthly means from the location of interest.

Pickering (1982) developed two models to generate rainfall and mean temperature. The "simple" model used readily available secondary weather data such as mean monthly temperature and mean monthly rainfall and did not consider the effect that rain had on temperature or the serial correlation of either variable. The "complex" model used primary data (daily rainfall, daily average temperature) to generate more realistic data by considering the cross and serial correlations. This complex model used a first-order Markov chain to generate wet and dry days and a two parameter gamma distribution to generate rainfall amounts. Mean temperature was then generated from a normal distribution adjusted for seasonal variation, wet or dry day, and serial correlation of temperature. Seasonal variation in both rainfall and temperature was handled by using different parameters for each of 26 biweekly periods. The use of Fourier series to estimate the seasonal effect reduced the number of parameters which had to be supplied to the model, but also reduced the ability to account for extreme values. The author felt that the increased accuracy was worth the extra effort of supplying more parameters. A total of 212 parameters must be supplied to run this model. By comparison, WGEN can be run with as few as 61 parameter inputs.

Parmar (1989) used WGEN and Pickering's "simple" model to generate daily minimum and mean temperatures for Roanoke, Virginia. He compared the generated data using an F-test and found that Pickering's model appeared to be somewhat superior to WGEN for the generation of these data. However, Pickering's model does not preserve the cross correlation between minimum and mean or minimum and maximum temperatures since each set of temperatures is generated independently. Only the serial correlations are preserved. Richardson (1982) found that the average cross correlation between minimum and maximum temperatures was 0.633 and that it varied with location and season. Also, Parmar used the simple form of WGEN to generate these temperatures. This simple model used input data interpolated from a grid of locations throughout the United States. The output of WGEN can be improved significantly if local data is available and used in WGENPAR, a program also developed by Richardson and Wright (1984), to generate more accurate localized input parameters for WGEN.

Cengiz et al. (1981) developed a method of estimating solar radiation for a given location based on maximum and minimum temperature. The authors found that these factors accounted for 76% of the variation in the data. The prediction was improved to account for 85% of the variation when the minimum relative humidity was included. Baier and Robertson (1965) analyzed data at six locations in Canada to see if simple meteorological observations could be used to estimate latent evaporation. The daily observations studied included maximum temperature, temperature range, wind, duration of bright sunshine, vapor pressure deficit, solar energy at the top of the atmosphere, day length, and total sky and solar energy on a horizontal surface. Maximum temperature and temperature range (or minimum temperature) are readily available at almost any location with a weather station. Solar radiation, wind, and vapor pressure deficit (or relative humidity) are available at a very few locations. Solar radiation at the top of the atmosphere is available for any location for which the latitude is known (Smithsonian, 1971). When all of the above observations were used in a regression analysis, the resulting R statistic was 0.84. When only the temperatures and solar radiation at the top of the atmosphere were used, the R statistic was 0.68. This last model was used by Dyer and Baier (1979) in their soil trafficability model. When solar radiation at the earth's surface was added, the R statistic improved to 0.75.

2.6.3 Harvest Simulation Model

Production Factors

Four factors are of primary interest in evaluating the quality of sweet sorghum as an energy crop.

1. Total biomass yield is of interest primarily because of the possibility of cellulose conversion to ethanol or digestion to produce methane.

2. Total fermentables yield is of interest because fermentables are easily converted to ethanol. Two other terms are often used in the literature which are similar to total fermentables.

    - Total Nonstructural Carbohydrates (TNC) is a measure of soluble sugars and starches. Starches may provide as much as 25% of TNC if the seedhead is included, but are usually less than 2% if the seedhead is not included.
    - Total Soluble Sugars (TSS) includes only soluble sugars. Total fermentables would be equivalent to TNC if the starches are saccharified before fermentation. Otherwise, total fermentables is equivalent to TSS.

3. Concentration of sugars in the juice, measured in ° Brix (or mass of sugar divided by mass of solution) is of interest because a higher concentration of sugars in the juice requires less evaporation in order to make syrup and also, less water which has to be hauled to the evaporation site.

4. The size of the stalk is of interest since this affects the percent of sugar which can be removed from the stalk using the Piedmont system. Also, stalks with larger diameters are less subject to lodging (falling down due to wind, rain, and/or heavy seedhead) than smaller stalks.

A number of factors contribute to the expected yield of both total biomass and fermentables in sweet sorghum. One of the primary factors is the plant maturity at the time of harvest. Freeman et al. (1986) indicated that yields of syrup peak when the seed is in the dough to ripe stages. The progression of ripening stages as related to seed development is as follows: flowering, milk, dough, ripe, and post-ripe. In one test of 100 observations, Brix readings ranged from 11.23° at early flowering to 16.54° at the ripe stage to 14.65° at 3 weeks after ripe stage.

The weather during harvest haas an important influence on yields. Specifically, frost and freezing temperatures have a serious detrimental effect on sugar levels as well as total biomass yields. Neuse and Hunt (1983) measured the Brix of juice samples from the Waconia Orange variety. Measurement were taken from the flowering stage until mid-November. They found that the Brix readings increased almost linearly at 0.10° Brix per day until the first killing frost which occurred on October 9. After the frost, the Brix readings decreased at approximately 0.047° Brix per day. When a hard freeze occurs, rupturing the cell walls, apparently a much more rapid decline in sugar levels occurs. Brinkley (1984) measured dry matter and TNC levels at intervals from September through March in Dale variety sweet sorghum grown in Virginia. The TNC yield remained fairly constant until a killing freeze (-3° C) was experienced on November 7. Then the yields began to drop at approximately 10% per week. A moderate frost (3° C) occurred between mid and late October, but this did not significantly reduce TNC levels. Gammon (1984) observed that after a killing frost, the leaves of the plant die and no more sugar is deposited in the plant. Sugar continues to be burned by transpiration, thereby reducing sugar levels. After a hard freeze, which can rupture and kill the majority of pith cells, the sugar disappearance rate is much higher. Brinkley (1984) observed the same phenomenon on some stalks which she cut and froze for four days and then allowed to thaw. Neither author was able to determine with certainty what made this difference, but one probable explanation is that the ruptured cells allowed a rapid increase in microbial action. Worley and Cundiff (1988) also observed this rapid drop in sugar levels after a hard freeze.

Monroe et al. (1984) found that for the Wray variety grown in Georgia, medium sized stalks (around 2.2 cm diameter at the first internode) yielded more sugar per unit mass than smaller or larger diameter stalks. Freeman et al. (1986) recommended a row spacing of 15 to 20 cm in the row. Closer spacing may cause small stalks which are more prone to lodging. Also, these smaller stalks tend to have more leaves and while total sugar produced per hectare may be higher, the amount of sugar extracted may be reduced and processing is much slower due to the excess of vegetative matter. This is a problem for the Piedmont system as well as other processing systems. A row spacing wider than 20 cm will result in larger stalks, but the number of stalks per hectare will be reduced so much that total yield per hectare is significantly reduced. Worley et al. (1990) found that sweet sorghum could be planted using a row-till planter without affecting the yields or stalk diameter as compared with conventional tillage.

Storage Factors

Brinkley (1984) found a 15% loss in dry matter for stalks cut and left lying in the field for 30 days between September and October. She also found large losses in TNC in these stalks (up to 20% per week) when stored at room temperature (approximately 24 to 27° C). Cundiff and Parrish (1985) found that stalks can be stored for up to 30 days in the field without significant loss of TNC. Two factors can help explain the difference in these two studies.

1. Brinkley's TNC study was done on material stored at room temperature, while the Cundiff and Parrish study was done later in the year (October and November) at outside temperature. The higher temperatures in the Brinkley study may have increased the degradation of TNC levels.

2. In the Cundiff and Parrish study, TNC was measured as a percentage of dry matter. No attempt was made to account for losses in dry matter; therefore, if the dry matter decreased by 15% with no significant change in TNC as a percentage of dry matter, then the total amount of TNC was reduced by approximately 15%.

Other Harvest Simulation Models

Mehner et al. (1988) simulated harvest seasons in order to optimize a system for production of sorghum for methane production. The model was used to determine the optimum number of harvesters and to schedule optimal hydraulic retention times in a batch type digester. Oskoui (1983) used a regression technique to illustrate a method for assessing yield penalties when agronomic practices (such as planting date or harvest date) are accomplished at other than the optimum time. This method was used for small grains, but could be used for other crops if enough data were available.

3.0 By-product Analysis

By-product value is an important part of the economic model. In this section, some of the various possible uses of by-products, listed in Section 2.3, are analyzed to determine the economic worth of these products.

3.1 Laboratory Analysis of By-products

No reports were found in the literature on the ensiling of sweet sorghum; consequently, an experiment was run using samples of pith presscake, filtercake, rind-leaf, and chopped whole stalk from one of the full-scale test runs of the processor (Crandell et al., 1989). These samples were analyzed to objectively evaluate the nutritional and chemical makeup of the by-products, and their fermentation characteristics (suitability for ensiling). They were analyzed for initial composition and then mixed together, ensiled, and reanalyzed according to the following procedure.

Samples of the whole-stalk, rind-leaf, pith presscake, and filtercake fractions were taken to determine their initial composition. In addition, a sample of air-dried rind-leaf material was analyzed using the same procedures. A 300 g sample of each component was blended with 3000 ml of water for 2 min in a Waring blender to make a water extract. The blended material was strained through a wire mesh cloth and an aliquot of the liquid component collected. Determination of pH on the extract was done electrometrically immediately following preparation of the water extract. Aliquots of the extract were saved for later analysis of total lactic acid by the method of Barker and Summerson (1941) as modified by Pennington and Southerland (1956), L-lactic acid using a YSI Model 27 Industrial Analyzer[1], volatile fatty acids (VFA) using 4-methylvaleric acid as an internal standard (Erwin et al., 1961), and water soluble carbohydrates by the procedure of Dubois et al. (1956) as modified by Johnson et al. (1966). Duplicate 100 g samples of each component were subjected to oven drying at 50 ° C for 48 h for the determination of dry matter. Following drying, the duplicate samples were composited and ground through a 1 mm screen in a cyclone mill[2] and packed in sealed glass containers pending analysis for crude protein (AOAC, 1984), neutral detergent fiber (NDF)(VanSoest and Wine, 1967; Goering and VanSoest, 1970), acid detergent fiber (ADF)(VanSoest, 1963; Goering and VanSoest, 1970), cellulose (VanSoest and Wine, 1968; Goering and VanSoest, 1970), and permanganate lignin (VanSoest and Wine, 1968; Goering and VanSoest, 1970). Hemicellulose was estimated as the difference between NDF and ADF. Total Digestable Nutrients (TDN) and net energy (NE) were estimated using Eq. [3.1] and [3.2], respectively, which are regression equations developed for sorghum-sudan grass. Since no regression equations were available for sweet sorghum fractions, these equations were thought to be the most likely to give a close estimate of the desired quantities.

$$\mathrm{TDN} = 89.8 - 0.768\mathrm{ADF}, \qquad [3.1]$$

where TDN = Total digestable nutrients (% d.b.), and

ADF = Acid detergent fiber (% d.b.).

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[1] YSI Model 27 Industrial Analyzer, YSI Scientific Division, Yellow Springs Instrument Co., Yellow Springs, OH.

[2] Cyclotec 1093 Sample Mill, Tecator Inc., P.O. Box 405, Herndon, VA.

$$NE = 0.0234TDN - 0.106, \qquad [3.2]$$

where NE = Net energy available to cow (Mcal/kg).

The results of these tests are shown in Table 1. Placement of materials in the experimental silos took place within three to four hours after the fractions were created. This short delay was apparently acceptable, since the relatively high pH levels and low lactic acid levels indicate that very little fermentation took place before the material was ensiled. The high level (41.7% of dry matter) of water soluble carbohydrates (primarily sugars) found in the whole-stalks is expected, since none of the sugar has been removed from these samples. The low level (24.7%) in the rind-leaf is indicative of the expected result that most of the sugar was separated into the pith fraction. The 30.4% sugar level in the pith presscake indicates that a large portion of the sugar was removed with the juice. The filtercake contained a fairly high concentration of sugar (36.7%), but since this fraction only makes up 1% of the total plant mass, the sugar loss in the filtercake is minimal.

It has been hypothesized that the pith presscake might be a superior feedstock for cellulose conversion because of its expected lower hemicellulose content relative to rind-leaf and other herbaceous feedstocks. Since cellulose is easier to convert to sugar than hemicellulose, a high-cellulose material should have some advantage as a feedstock. As shown in Table 1, the hemicellulose and cellulose concentrations for pith presscake were actually very similar to those for rind-leaf (within 3.2%). Therefore, there is little to suggest that the pith presscake is a superior candidate for cellulose conversion.

Four types of forage mixtures were prepared and ensiled. One silage consisted of the chopped whole plant with no juice removed. A second silage was prepared by combining 53% rind-leaf, 46% pith presscake, and 1% filtercake. These percentages represent the whole plant less the juice. Two partial-plant residue silages were prepared. One was composed only of the rind-leaf fraction and the other was composed of 97.9% pith presscake and 2.1% filtercake. Preweighed quantities of these residue mixtures, enough to fill a single silo, were placed in a horizontal mixer and mixed

Table 1. Initial composition of different sweet sorghum materials

Item	Whole Stalk	Rind-Leaf	Pith Presscake	Filter Cake	Rind-leaf Hay
pH	5.92	6.10	6.04	5.80	*
Dry matter (%)	30.8	29.5	41.4	18.1	91.2
Composition of dry matter (%)					
Crude Protein	5.9	6.8	6.9	4.1	5.7
Neutral Detergent Fiber (NDF)	47.2	55.5	49.9	18.0	65.9
Acid Detergent Fiber (ADF)	27.4	30.3	27.9	8.6	40.6
Hemicellulose	19.8	25.2	22.0	9.4	25.3
Cellulose	22.8	25.0	23.0	7.3	33.5
Lignin	4.1	4.7	4.6	1.5	6.0
Water soluble carbohydrates	41.7	24.7	30.4	36.7	*
Total lactic acid	0.04	0.05	0.03	0.09	*
L-lactic acid	0.02	0.01	0.01	0.05	*
Total Digestable Nutrients (TDN)					58.6
Net Energy (estimated Mcal/kg)					1.27

* Not measured

for two minutes. With the aid of a hydraulic press, residue mixtures were then packed into 7.6 L plastic silos to achieve a density of 0.59 kg/L for a total mass per silo of 4500 g. Each silo was then sealed and a Bunsen valve was placed in the lid to allow gas to escape. The silos were weighed initially and again on day 45, the time of opening, to determine weight loss.

When the silos were opened, the entire contents of a silo were mixed in a horizontal mixer for one minute. Following this, a 300 g sample of the ensiled forage was extracted and analyzed for pH, total lactic acid, L-lactic acid, VFA and water soluble carbohydrates as described previously. Duplicate 100 g samples of the ensiled forage were dried, ground and analyzed for dry matter, crude protein, NDF, ADF, and hemicellulose as described previously. TDN and NE were also estimated as described previously. The results are shown in Table 2.

All of the mixtures ensiled well as indicated by the pH and acid levels of the final products. The silo weight losses were all approximately 5% of the original 4500 g. The values for protein, fiber, TDN, and energy were similar for each of the four mixtures. The estimated values for TDN and net energy in 32-40% M.C. corn silage are 65% and 1.50 Mcal/kg, respectively. As expected, the estimated values in Table 2 indicate that whole-stalk sorghum is approximately equal in nutritional value to corn silage, but the by-product silages are slightly less nutritious. It must be remembered that these values represent samples from only one test run, and therefore can only be used as a guide for estimating reasonable nutritional values. Stallings (1990) indicated that Equations [3.1] and [3.2] may be overpredicting values for TDN and net energy for these by-products. He stated that he would expect a TDN value between 50% and 60% and a net energy between 1.1 and 1.3 Mcal/kg. In order to be conservative, the values used for estimating the value of sorghum by-products were TDN = 55% and net energy = 1.2 Mcal/kg.

Table 2. Silo losses, fermentation parameters, and silage compositions.

Item	Chopped Whole-stalk	Combination (Presscake + Rind-leaf)	Rind-leaf	Pith Presscake
Silo weight loss (g)	42.0	53.0	42.0	51.0
pH	3.74	3.75	3.78	3.74
Dry matter (%)	26.5	32.1	28.4	38.1
Composition of dry matter (%)				
Crude protein	6.4	6.1	5.7	7.1
Neutral Detergent Fiber (NDF)	52.8	67.8	67.6	65.2
Acid Detergent Fiber (ADF)	29.2	37.5	39.4	32.7
Hemicellulose	23.6	30.3	28.2	32.5
Water soluble carbohydrates	11.8	6.3	7.0	1.9
Total lactic acid	3.98	4.88	3.77	3.34
L-lactic acid	3.31	3.81	2.42	3.34
Acetic Acid	3.55	3.37	3.23	2.29
Propionic acid	0.18	0.93	0.58	0.53
Total Digestable Nutrients (TDN)	67.4	61.0	59.5	64.7
Net Energy (estimated Mcal/kg)	1.47	1.32	1.29	1.41

3.2 Rind-Leaf Hay Analysis

The rind-leaf fraction might be handled in a number of ways including leaving it on the field to increase organic matter in the soil. Leaving organic matter on the soil has some long-term value, but there is no agreement in the scientific community as to the amount of economic benefit. Other possibilities include feeding it as hay, using it as a feedstock for paper or building board, using it for direct combustion (biofuel) to produce heat, and conversion of cellulose to ethanol via enzymatic or acid hydrolysis. For any of these products, the most probable method of handling the rind-leaf is to dry it to a storable moisture content (approximately 10% w.b.) and bale it into large round bales.

The rind-leaf hay might be harvested by a contractor who would be responsible for raking and baling the hay and loading it onto a contract hauler's truck for transport. Equipment required would include a side delivery rake and a large-bale hay baler, tractors to operate this equipment, and a front-end loader mounted on the tractor which operates the rake. The loader would be used to load the bales onto the truck. Two employees would be needed to operate the tractors. It was assumed that the employees can be hired only when needed, or that they can be profitably used elsewhere in the contractor's operation when not needed for rind-leaf hay harvesting. The baler chosen for the operation will produce bales 1.45 m wide × 1.52 m in diameter with an average mass of 0.544 Mg. Specifications and prices for the equipment were obtained from local farm equipment dealers.

In addition to baling rind-leaf hay during September and October, the contractor would use the equipment for baling other types of hay during the spring and summer months. If the baler were used 80 hours per month from May through September and 60 hours per month in April and October, the total hours of operation for the hay baler would be 520 hours per year including the rind-leaf hay operation. It was estiated that the tractors are used for tasks other than hay harvesting for an additional 100 hours per year.

The average rate of production of sweet sorghum was taken as 42 Mg/ha. Of this amount, 30% (the rind-leaf fraction) will be left scattered in the field to dry. This material will be approximately 72% moisture content (w.b.) when produced and will be allowed to dry to approximately 10% before being harvested as hay. Production losses will probably be rather high due to the nature of the ground stubble, rows of large stalk stumps instead of the matt of grass usually expected in hay. Also, some of the material will be small pieces which will tend not to be picked up by the equipment. Based on the work by Coble and Egg (1986) and Martin (1980), the production losses were taken as 20% ofdry matter. The storage losses for hay stored seven to nine months were taken as 20% based on the work by Coble and Egg (1986) and Verma and Nelson (1983). If the material is used at a steady rate over this period, the average loss would then be 10% of the original bale dry matter. The amount of hay to be baled and hauled per hectare is given by

$$HY = \frac{Y_{WS} \times RL \times X_{RL}}{X_H} \times (1 - PL), \qquad [3.3]$$

where HY = Mg/ha of rind-leaf hay,

Y_{WS} = Mg/ha of whole-stalks,

RL = fraction of whole-stalks in the rind-leaf,

X_{RL} = dry matter content of undried rind-leaf,

X_H = dry matter content of hay, and

PL = production losses (fraction).

Inserting the assigned values in Equation [3.3], the yield was computed to be 3.14 Mg/ha before storing and 2.82 Mg/ha after storage losses.

The expected speeds and field efficiencies of the equipment were taken from ASAE Standard D230.4, Agricultural Machinery Management Data (ASAE, 1988). Expected speed for a hay rake is 7.25 km/h with a field efficiency of 80%. Using these figures, a 2.44-m wide rake would travel 4.1 km to cover one hectare and would rake approximately 1.4 ha/h. The baler, moving at an average speed of 5.63 km/h would travel the same 4.1 km/ha, and at a field efficiency of 65% would harvest 0.89 ha/h.

Eight hours of hay baling per day should be possible in September. Probable hours of operation would be from 1100 to 1900 hours. In that 8-hour day, the baler could cover approximately 7.1 hectares. The rake can cover the same area in approximately 5 hours. The tractor which pulls the rake could therefore spend the remaining 3 hours loading the bales on the trucks. Approximately 38 bales would be produced, and while efficiency figures are unavailable for loading bales on a truck, 3 hours should be sufficient for this task. If 1 hour per day is allowed for transporting the equipment to and from the field, then a reasonable estimate of the system capacity would be 7.1 hectares per 9-hour work day. Harvesting at this rate, the production of rind-leaf hay would be 22.2 Mg or 41 bales of material per day. During a workday, the tractors would operate 9 hours, the baler 8 hours, and the rake 5 hours. In October, due to colder temperatures and shorter daylight hours, baler opoeration was reduced to 6 hours per day, resulting in a production rate of 5.3 ha, 16.6 Mg, or 31 bales per day.

To estimate the number of available work days in the two month period, 10 years of daily rainfall amounts were retrieved from the weather data available at the Northern Piedmont Experiment Station. The number of available work days for each year in September and October were estimated using the following guidelines:

1. Harvest of sweet sorghum begins on the first dry day of September.
2. Approximately 2 days in September and 3 days in October would be required to dry the material to a storable moisture content of 10%. Therefore, after a rain, 2 dry days must occur before a work day can occur in September (3 days in October).
3. Hay is always available to bale when it is dry enough, although some of the material will have been rained on. In the event of a small (less than 0.13 cm) rain in an otherwise dry period,

hay harvest would resume the following day. If a moderate (0.13 to 0.38 cm) rain occurs in an otherwise dry period, harvest would resume in two days.

Using these guidelines, the 10-year average number of available days for September was 16 with values ranging from 10 to 23, and the average number of available days for October was 13 with values ranging from 4 to 20. This number of available days would theoretically enable the harvest of (16 × 7.1) + (13 × 5.3) = 182.5 ha/y. However, it would not be prudent to plant 182.5 hectares expecting to harvest all of the rind-leaf. An hypothesized harvester that would move through the field, collect the pith, and drop the rind-leaf hay back on the surface could operate in wetter soil conditions compared to the hay operation and could therefore produce rind-leaf material during some periods when the hay could not be harvested. Therefore, in some wet years, much of the material might be left to rot. Also, material may not be available every time the weather is right. Considering these factors, conservative estimates of 13 workdays in September and 10 workdays in October were used, resulting in a harvest of approximately 145 ha/yr. Rind-leaf baling should operate within an 8-km radius of the base of operation to minimize the time spent moving equipment from one field to the other. There are 20,106 hectares in an 8-km radius; therefore, only 0.72% of the land would need to be planted in sweet sorghum to operate efficiently.

Summary of Hay Production: The harvesting operation is expected to harvest 23 days per year. It will harvest 145 ha or 455 Mg or 837 bales with an average mass of 0.544 Mg/bale. After storage, these 837 bales will have an average mass of 0.490 Mg and a total mass of 410 Mg. The 23 days of operation will require (13 × 8) + (10 × 6) = 164 h of baler time, (13 × 5) + (10 × 4) = 105 h of rake time, and (13 × 9) + (10 × 7) = 187 h of operation time for two tractors and their operators. The baler is expected to operate 520 h/y, so this operation utilizes approximately 31.5% of the baler time each year. Also, this operation will utilize approximately 31.5% of the rake time, and since the rake is used 105 h/y in this enterprise, the total expected hours of operation for the rake is 105 / 0.315 = 333 h/y. The tractors will operate approximately 187 / 0.315 = 594 h/y in the hay operation plus an additional 100 h/y in other operations for a total of 694 hours per year.

3.2.1 Harvesting and Handling Costs of Rind-leaf Hay

Estimated life of the equipment was taken from ASAE Standard D230.4 Agricultural Machinery Management Data (ASAE,1988). No estimated life expectancy was found for a front-end loader. The loader should last as long as a tractor and was therefore considered an addition to the cost of the tractor. ASAE Standard D230.4 also gave guidelines for estimating the cost of repairs and maintenance over the life of a machine. These values were used and divided by the number of years of expected life to obtain an average yearly expense. Straightline depreciation was assumed with a salvage value of 10% of the original cost of the equipment. Accelerated depreciation methods could have been used. Repair and maintenance costs are equipment dependent, but often are higher toward the end, so that the effects of declining depreciation tendto be offset by increasing repair and maintenance costs. Two % of equipment cost per year was used for taxes, insurance, and housing (ASAE Engineering Practice EP391.1, Agricultural Machinery Management, ASAE,1988). The Nebraska Tractor Tests (1982) were consulted for estimates of fuel usage. It was estimated that the tractors were operated at 75% of rated horsepower for much of the day and the corresponding fuel consumption was used. Labor cost was estimated as $5.50/h, including benefits, based on information from VASS (1988). Costs of operating the machinery are summarized in Table 3. Analyses of each piece of equipment used are shown in Appendix A.

A reasonable profit margin for the contractor would be $2.20/bale which would yield a return of $1841 for 23 days in September and October, and would add $4.04/Mg to the cost of hay. The total cost of hiring the contractor to rake, bale, and load hay is then $22/Mg.

The cost of freight is, of course, primarily dependent on how far the material has to be hauled, and the hauling distance is determined by what the use of the material. For instance, if it is fed as cattle feed, it may be hauled only a short distance; on the other hand, if it is used as a feedstock for ethanol, it will be hauled an assumed average distance of 48 km. Most research on cellulose conversion indicates that enzymatic conversion of cellulose can be done most efficiently by simultane-

Table 3. Costs of operating hay equipment

Equipment	Purchase Price $	Cost (Fixed + Operating) $/Productive Hour	Cost (Fixed + Operating) $/Mg
31 kW Tractor w/Loader	15,900	14.09	5.63
Side Delivery Rake (2.44 m)	2,500	2.73	.70
48 kW Tractor	19,800	17.73	7.09
Round Baler	12,000	11.43	4.57
Total	**50,200**	**45.98**	**17.99**

ous saccharification and fermentation (Wright, 1988) which means that the conversion of cellulose to sugar must be done at a centralized location (probably near a large distillery.) For long hauls, 30 bales could be stacked on a 12.8-m flat bed trailer. At 0.544 Mg each, these 30 bales would have a mass of approximately 16.3 Mg which is close to the trailer capacity of 18.1 Mg. Transportation cost is given by

$$\mathrm{TC} = \frac{\mathrm{RATE} \times \mathrm{DIST}}{\mathrm{LOAD}}, \qquad [3.4]$$

where TC = transportation cost ($/Mg),

RATE = freight rate ($/km),

DIST = distance traveled (km), and

LOAD = size of load (Mg).

For an average distance traveled of 48 km and a freight rate of $0.93 per loaded km, the freight cost is $2.74/Mg. If the hay is used locally, it would probably be hauled on smaller vehicles and thus would have a higher freight rate. As an example, if the hay is hauled 3 km at $4.00/km on a vehicle with a capacity of 8 Mg, the transportation cost would be $1.50/Mg.

3.2.2 Rind-leaf Hay Economics

When used as a feedstock for cellulose conversion to ethanol, the value for rind-leaf hay was taken as $44/dry Mg delivered to the conversion plant (Wright, 1988). Rind-leaf hay used as paper pulp was valued at $50/dry Mg (Paturau, 1969 and Moore et al., 1976). Using the heat energy content determined by Jenkins and Ebeling (1985), the value of hay for direct combustion (biofuel) was estimated at $35/dry Mg.

To evaluate the value of rind-leaf hay as an animal feed, a ration formulation program called DAIR4 (Stallings et al., 1988) was used. This program enables the user to balance a ration for a dry or lactating dairy cow or for a growing heifer, given a list of feed ingredients with known nutritional values. The nutritional value of rind-leaf hay was estimated based on the analyses in Section 3.1 and these values were entered into the program. Rations were first developed for dry cows and heifers using fescue hay, valued at \$55/Mg, as a main ingredient. Then, rind-leaf hay was substituted for the fescue hay and other ingredients (soybean meal, corn, and alfalfa hay) were adjusted to rebalance the ration. The price of rind-leaf hay was adjusted so that the total cost per cow per day was the same as the original ration. More detail and a listing of the actual feed formulae are shown in Appendix B. Using this method, the value of rind-leaf hay as a cattle feed was estimated at \$35/Mg for the dry cow ration and \$52/Mg for the heifer ration. An average value of \$40/Mg was used for the subsequent analyses.

The cost of raking, baling, and loading the hay onto a truck was estimated at \$22/Mg and the cost of freight was calculated as \$2.74/Mg for a 48-km trip (cellulose conversion) and \$1.50/Mg for local feeding. The value per dry Mg can be converted to a value per wet Mg by

$$WV = DV \times (1 - MC), \qquad [3.5]$$

where WV = value of a Mg of wet material,

DV = value of a Mg of dry matter, and

MC = moisture content (w.b.) of wet material.

Using this equation, the value of 10% moisture hay delivered to a cellulose conversion plant is \$39.60/Mg. The value of the hay in the field is \$39.60 - \$2.74 = \$36.86/Mg, and adjusting for 10% storage losses and the cost of raking and baling, the value for hay is (0.9 × \$36.86) - \$22 = \$11.17/Mg. The equivalent value of rind-leaf material before drying (72% moisture) is \$3.48/Mg. If 30% of the assumed whole-stalk yield of 42 Mg/ha is rind-leaf, then, after adjusting for 20% production losses, the projected value of hay in the field is \$35.08/ha. If the rind-leaf hay were used to produce paper, a similar analysis yields an estimate of \$3.73/Mg for 72% moisture material, or \$37.60/ha. If the hay were used for direct combustion, it would be worth approximately \$1.21/Mg, or $12.20/ha. If it were fed locally to cattle, using the freight cost of $1.50/Mg calculated earlier and the value of $40/Mg at 10% moisture, then the value is $3.94/Mg, or $39.72/ha. A ranking of the uses of rind-leaf hay according to value is given in Table 4.

3.3 By-product Silage Analysis

3.3.1 Processing and Storage Costs

The cost of by-product silage includes the cost of transporting the material to the silo and the cost of ensiling it. Ensiling cost includes the fixed cost of owning the silo, the cost of loading the silo, and any material cost, such as plastic covering. Novaes (1981) estimated the cost of ensiling material in a bunker silo at $12/dry Mg which is equivalent to $4.80/Mg for 60% moisture silage. According to the National Agricultural Statistics Service (1989), prices on farm buildings and fences have risen approximately 12% since 1980, so the present estimated cost of storing 60% M.C. silage is then $5.38/Mg. The freight cost was estimated as $.40/Mg, but this value would, of course, depend greatly on how far the material had to be transported. Thus, the total cost for ensiling 60% moisture material is $5.78/Mg. If the material is transported an average distance of 48 km to a cellulose conversion plant, at a cost of $0.93/km and with a truck capacity of 20.4 Mg, the freight cost is $2.19/Mg rather than the $0.40/Mg calculated for ensiling and feeding on the farm. Thus, the total cost for ensiling and transporting 60% moisture material to a cellulose conversion facility is $7.57/Mg.

Estimates of the nutritional value of pith presscake silage and combination (rind-leaf and presscake) silage were obtained from the analyses in Section 3.1. It appears that both products are equally well suited as a silage material. The only difference expected between the two by-products is that

Table 4. Value of rind-leaf hay for various uses.

Potential Use	Value	
	$/Mg	$/ha
Hay Fed Locally	3.94	39.72
Paper Production	3.73	37.60
Cellulose Conversion to Ethanol	3.48	35.08
Direct Combustion	0.97	12.22

the rind-leaf material is approximately 72% moisture and the pith presscake is approximately 60%. Both the pith presscake and rind-leaf fractions are projected to represent 30% of the total mass of whole-stalks. If the two are combined, the resulting product would have a moisture content of approximately 66%. The cost of ensiling a Mg of this combination material would be slightly lower due to the higher moisture content. Using the method described above, the ensiling and transportation cost for 66% moisture material is $4.97/Mg for local feeding and $6.76/Mg for cellulose conversion.

The samples used in the ensiling experiment lost approximately 5% of dry matter, and the experimental silos are more efficient than a full-sized silo. Therefore, production and ensiling losses were estimated as 10% of the original dry matter. The production of by-product silage would then be $(0.3 \times 0.9) = 0.27$ Mg 60% moisture silage per Mg whole-stalks if only the pith presscake is used, or 0.54 Mg 66% moisture silage per Mg whole-stalks if the pith and rind-leaf fractions are mixed and ensiled.

3.3.2 By-product Silage Economics

DAIR4 (Stallings et al., 1988) was used to estimate the value of sorghum by-product silage. By-product silage was substituted for fescue hay (valued at $55/Mg) in dry cow and heifer rations, and for corn silage (valued at $22/Mg, the value used by Maxey et al., 1989b) in a lactating cow ration. Details and actual feed formulae are shown in Appendix B. The value of by-product silage as a replacement for conventional feeds was $18/Mg for dry cows, $11/Mg for lactating cows, and $25/Mg for heifers. All of these values were based on a 60% moisture silage. If the combination silage (at 66% moisture) were used, the value would be approximately 85% of that of the 60% moisture silage, or $15/Mg for dry cows, $9/Mg for lactating cows, and $21/Mg for heifers. The low value for lactating cows is due primarily to the low energy content of this silage and the need by lactating cows for large amounts of energy. The use of by-product silage for a lactating cow ration is not indicated. The average, or representative, values for the subsequent analysis were chosen to be \$22/Mg for pith presscake silage and \$19/Mg for combination pith presscake and rind-leaf silage. Both of these formulations included the filtercake.

If only the pith presscake were ensiled, the value would be \$22 - \$5.78 (cost of ensiling 60% moisture material) = \$16.22/Mg. With a whole-stalk yield of 42 Mg/ha, the resulting value is 0.27 × 42 × \$16.22 = \$183.93/ha. If both rind-leaf and pith presscake were ensiled, the value would be \$19 - \$4.97 (the cost of ensiling 66% moisture material) = \$14.03/Mg, and the total value would be 0.54 × 42 × \$14.03 = \$318.20/ha.

If the pith presscake silage were used for cellulose conversion, the value of the material would be \$44/dry Mg delivered to the plant. Using Equation [3.5], the value of 60% moisture silage is \$17.60/Mg. The cost of ensiling this material and transporting it to a cellulose conversion plant was estimated at \$7.57/Mg, which yields a net estimated value of \$10.03/Mg or \$113.74/ha. If both rind-leaf and pith presscake were ensiled together, the value is \$14.96/Mg, and the cost of ensiling and transporting is \$6.76/Mg yielding a net value of \$8.20/Mg, or \$185.98/ha.

3.4 Whole-stalk Silage

Another material which might be considered a by-product is whole-stalk silage. When more area has been planted than can be harvested with the Piedmont system, the excess area can be harvested with a conventional silage harvester and ensiled. If suitable for cattle feed, it would be fed by the farmer who grew the crop. Otherwise, it would be sold as feedstock for cellulose conversion for ethanol. DAIR4 was again used to estimate the value of this product for local feeding. The nutritional values supplied in the software were used rather than the values obtained in Section 3.1 since the supplied values were an average of many samples of sorghum silage and should be a better estimate of the mean values. For a 70% moisture silage, the estimated value of whole-stalk silage is $15/Mg for dry cows, $12/Mg for lactating cows, and $21/Mg for heifers. An average value of $17/Mg was used for the subsequent analysis. With an ensiling and freight cost of $4.43/Mg, calculated as in Section 3.2, the net value would then be $17 - $4.43 = $12.57/Mg if the silage were fed locally. Ensiling losses are expected to be equivalent to by-product silage losses (10%).

If the whole-stalk silage were used for cellulose conversion to ethanol, the value would be $44/dry Mg delivered to the plant. Using Equation [3.5], the value of 70% moisture silage is $13.20/Mg. The cost of ensiling and transporting the material to the plant is estimated at $6.22/Mg, which yields a net value of $6.98/Mg.

3.4 Summary of By-product Values

The estimated values of sweet sorghum by-products for different uses are summarized in Table 5. In order to compare all products on an equal basis, all values are given for the products as they are produced by the processor. For instance, the values given for rind-leaf material are for the 72% moisture rind-leaf fraction as it comes from the processor rather than 10% moisture hay after it has been dried, baled, and delivered.

The value-per-hectare column reveals that the rind-leaf fraction has a higher value when ensiled than when harvested as hay. This higher value occurs primarily because most of the processing for silage (chopping and transporting from the field) is done as a part of the juice harvest, and the cost of these operations is therefore not charged to the silage. Most of the hay operation (raking, baling, and transporting) must be done separately from the juice harvest. Another factor which lowers the value of rind-leaf hay relative to rind-leaf silage is the expected higher field losses for hay production.

Table 5. Total value of Piedmont System by-products assuming 42 Mg/ha whole-stalk yield

By-product Use	Yield	Value	
	(Mg/ha)	($/Mg)	($/ha)
Combination Silage Fed Locally	22.68	14.03	**318.20**
Pith Presscake Silage Fed Locally	11.34	16.22	183.93
Rind-leaf Hay Fed Locally	10.08	3.94	39.72
Total			**223.65**
Pith Presscake Silage Fed Locally	11.34	16.22	183.93
Rind-leaf Hay for Paper Production	10.08	3.73	37.60
Total			**221.53**
Pith Presscake Silage Fed Locally	11.34	16.22	183.93
Rind-leaf Hay for Cellulose Conversion	10.08	3.48	35.08
Total			**219.01**
Pith Presscake Silage Fed Locally	11.34	16.22	183.93
Rind-leaf Hay for Direct Combustion	10.08	1.21	12.20
Total			**196.13**
Combination Silage for Cellulose Conversion	22.68	8.20	**185.98**
Pith Presscake Silage for Cellulose Conversion	11.34	10.03	113.74
Rind-leaf Hay for Cellulose Conversion	10.08	3.48	35.08
Total			**148.82**
Whole-stalk Silage Fed Locally	37.8	12.57	475.15
Less Harvesting Cost			246.00
Net			**229.15**
Whole-stalk Silage for Cellulose Conversion	37.8	6.98	263.84
Less Harvesting Cost			246.00
Net			**17.84**

4.0 Procedure

4.1 Description of Harvest Systems Being Compared

As previously discussed, three harvesting systems were modeled and compared to determine which system emerged as the most economical. This section gives a detailed description of each system.

4.1.1 Crossroads Processing System (System A)

The concept for System A is pictured in Figure 2, and the hypothesized operation is as follows. The whole stalk harvester cuts the stalks, collects them into 0.5-m diameter bundles, and deposits them on the ground in windrows. The stalks are then loaded onto a dump trailer with a field loader and stockpiled at a central processing site located at the edge of the field, or to a nearby crossroads location convenient to several fields. It is assumed that two tractors with dump trailers will be able to transport material at the rate it is cut, expected to be approximately 0.3 ha/h. The stalks are then removed from the stockpile with a loader and dumped into the processor.

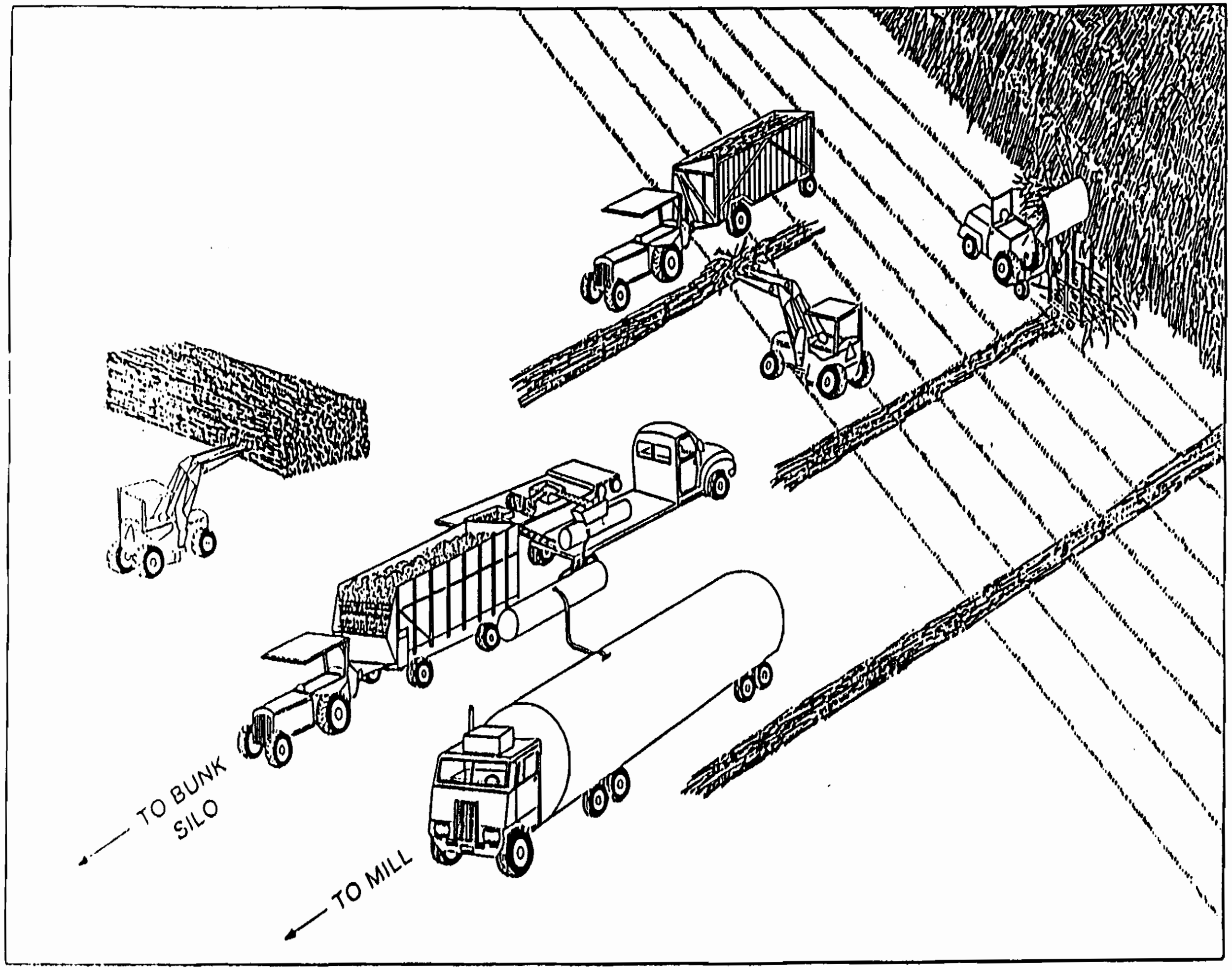

Figure 2. Conceptual drawing of crossroads system (System A)

The processor consists of three subsystems; feeder, chopper, and pith separator; and is mounted on a flat bed trailer to provide mobility. Whole-stalks are fed into the chopper in 10-cm deep layers by the feeder. The chopper blades impact the stalks at 1-cm intervals, and the resulting mixture is separated into pith and rind-leaf fractions as it passes over the separator. The pith fraction falls through the separator and is conveyed to the screw press (mounted on the same trailer or an adjacent truck as shown in Figure 2) where the juice is expressed. The rind-leaf fraction passes over the separator and accumulates at the rear of the processor. The output of System A is then three plant fractions: juice, pith presscake (the fiber that emerges from the screw press after juice expression), and rind-leaf.

The pith presscake is handled like a crop cut for silage. Because of the residual sugar and relatively high moisture content (approximately 60% w.b.), it will rapidly begin to ferment; therefore, it must be ensiled as quickly as possible. It is envisioned that the juice will be filtered and the filter-cake added to the pith presscake. The juice is then trucked to a central plant, expected to be located such that the average transport distance is 16 km. The rind-leaf fraction can be handled in one of three ways. It can be spread back on the field to provide a winter cover and add organic matter to the soil, spread back on the field to dry so that it can be baled as hay, or mixed with the pith presscake and ensiled.

System A offers several advantages and several disadvantages. The advantages are as follows:

1. The whole-stalk harvester is a relatively light machine (2 Mg) and can operate when soil moisture content is too high for a heavier machine. In a typical season there should be more days when the whole-stalk harvester can operate.
2. As long as the integrity of the rind is maintained, whole stalks can be stored for up to 30 days with very little deterioration (see Section 2.6.3). Storage gives flexibility between the harvesting and processing operations. Harvesting need not be paced to match the processing rate and vice versa. Both equipment systems (harvesting and processing) should proceed at maximum machine productivity for System A.

3. Stockpiling of stalks enables the processor to operate for three to four weeks after the harvesting season is over.

The disadvantages are as follows:

1. Excess handling is the main disadvantage of System A. Whole-stalks are picked up, loaded onto a dump trailer, dumped into a storage pile, and then picked up from this pile for loading into the processor. This handling increases equipment and labor costs and damages the stalks.
2. A crew of six would be required to operate System A: a harvester operator, a field loader operator, two dump trailer/tractor drivers, one loader operator, and one processor operator.

4.1.2 Pith Combine System (System B)

The concept for System B is pictured in Figure 3. System B utilizes an hypothesized ″pith combine″ to remove the pith fraction from the stalks in the field as the stalks are harvested. The pith combine is envisioned as an assembly of the following subsystems: a forage chopper pickup mechanism, the same chopping and separation device used for the processor in System A, and a conveyor to load the pith fraction onto the forage wagon. After the pith wagon is filled, it is towed to a nearby location where the juice is removed. Ideally, the screw press would be located so that the pith presscake could be conveyed directly into a bunk silo. Alternatively, the pith presscake could be reloaded into a forage wagon and hauled to the silo. In System B, the juice is filtered and handled like in System A. The rind-leaf fraction would be left scattered in the field to dry. It can then be raked, baled and handled like any hay crop, or it can be left to add organic matter to the soil. System B would be operated two shifts per day as would both System A and System C.

Advantages of System B are as follows:

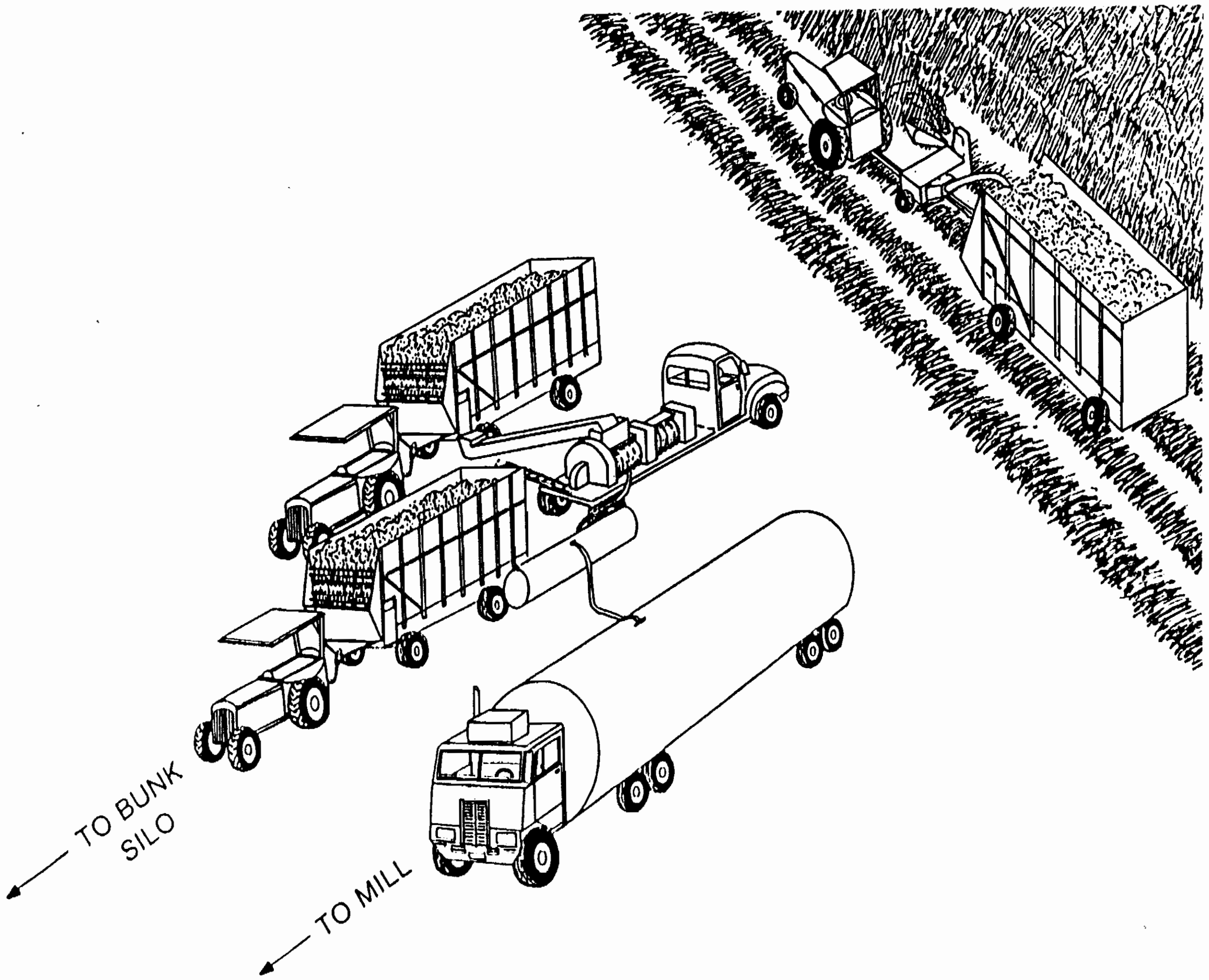

Figure 3. Conceptual drawing of pith combine system (System B)

1. The device to feed stalks from bundles into the processor would be unnecessary because the stalks would be fed directly into the chopper as they are cut. The elimination of this device would be a major advantage since numerous attempts have been made over the last several years to develop an efficient, reliable feeder and these attempts have so far been unsuccessful. The leaves of the sorghum stalks intertwine around other stalks in the bundle. This characteristic makes the job of separating a layer from the bundle extremely difficult.
2. The field loader and stockpile loader would be unnecessary, thus saving equipment costs as well as labor costs.
3. The dump wagons in System A would be replaced by forage wagons which are much more readily available in the Piedmont.
4. System B would only require a crew of four: a pith combine operator, two pith wagon/tractor drivers, and one screw press operator.

The disadvantages of System B are as follows:

1. The pith combine would be unable to operate in soils as wet as the whole-stalk harvester because of the weight of the machine (estimated at 3 Mg) and the weight of the loaded forage wagon (estimated at 13 Mg), which must be towed behind it. The assumption was made that System B cannot operate in a field where the soil moisture is above 95% of field capacity, but the whole-stalk harvester of System A can operate on soils up to 100% of field capacity. (Justification for this assumption is developed in Section 2.6.1.) Bardovsky (1978) found that light field work, such as spraying and fertilizer application could be done at field moisture levels 5% higher than work requiring heavy equipment, such as combining. The whole-stalk harvester is a relatively light piece of equipment and probably is comparable to a sprayer. It was assumed that the pith combine would be similar to a grain combine and, being a heavier machine, will require a soil 5% lower in moisture content for satisfactory trafficability.
2. Once the pith fraction is removed from the stalk, it is highly susceptible to microbial degradation; therefore, the juice must be expressed and the pith presscake ensiled no more than 2 to

3 hours after harvesting. No stockpiling of materials is possible, consequently the processing season ends with the harvesting season.

4.1.3 Combination Harvesting System (System C)

The third harvesting system is a combination of System A and System B. A conceptual drawing of System C is shown in Figure 4. The whole-stalk harvester is used to cut and pile stalks in the field. Then, a mobile processing unit picks up the piles of stalks and feeds them into a chopper/separator. The pith fraction is conveyed into a forage wagon, as is done by the pith combine in System B, and from this point forward, the handling for Systems B and C is identical.

The advantages of System C are as follows:

1. As compared to System A, the field loader and stockpile loader are not necessary.
2. As compared to System B, the crop can be harvested on wetter soils (as in System A) and stored in the field to extend the season.
3. Like System B, System C uses forage wagons which are more readily available than the dump wagons required by System A.

Disadvantages of System C are as follows:

1. Processing can only be done when the soil moisture is at the lower level required by System B. The System C processor would be at least as heavy as the pith combine, and it would also be pulling a 13-Mg forage wagon.
2. System C would still require a device to separate layers of stalks from large bundles (as in System A), and feed these layers into the chopper/separator.

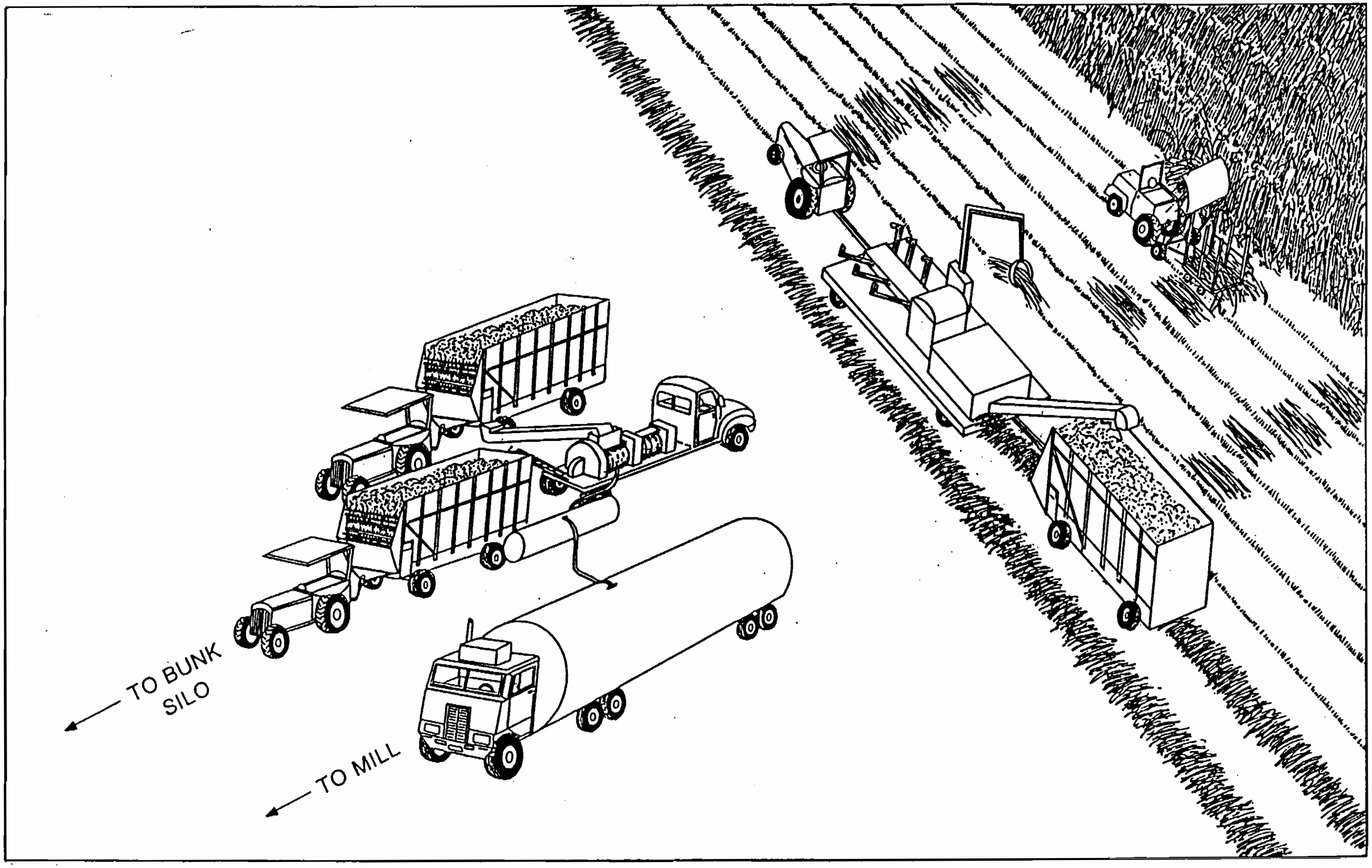

Figure 4. Conceptual drawing of combination system (System C)

3. A grapple loader is required to pick the bundles up from the field and place them into the feeder.
4. A crew of six would be required to operate System C: a harvester operator, a field processor driver, a field processor operator, two forage wagon/tractor drivers, and a screw press operator.

4.2 Weather Generating Submodel

The weather data needed by the soil trafficability submodel are daily minimum temperature, rainfall, and potential evaporation. The location chosen for this study was the Northern Piedmont Experiment Station at Orange, Virginia. This location has a large amount of historical weather data available, including 38 years of rainfall records and maximum and minimum temperature records, and 12 years of evaporation data. The main advantage of choosing this location, however, was the availability of work records which could be used to verify the accuracy of the soil trafficability submodel. As stated earlier, data to calibrate and verify soil trafficability models are scarce.

WGEN (Richardson and Wright, 1984) was chosen to generate maximum and minimum temperatures and rainfall because of its ability to preserve serial and cross correlations between these variables. WGENPAR (Richardson and Wright, 1984) used localized weather data from the Northern Piedmont Experiment Station to generate the parameters required by WGEN. Based on the work done by Baier and Robertson (1965), daily evaporation was predicted by linear regression using maximum temperature, temperature range, and solar radiation at the top of the atmosphere as the regressors. The 12 years of actual evaporation data were used to derive the following regression equation.

$$\mathrm{EVAP} = -0.585 + 0.00755 \times \mathrm{TMAX} + 0.0237 \times \mathrm{RANGE} + 0.0162 \times \mathrm{RO}, \qquad [4.1]$$

where EVAP = estimated potential evaporation (cm), TMAX = daily maximum temperature (° C),

RANGE = daily range of dry bulb temperature (° C), and

RO = Radiation at the top of the earth's atmosphere (MJ/m^2).

Forward selection, backward elimination, and stepwise regression techniques were each used and the results compared to assure the best possible fit. In each case, all three regressors were chosen as having significant effect on the prediction of evaporation. The F statistic values were 447, 190, and 308 for maximum temperature, solar radiation, and temperature range respectively. The P statistic was 0.0001 or less in each case indicating a high level of significance for each regressor. The prediction of evaporation could probably be improved by adding local radiation to the equation as a regressor, but no local solar radiation data were available.

4.3 Soil Trafficability Submodel

The submodel developed by Dyer and Baier (1979) was used to predict soil trafficability because it was designed specifically for the fall harvest season and makes predictions based on the limited amount of weather data available. The computer code for the Dyer and Baier model is included as Appendix C. The model was modified slightly to adapt it to the specific needs of this study. Modifications included the following:

1. The possibility of snow was not included as it is considered highly unlikely to be a significant factor in the Virginia Piedmont in September or October.
2. In the original model, the assumption was made that the soil was trafficable any time the moisture content was below 100% of field capacity. The revised submodel allows the user to supply a critical moisture level (% of field capacity) which is estimated to determine the trafficability of the soil for a given operation. Remember that the field capacity is defined as,

"the amount of water remaining in the soil two or three days after the soil has been saturated and free drainage has practically ceased."

3. In the original model, runoff was neglected since it was assumed not to be a factor during the fall season in Canada. Due to the rolling hills typical of the Piedmont, the revised submodel assumes that no more than 0.5 cm of water can be stored in puddles on the soil surface. Any additional rainfall is assumed to run off.

The basic assumption of the Dyer and Baier model is that two zones are of interest in the soil, zone 1 (approximately 10 cm) at the surface , and zone 2 (approximately 50 cm) underneath zone 1. Zone 1 is of primary interest because it determines whether or not the soil is trafficable. The principle moisture balance equation for each zone is given by

$$S1_i = S1_{i-1} + P_i - PDL_i + PDL_{i-1} + DF_{i-1} - DRN1_{i-1} - ASE_i, \qquad [4.2]$$

and

$$S2_i = S2_{i-1} + DRN1_{i-1} - DRN2_{i-1} - AERT_i - DF_{i-1}, \qquad [4.3]$$

where S1,S2 = plant available water in zone 1,2 (cm),

P = daily rainfall (cm),

:s (cm),

water from zone 1,2 (cm),

(cm),

), and

alled Z tables, which represent the drying characteristics : is below field capacity. When a Z table value is called lant available water as a percentage of field capacity is first calculated. The result is used as a subscript to obtain the corresponding coefficient from the Z table. For instance, if the plant available water were 50% of field capacity, then Z(50) would return the proper coefficient from the Z table for use in the equation. Actual surface evaporation (ASE) and root extracted water (AERT) were estimated by

$$AERT_i = RTX \times Z_2 \times PE_i \times \frac{S2}{C2}, \qquad [4.4]$$

and

$$ASE_i = (Z_1 \times PE_i \times \frac{S1}{C1}) - AERT_i, \qquad [4.5]$$

where C1,C2 = field capacity for zone 1,2 (cm),

Z_1,Z_2 = value from Z table used for zone 1,2,

RTX = root extraction coefficient (decimal)($0 < RDC < 1$), and

PE = potential evaporation (cm).

Root extracted water was assumed to be zero when the smoothed minimum temperature reached 0° C or below since all plants will be dormant at this temperature. Temperature was smoothed with a 5-day binomial function (Baier and Russelo, 1968).

$$TN = \frac{(TMIN_{i-2} + 4 \times TMIN_{i-1} + 6 \times TMIN_i + 4 \times TMIN_{i+1} + TMIN_{i+2})}{16}, \qquad [4.6]$$

where TN = 5-day smoothed minimum temperature(° C), and

TMIN = daily minimum temperature(° C).

Potential evaporation (PE) was estimated by Equation [4.1]. Variable RTX was estimated at 0.1, the value used by Dyer and Baier (1979). The Z table used was table D from Dyer and Mack (1984). This table was used by the authors to describe the soil drying characteristics of a clay soil, and the soil at the Northern Piedmont Experiment Station can be generally described as a clay soil.

Variables C1 and C2 were estimated at 2.54 and 12.7 cm respectively, the values used by Dyer and Baier (1979).

The diffusion between soil layers (DF) is estimated by

$$DF_i = \left(\frac{S2}{C2} - \frac{S1}{C1}\right) \times RDC \times C1, \qquad [4.7]$$

where RDC = redistribution coefficient (decimal)($0 < RDC < 1$).

Variable RDC was estimated at 0.2, the value used by Dyer and Baier (1979).

The surface moisture (PDL) was the amount of water stored on the soil surface. Gravity water drainage out of zone 1 (DRN1) was estimated to be

$$DRN1 = (S1 - C1) \times DRS, \qquad [4.8]$$

where DRS = drainage coefficient (decimal)($0 < DRS < 1$), and

$S1 > C1$.

The drainage coefficient (DRS) was set at 0.7, the value used by Dyer and Baier (1979) for a clay soil. This drainage is also limited by the unfilled void space in zone 2 (V2). V1 and V2 were assumed to be 4.06 and 20.32 cm as in the Dyer and Baier model. Gravity water drainage out of zone 2 (DRN2) was assumed equal to the drainage into zone 2 on the previous day which is also equal to the drainage out of zone 1 (DRN1) on the previous day. In equation form,

$$DRN2 = DRN1_{i-1}, \qquad [4.9]$$

where $DRN2 \leq (S2 - C2)$, and

$S2 > C2$.

Estimation of the initial moisture content of the soil at the beginning of the harvest season is not dealt with specifically by the Dyer and Baier model. Since the weather is being simulated, it is impossible to make physical measurements. A random number for the initial moisture content would provide a lack of bias in estimating this value. However, a dry September has some probability of being preceded by a dry August, so that the initial (September 1) conditions of a particular year should be influenced to some degree by the conditions in August. To account for this influence, yet keep the initial conditions as unbiased as possible, a uniform random value between 0 and 100% of field capacity for both zones was assigned at the beginning of August. Then, the model was run for the month of August in order to simulate the season preceding harvest.

The soil trafficability submodel was run using actual weather data for seven years and the results were compared to work records maintained at the Northern Piedmont Experiment Station at Orange. The work records provided a basis for estimating which days fields were trafficable. They were limited by the fact that they did not include weekends, and the fact that the absence of field work on a given day did not necessarily mean that the field was untrafficable. However, when studied in combination with a record of rainfall, they were very helpful in determining most of the days when the fields were not trafficable.

After the above validation procedure, the submodel was run for 100 years with the criteria that the soil is trafficable at 100% of field capacity and for the same 100 years with the criteria that the soil is trafficable at 95% of field capacity. The output was a yes or no prediction for each day during the harvest season concerning its suitability as a workday.

4.4 Harvest Simulation Submodels

A harvest simulation submodel was developed for each of the three harvest systems. These submodels used the daily minimum temperature and rainfall from WGEN and the output from the soil trafficability submodel to predict how many hectares of sorghum can be harvested and processed in a particular year and how many Mg of by-products and sugar will be produced. Parameters for three major quantities had to be determined or estimated for the models. The distribution of whole-stalk yield over time and area must be known or estimated, the number of hectares which each system can be expected to process must be determined, and the sugar level in the juice must be estimated or assumed. Sugar level varies with weather and plant maturity. All of these factors are random variables which are expected to have a significant effect on the final results. The methods used to achieve a best estimate for these factors is described in the following section.

4.4.1 Parameter Estimation for Simulations

4.4.1.1 Whole-stalk Yield Distribution

The estimated yield, Mg whole-stalks per hectare, was estimated for each hectare using Monte Carlo techniques. The yield of a hectare is a function of at least three variables: weather, soil type at the particular location, and management. The weather tends to be similar for all fields in a given production area (area served by one harvesting operation) for a given year. For instance, a drought would tend to affect all of the fields served by one harvesting operation. Different fields within that production area, however, would be affected by different amounts due to differences in soil type and management.

In the simulations, a yearly mean yield of whole-stalks for a given production area was first generated from an estimated distribution. This yearly mean is indicative of the suitability of a particular growing season for growing sweet sorghum in the production area. The yield of each individual hectare in the production area was then generated from a "within-year" distribution. This distribution gave the variation about the yearly mean. The following function was used to generate these random variates from bounded Johnson distributions.

$$\text{Yield} = \xi + \lambda \times [1/(1 + e^{-z})], \qquad [4.10]$$

where Yield = estimate of the yield of whole-stalks (Mg/ha),

ξ = a location parameter,

λ = a scale parameter,

e = base of natural logarithms,

$z = (sn - \gamma)/\delta$,

sn = a standard normal variate,

γ = a shape parameter, and

δ = a shape parameter.

The parameters for these distributions were estimated using software developed by Wilson (1989). The software package, VISIFIT, estimates generation parameters based on the input of experts who can make an intelligent estimate of some of the characteristics of the distribution. In this case, expert opinions were solicited from Dr. D.J. Parrish of the VPI & SU Crop and Soil Environmental Science Department and from Dr. J.S. Cundiff of the Agricultural Engineering Department. It was estimated that the mean and mode of the yearly mean distribution was 42 Mg/ha and the end points were at 20 and 64. The generation parameters used were ξ = 20.0, γ = 0., λ = 44.0, and δ = 1.338. The curve generated by these parameters is shown in Figure 5. It has a mean and mode at 42.0 and a standard deviation of 7.333.

The within-year variation was generated from a distribution with the mode and mean located at 0., end points located at -20 and +20 Mg/ha, and a standard deviation of 6.666. The yield of each hectare was generated by adding the within-year variation to the yearly mean yield. The generation parameters used for the within-year distribution were ξ = -20., γ = 0.0, λ = 40., and δ = 3.038. The distribution of this random variable is also shown in Figure 5.

The experts consulted were more confident of the location of the mean and the endpoints of the distributions than of the shape (standard deviation); therefore, a sensitivity analysis was done to determine the effect of an error in estimation of the standard deviation of these distributions. By changing the shape parameter, δ, from 1.338 to 3.038, the standard deviation of the yearly mean distribution was narrowed from 7.333 to 3.528. Then, the standard deviation was broadened to 10.42 by changing δ to 0.8294. The resulting distributions are shown in Figure 6. The within-year yield distribution was varied in a similar manner by changing δ from 0.8294 to 1.338 to 3.038 which changed the standard deviation from 9.473 to 6.666 to 3.207, respectively. The resulting distributions are shown in Figure 7.

If the yield estimation for a given hectare was less than 20 Mg/ha, that hectare was not harvested since the yield was considered too low to pay for harvesting costs. Harvesting costs for a conventional forage harvesting operation were estimated at $246/ha based on the work by Maxey et al. (1989b). The value of whole-stalk silage, if fed locally, was estimated in Section 3.4 to be $12.57/Mg; consequently, any yield less than 20 Mg/ha would not pay for the harvesting costs.

Recognizing that the harvesting cost using Piedmont System equipment will be higher than conventional harvesting equipment, it was hypothesized that economics might dictate a higher minimum yield for harvesting. In other words, if the yield of a hectare were less than 30 Mg (termed the low-yield cutoff), it might be more worthwhile to harvest it with conventional equipment for silage and use the Piedmont System equipment on the higher yielding fields. Additional runs of the three models were made with the low-yield cutoff set at 25 and 30 Mg/ha to test this hypothesis.

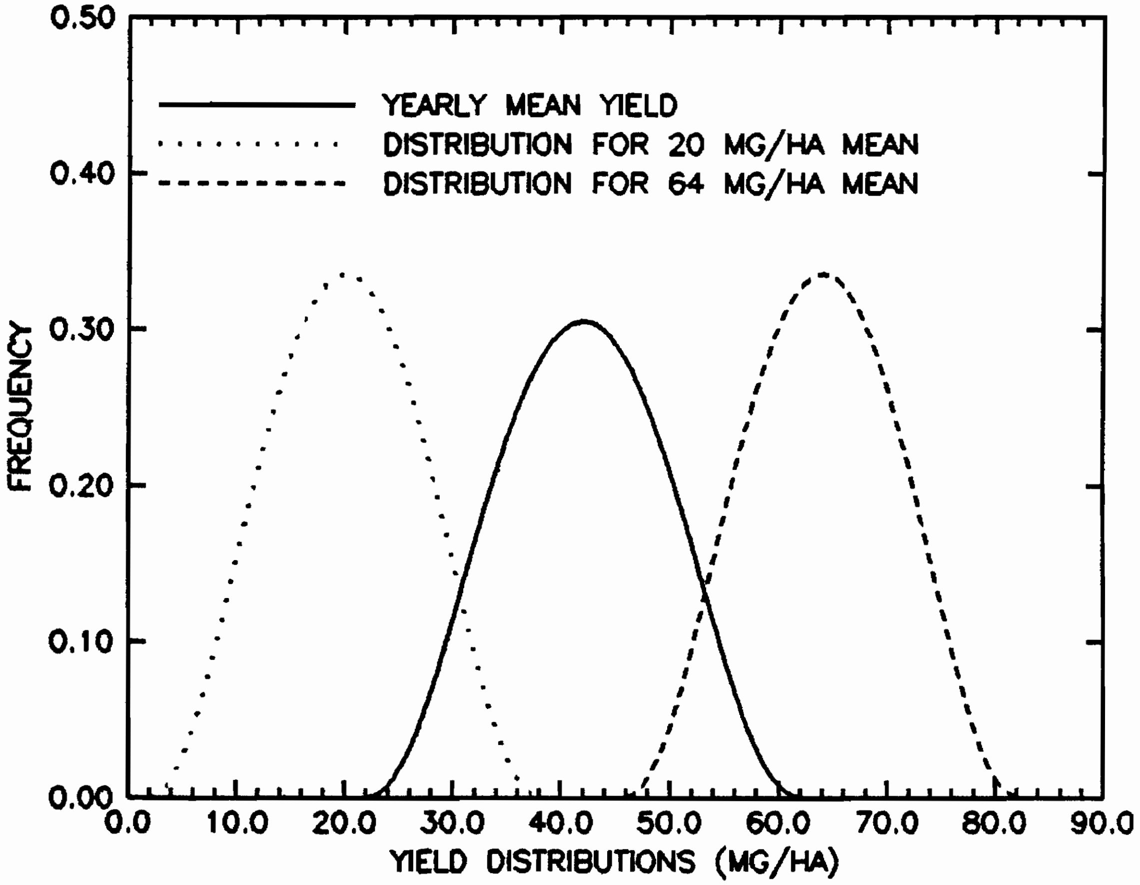

Figure 5. **Estimated distribution of whole-stalk yield (Mg/ha)** The solid line represents the distribution of the yearly mean yield. The dotted line represents the within-year distribution if the yearly mean yield is 20 Mg/ha. The dashed line represents the within-year distribution if the yearly mean is 64 Mg/ha.

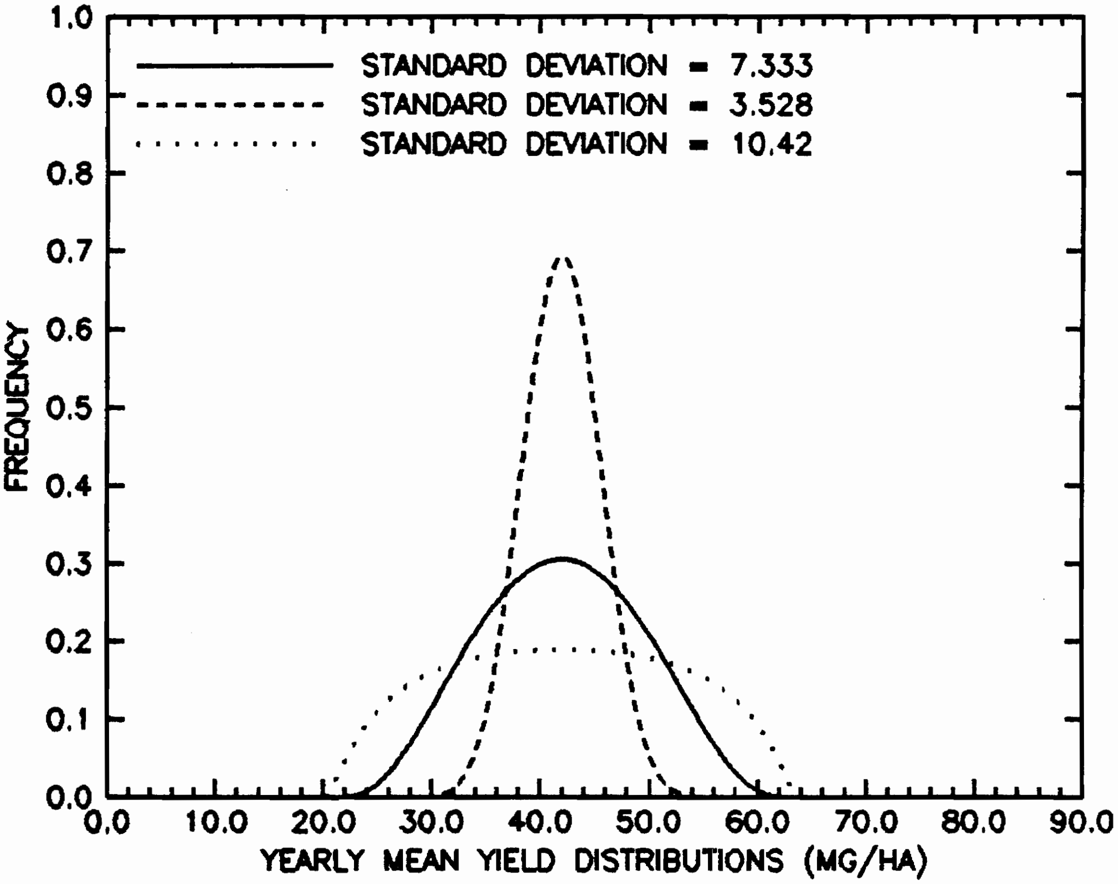

Figure 6. Yearly mean distributions used in sensitivity analysis

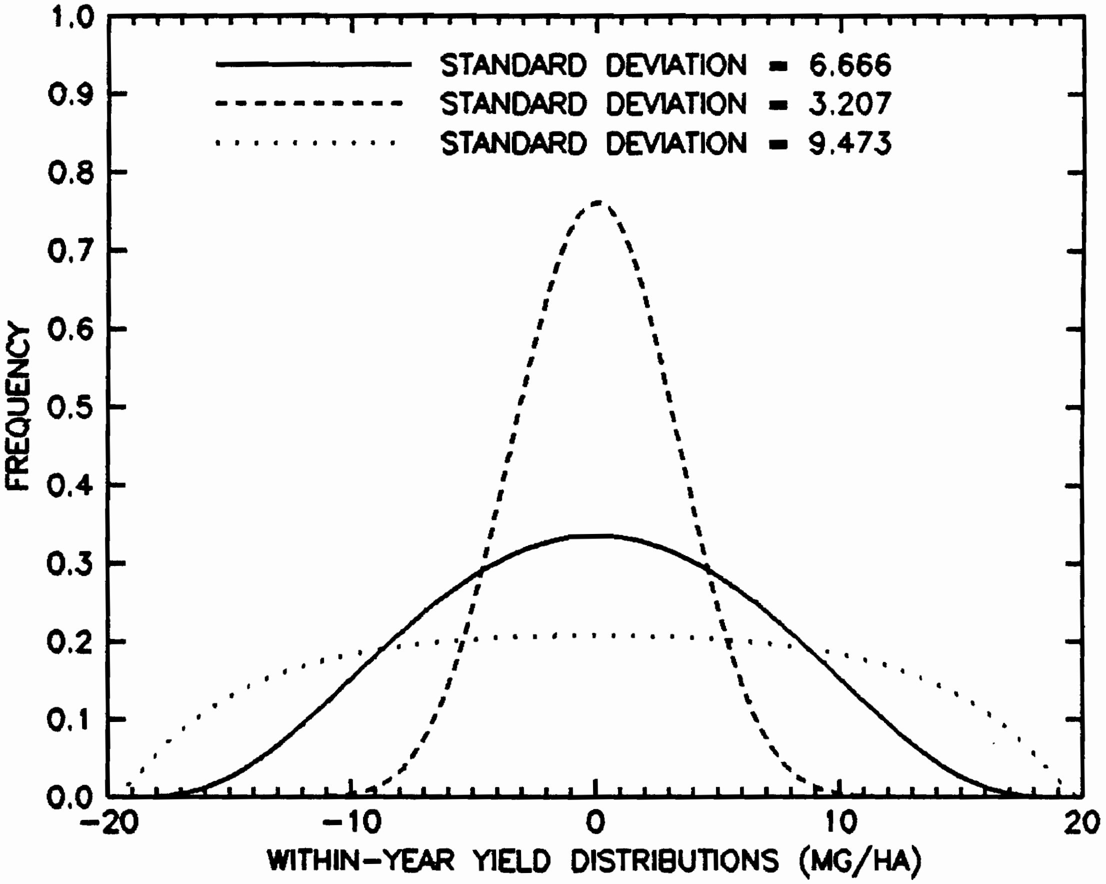

Figure 7. Within-year distributions used in sensitivity analysis

4.4.1.2 Number of Hectares Planted for Each System

Harvest simulations were run for each of the three systems; A, B, and C; and they yielded estimates of how many hectares of sorghum could be harvested and processed by that system if an unlimited amount (200 ha) of sorghum had been planted. The harvest simulations were run for 100 years and the number of hectares harvested each year by each system was recorded. It was assumed initially that it would be desirable to plant only enough hectares so that all of the sorghum could be harvested 90% of the years. The number of hectares which can be harvested 90% of the years (90% confidence level harvest area) was determined from the first 100-year run of each submodel, then the submodels were rerun with the assumption that this 90% confidence level harvest area was planted each year. When the total planted area could not be harvested by the system (A, B, or C), the unharvested area with a yield over 20 Mg/ha was harvested by a conventional silage system at a cost of $246 per hectare, and the resulting silage was valued at $12.57/Mg based on its value as a cattle feed.

The number of hectares planted has at least three effects on the cost: (1) The production cost will increase in direct proportion to the planted area. (2) When a larger area is planted, there will be more years when all of the crop cannot be harvested by the Piedmont System due to weather conditions. (3) More hectares will be harvested during the favorable seasons, lowering the unit cost of a liter of ethanol for those years. A sensitivity analysis was done to assess the net effect of planted area on cost per liter of ethanol. The confidence level for harvest area was reduced from 90% to 40% at intervals of 10%. The results were then analyzed to determine the effect of planted area on overall costs. Using this procedure, a different size production area was determined for each of the three systems; A, B, and C; depending on the capabilities of each system.

4.4.1.3 Changes in Sugar and By-product Yields During Season

The yield of sugar is dependent on the juice Brix (mass of sugar as a fraction of juice mass) at the time of processing. The juice sugar was estimated to be 12.5° Brix on September 1, and it increased at the rate of 0.1° Brix per day until fully ripe on October 15 (Neuse and Hunt, 1983; and Freeman et al., 1986). Once mature, the sugar content dropped 0.1° Brix per day until the end of October, the end of the harvest season. If a frost occurred (defined as 2° C) before maturity, sugar content was assumed to drop slowly at the rate of 0.05° Brix per day. If a hard freeze occurred (-2° C), it was assumed to drop rapidly at the rate of 0.2° Brix per day. If the sugar level dropped below 10° Brix, harvest was halted, since the quality of the juice was considered too poor to continue harvesting.

Once the stalks were cut, the daily increase in Brix was halted. There is not widespread agreement concerning the rate of decrease in sugar content of harvested stalks. The rate of decrease seems to be a function of the weather, and perhaps other unknown factors, but has not been accurately determined. Based on the work of Brinkley (1984) and Cundiff and Parrish (1985), described in Section 2.6.3, a reasonable estimate appears to be a Brix decline of 0.05° per day after cutting, and this value was used. The dry matter of stored stalks will also decrease somewhat. Each day, the model reduces the amount of dry matter in the stalks awaiting processing by multiplying the amount of by-products per Mg of whole-stalks by 0.995 (0.5%/day reduction). This value was based on the work by Brinkley (1984).

4.4.2 Submodel Descriptions

The submodels were written in SLAM II and were combined network and discrete event models. A conceptual flow diagram of the harvest simulation submodels is shown in Figure 8. At the be-

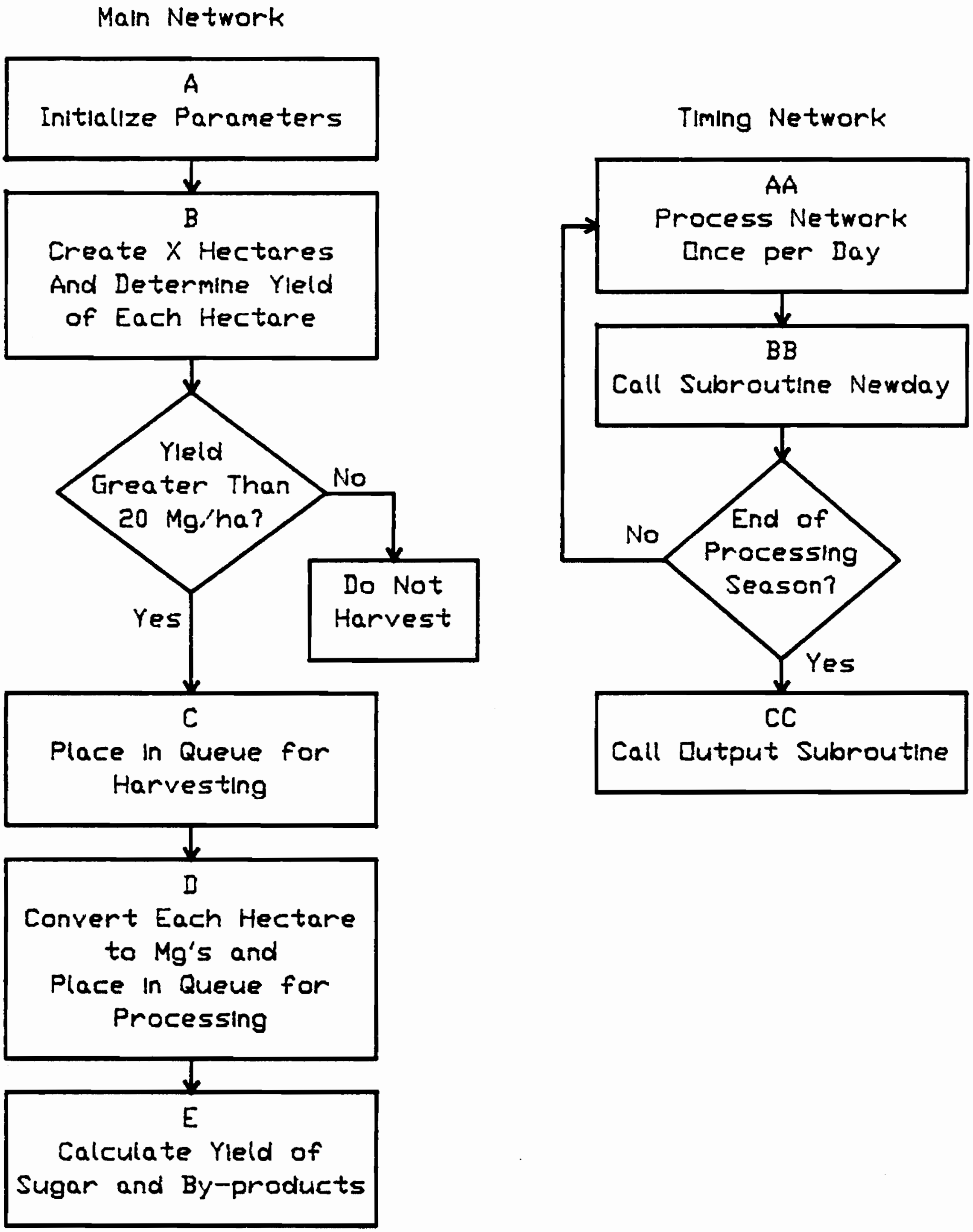

Figure 8. Conceptual flow diagram for harvest simulation models

ginning of each simulated year, block A in the main network initialized the juice sugar level at 12.5° Brix and generated the mean yield for that year. Then block B created X hectares (the number of hectares which were expected to be harvested by the system being modeled during the season) and generated the yield of each hectare created. If the yield of a hectare was less than 20 Mg, it was not harvested. Hectares with yields greater than 20 Mg were put into a queue waiting to be harvested (block C).

After a hectare was harvested, it was divided into X one-Mg units, X being the yield determined by block B. Each one-Mg unit was then placed into a queue waiting for processing (block D). In Systems A and C, this queue represented stalks which had been harvested and stockpiled and were waiting to be processed. In system B, the stalks were not stockpiled. Each hectare waited in queue (block C) until the harvester was ready to harvest it, then it was converted into one-Mg units, and put into another queue as in Systems A and C. The System B one-Mg unit queue only held the production from one hectare, which reflects the fact that the material was processed quickly after it was harvested. By using this mechanism, the number of hectares remaining at the end of the season could be determined. If the crop were all converted to one-Mg units at the beginning of the simulation, it would be impossible to determine how many hectares were left unharvested at the end of the save.

After the stalks were processed, the mass of juice and by-products derived from each Mg of stalks and the sugar level of that juice at the time of processing were stored in memory. These data were later used by SLAM II to calculate sugar and by-product yields for the year.

The timing network created one entity per day (block AA) and sent it through the network. When it reached block BB, subroutine NEWDAY was called. NEWDAY determined, from information supplied by the soil trafficability submodel, whether or not the harvester and/or processor could operate that day. It also reserved one day out of every 10 work days for moving the equipmentto a new site. In addition, it determined when a frost or a hard freeze occurred. It was assumed that a frost occurred when the minimum temperature was less than or equal to 2° C and that a hard freeze occurred when the minimum temperature dropped to -2° C or below. The sugar level in the juice was then lowered by the model according to the assumptions made in the previous section. If stalks were stored in stockpiles (Systems A and C), the sugar level of the juice and the dry matter levels of the by-products were lowered daily as well. Subroutine NEWDAY was also used to end the harvesting season on October 31 by making the harvester unavailable after that date.

The processing season ended on November 30 when 91 entities (days) have been sent through the timing network. At this time, the output subroutine was called. This routine used the information collected in block E of the main network to calculate the number of Mgs of sugar and by-products produced, the number of hectares harvested by the Piedmont System, the number of hectares and the number of Mgs which had to be harvested conventionally for silage, and the number of hectares rejected (below 20 Mg/ha yield). The output subroutine also recorded the number of days the harvesting components and/or the processing components were operated. An additional function performed by the output subroutine was the maintaining of common random numbers for the sensitivity analyses as described below.

In performing sensitivity analyses, it is important to keep as many factors as possible common between the systems being compared. It was desirable to use the same set of within-year yields for each of the systems. Therefore, the output subroutine called the random variate generator (200 – X) times, X being the number of years that were simulated for the system. In this manner, the random variate generator was called 200 times for each simulated year, regardless of how many hectares were planted for that system, and each year began with the same random number string for within-year yield. The same yearly mean yields were used for each of the three systems simply by using the same SLAM II random number string to generate these values. The same weather data was also used for each system. These three factors, weather, yearly mean yield, and within-year mean yield were the random variable inputs to the models, and therefore common random numbers were maintained. The only exception to this policy was caused by the necessity of generating a different number of hectares for each system. If, for instance, 120 hectares were generated for System B and 160 for System A, the within-year yield for hectare number 135 might be a value in the extreme tail of the distribution, which would shift the mean slightly. This exception to common random numbers was unavoidable due to the nature of the models.

The following sections describe details which are specific to each of the three system models. Network flow diagrams are shown for each model providing a higher level of understanding to the reader who is familiar with SLAM II network symbol notation. A detailed explanation of these symbols is given in Pritsker (1986).

4.4.2.1 Crossroads System (System A) Submodel

The whole-stalk harvester used in System A was light enough that it could be operated when the soil moisture content was at 100% of field capacity. Consequently, the submodel for System A used the data set (days when harvesting could occur) calculated with the trafficability submodel using a critical soil moisture content equal to 100% of field capacity. Simulation of the harvest began on September 1. Each hectare planted was assigned a yield and placed in a queue (called HARVQ) on September 1, provided the yield was 20 Mg/ha or more. Also assigned at this time were estimates of the yield of by-products from each Mg of stalks processed. The rind-leaf and pith presscake fractions were combined and ensiled in System A. The by-product yield estimate was 0.54 Mg silage per Mg whole-stalks processed based on the by-product analysis in Section 3.3.1.

In the simulation, the whole-stalk harvester cut sorghum as long as stalks were available, the trafficability model indicated that the soil was trafficable, it was not a moving day (day for moving from one location to the next), and November 1 had not passed. If any of these conditions were not met, subroutine NEWDAY made the harvester unavailable.

The harvester had an estimated capacity of 0.3 ha/h. A 16-hour (2 shift) workday was used, and with stops for maintenance, lunch breaks, and other non-productive time, 14 productive hours per day were available; therefore 4.2 hectares were harvested per workday. This value is equivalent to a harvesting rate of 0.24 days/ha. The time to harvest one particular hectare would, of course, be a random number, but since only limited data is available on the performance of the prototype harvester, it was not felt that the accuracy of the model would be improved by guessing at the characteristics of this random variable.

After a hectare was harvested, SLAM II divided the total harvest from that hectare into 1-Mg units. These 1 Mg units were put into a queue (called PROCQ) waiting to be processed. The processor was assumed to be able to operate any day that rainfall was less than 2.54 cm and stalks were available. If either condition was not met, the processor was made unavailable. The processor had an assumed capacity of 8 Mg/h. At 14 productive hours per day, 112 Mg of material will be processed, therefore it will take an average of 0.009 days to process a Mg of stalks. After 91 days (end of November), the simulation was halted and the data printed. The simulation for each harvest season proceeded in this manner. The network diagram for the submodel of System A is given in Figure 9, and the SLAM II computer code is given in Appendix D.

4.4.2.2 Pith Combine System (System B) Submodel

The submodel for System B was much like that for System A with the following exceptions. The processing season, like the harvesting season, ended on October 31. The data set used was based on a critical soil moisture of 95% of field capacity. Each hectare of sorghum stalks ready for harvest waited in queue HARVQ until it was ready to be harvested. Then, this hectare was converted to one-Mg units and harvested by the pith combine at the rate of 0.009 days per Mg. The capacity of System B was limited by mass of material rather than area covered. Since the stalks were not stored, no storage losses were calculated for the juice Brix or stalk dry matter. The rind-leaf fraction was assumed to be handled like hay. The estimates of by-product yields used were 0.07 Mg rind-leaf hay per Mg whole-stalks and 0.27 Mg pith presscake silage per Mg of whole-stalks. The network diagram for the submodel of System B is given in Figure 10, and the SLAM II computer code is given in Appendix D.

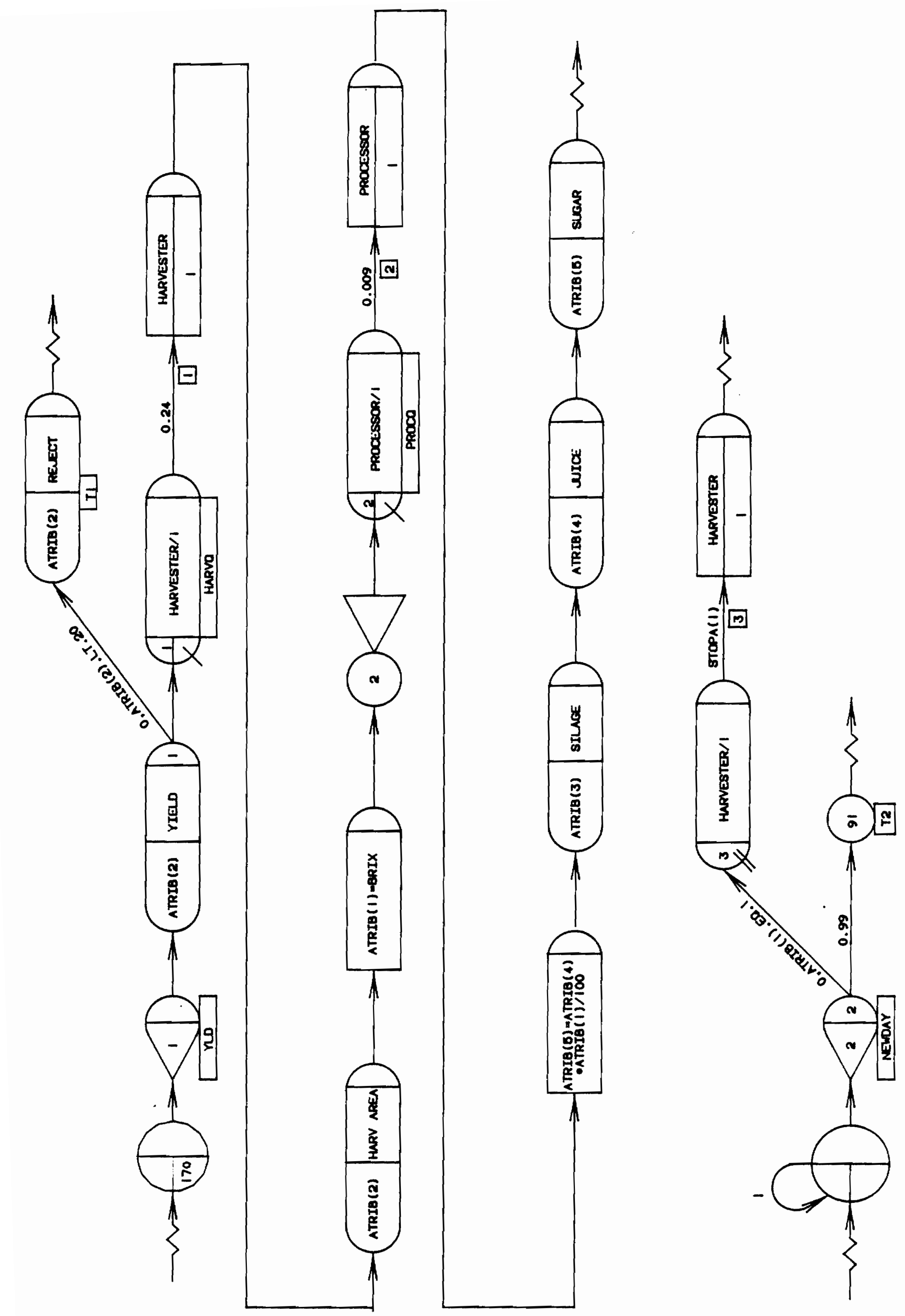

Figure 9. SLAM II network diagram for System A

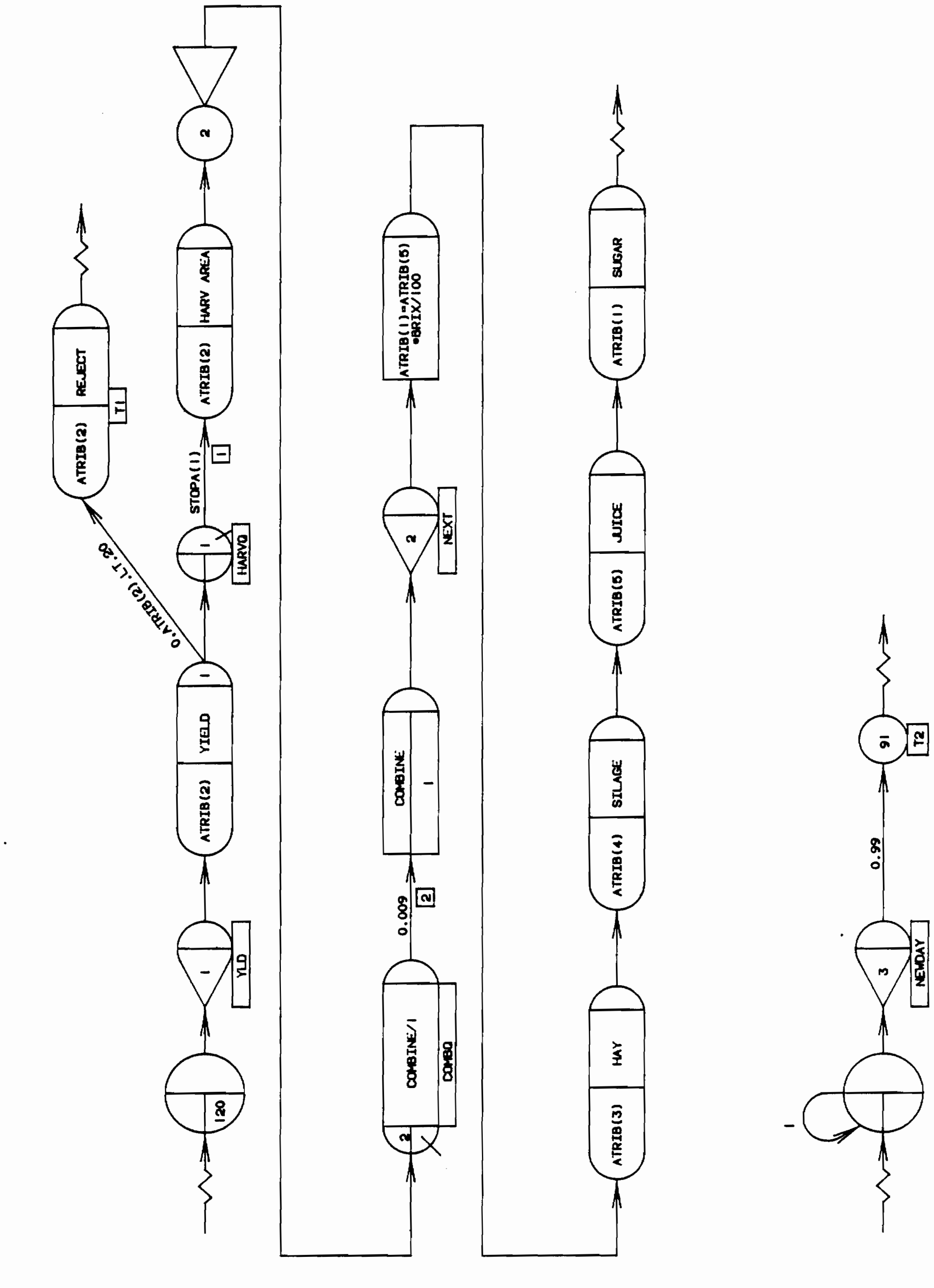

Figure 10. SLAM II network diagram for System B

4.4.2.3 Combination System (System C) Submodel

The submodel of System C is like that of System A except for the following changes. The data set used for harvesting day determination was based on a critical moisture content of 100% of field capacity. The 95% field capacity data were used to determine which days the processor could operate. Also, the rind-leaf was assumed to be handled like hay as in System B, so the same assumptions are used for by-product yield as in System B. The network diagram for the submodel of System C is given in Figure 11, and the SLAM II computer code is given in Appendix D.

4.5 Economic Submodel

The overall purpose of the economic submodel was to determine the probability distributions of the feedstock cost per liter of ethanol produced from the sweet sorghum juice collected with each of the three systems. This cost is a random variable which is determined by a number of factors, which are themselves random variables. Weather is the random variable which causes the most variation in cost per liter, affecting both yield and harvestability of the crop.

The concept was to generate random events which might occur in a given operating year. This process was repeated 100 times (100 years), and the resulting data were analyzed to estimate the cost-per-liter probability distribution. Each year was a real-time simulation. The events of one day were affected by the events of previous days within that year, but the events of each year were independent of the events of previous years. Each year, then, was an independent simulation. The objective was not to simulate the operation for 100 consecutive years, but rather to be able to predict the expected mean cost per liter and the probability that the cost per liter will be greater than $X for any given year, where $X might represent a break even cost or a cost above which a firm might not survive.

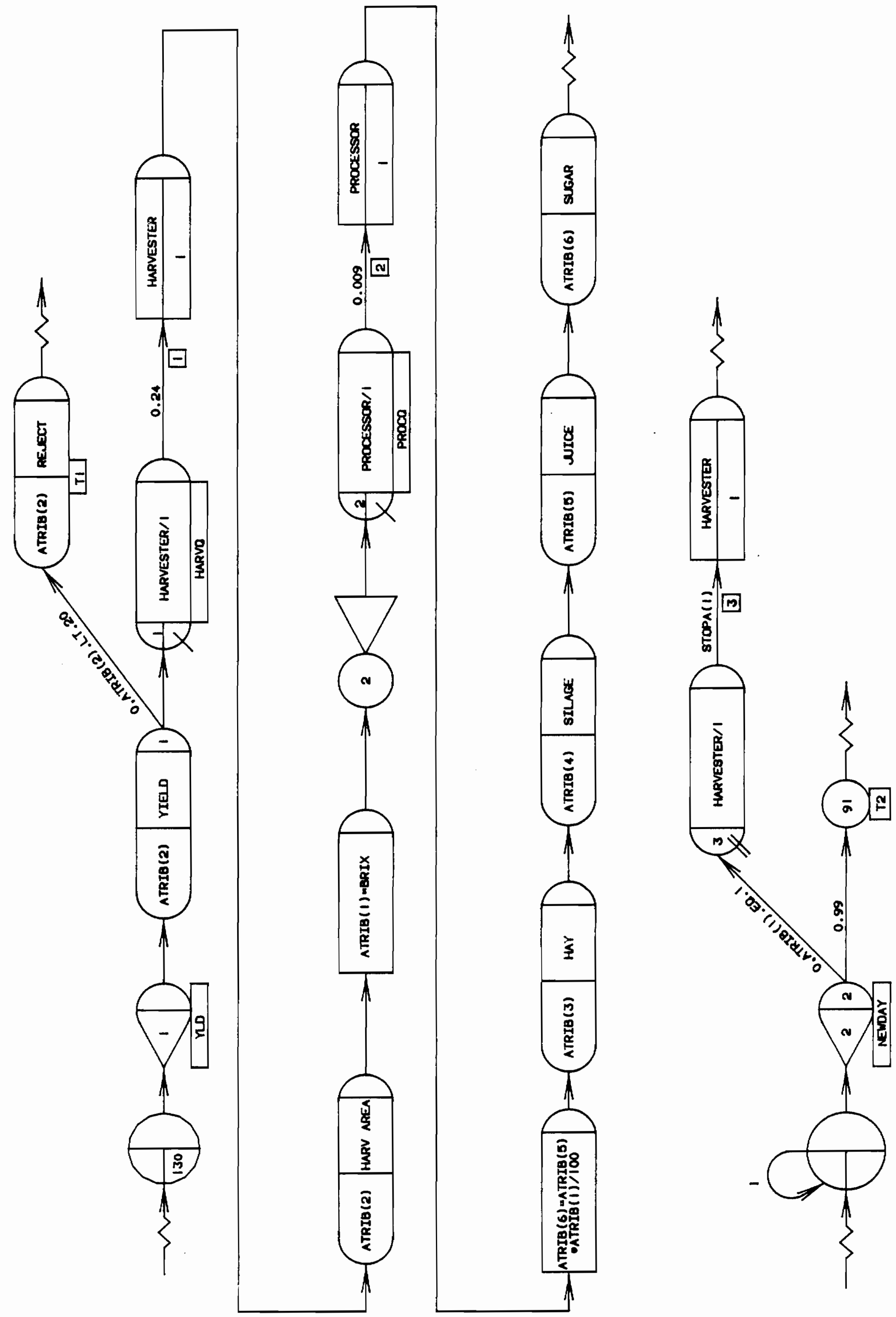

Figure 11. SLAM II network diagram for System C

The model is an attempt to establish the costs that will be incurred. It does not include any profit for the farmer or the processor. While it is recognized that profits are necessary to provide incentives to all parties involved, the amount of profit to be made and the way it will be divided among the parties is beyond the scope of this study.

A listing of the economic submodel program is included as Appendix E, and a block diagram of the submodel is shown in Figure 12. To begin the simulation, the system description data was read from a file. The system description data consisted of the cost, estimated life (h), estimated maintenance costs, power requirements, and the number of operators of each piece of equipment required for the system being simulated. Also included was the number of hectares planted and the value of the by-products ($/Mg). The program first read in the equipment used in the harvesting stage and then the equipment used in the processing stage. This was done so the costs of the two stages could be accounted for separately.

After this data was read, the program performed the calculations for each year simulated. The simulation data from one simulated year was read from the output of the harvest simulation submodel. This included the number of Mg of sugar, juice, and by-products produced, the amount of sweet sorghum (ha and Mg) which could not be harvested due to weather conditions, and the number of days which the harvesting and/or processing equipment was operated. The fixed and operating costs for the equipment and the labor cost were then calculated using subroutine COSCAL. (The details of these calculations are explained in Sections 4.5.2 and 4.5.3.) These calculations were used to determine the total cost of harvesting and processing for a season. The cost of transporting the juice to an evaporation plant was added, the cost of growing the crop (including that not harvested) was added, and the value of the by-products was subtracted. This net cost figure was further adjusted by adding the cost of using a conventional forage harvester to harvest the area that could not be harvested with the Piedmont System due to wet weather, and subtracting the value of the silage produced. The total production of ethanol was then calculated and used to determine the cost per liter of ethanol for the simulated year. Since the number of hectares

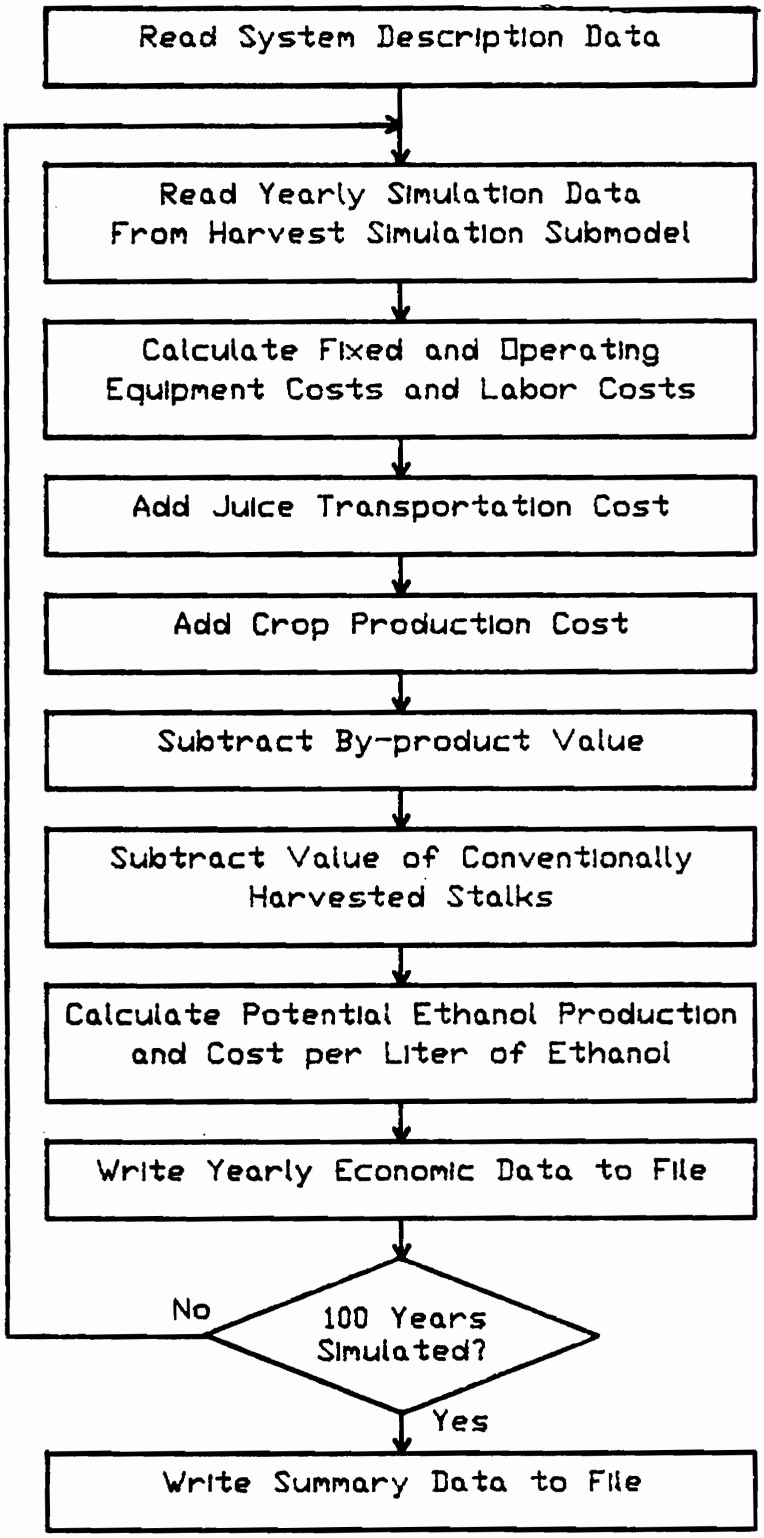

Figure 12. Block diagram of economic submodel

planted for each system were determined by the sensitivity analysis described in Section 4.4.1.2, this feedstock cost per liter of ethanol was considered to be the optimal cost for each system.

4.5.1 Equipment Cost Estimates

To objectively compare the overall costs of the three harvest systems, the investment cost for the equipment used by each system, as well as the expected life of the equipment, had to be estimated as accurately as practical. Much of the equipment in the three systems has yet to be invented; consequently, establishment of the costs is at best a "best guess" estimate. Prices of commercially available equipment were obtained from local farm equipment dealers and equipment catalogs. Attempts were made to obtain cost figures equivalent to what an individual would probably pay rather than list price or a special discounted price. The cost of unique equipment designed specifically for one of the three systems was determined using an estimated cost of \$6.60/kg of projected mass (Brantley, 1990). This figure is used by Amadas Industries, a company that manufactures peanut harvesting equipment and irrigation equipment, to estimate the projected cost of a new model machine. It includes the cost of engineering, materials, and fabrication and is considered to be a reasonable estimate of the cost to build farm equipment containing a moderate amount of hydraulics and mechanical drives. Amadas Industries has developed this figure for production of machines with expected sales of only 20 to 25 units per year. The scale of the hypothesized sweet sorghum-for-ethanol industry would initially be quite small, probably in the range of 20 to 25 units per year; consequently a cost estimate for this level of production is appropriate.

4.5.1.1 System A Equipment

A prototype whole-stalk harvester was developed by Rains (1989). This machine, which is approximately 85% complete, weighed 1.72 Mg. Ultimately, the production harvester will include a bin to accumulate a bundle of stalks for dumping into a windrow (Figure 2). This bin, or accumulator, has not been built so its mass was estimated. A production whole-stalk harvester would be somewhat lighter in overall design than the current prototype based on what has been learned from the prototype. Considering these facts, the harvester is expected to weigh 2 Mg. At $6.60/kg, the estimated cost of the harvester is then $13,200. It is expected to be similar to a corn picker in complexity and function and is therefore expected to have a similar service life. Based on ASAE Standard D230.4, the service life was assumed to be 2,000 hours, and a repair and maintenance cost of 70% of the purchase price over the total life of the machine was assumed. The harvester requires a 40 kW tractor to operate it, and the cost of this tractor was assumed to be $16,000. The service life of all tractors used in any of the three three systems was assumed to be 10,000 hours, and the lifetime repair cost was set at 120% of the purchase price, based on ASAE Standard D230.4. Tractors can be used for a number of other applications during the 10 months of the year when they are not being used for harvesting sweet sorghum. The amount of other uses could vary tremendously, however it was assumed for the purpose of this analysis that all tractors are used an average of 500 h/yr for operations other than sorghum harvest.

System A requires a field loader to load stalks onto a dump trailer for transport to the storage pile and a smaller loader to load stalks from the storage pile into the processor. The costs of the 42 kW field loader and the 32 kW loader which feeds the processor were estimated at $25,000 and $24,000, respectively. Since these machines are similar to tractors, the same values (10,000 hour service life and 120% of purchase price for lifetime repair cost) were used. These machines could be used for other purposes, but they are more specialized than a tractor. The assumption was made that these loaders are used 400 h/yr for uses other than sorghum harvest. The dump trailers had an estimated cost of $9,000 each and an expected life of 3,000 hours based on the estimate for a wagon in ASAE Standard D230.4. The estimated lifetime repair cost was 80% of purchase price. These wagons might have other uses, and an estimate of 100 h/yr for uses other than sorghum harvest was assumed. The wagons are pulled by 34 kW tractors which cost $14,000 each.

The processor for System A consists of the following components (with their approximate masses): chopping mechanism (1 Mg), separator (0.5 Mg), conveyors (0.5 Mg),and stalk feeder (1.5 Mg). The approximate total mass of the processor was then 3.5 Mg, and using the \$6.60/kg figure, the estimated cost was \$23,100. The processor is mounted on a trailer and the cost of the trailer was estimated at \$10,000. The total cost of the processor, less the engine to power it, was \$33,100. The service life of this equipment was estimated at 5,000 hours. Since the processor would be stationary when operated, it should have a longer life than most field equipment, but would not last as long as a tractor. The lifetime repair cost was taken as 90% of purchase price based on the figure for a combine in ASAE Standard D230.4. To drive the processor, a 45 kW engine with an expected cost of \$6,000 is required. This engine drives a pump drive with two hydraulic pumps. The cost of the pump drive and pumps was \$4,000, and the total cost of the power unit (engine and hydraulic pumps) was then \$10,000. The service life of this power unit was expected to be 10,000 hours and the lifetime repair costs were taken as 120% of purchase price based on ASAE Standard D230.4.

The screw press required for System A is a 30.5-cm diameter heavy duty press, costing approximately \$60,000 and having a capacity of approximately 4.5 Mg/h of pith material. The unit is mounted on a trailer expected to cost \$8,000. The expected life was 15,000 hours. The press only has two parts which experience significant wear, the screens and the screw. The screens are replaced periodically and the screw can be resurfaced or replaced, so that the press has a very long life compared to other equipment. The lifetime repair costs were taken as 100% of purchase price. A 30 kW engine, with an expected cost of \$4,000, is required to drive the screw press. The expected service life of this engine was 10,000 hours and the lifetime repair costs were taken as 120% of the purchase price.

The juice handling equipment consists of an 8,000 liter tank mounted on a trailer, along with a pump and the necessary hoses and fittings. The cost of this unit was expected to be \$5,000 and the service life was taken as 10,000 hours. Since the unit will be stationary most of the time, a long service life is expected. Lifetime repair costs were taken as 100% of purchase price.

4.5.1.2 System B Equipment

System B requires the same screw press and juice handling equipment as System A. The two dump trailers in System A are replaced in System B by three silage wagons valued at $8,500 each. The service life of these wagons was assumed to be 3,000 hours. These silage wagons can be used in the winter for feeding cattle and in the summer for harvesting grass forage crops, so they were assumed to be used 300 h/yr for uses other than sorghum harvest. The same tractors which pulled the dump trailers in System A can pull the silage wagons in System B. The pith combine is basically a forage harvester with a separator added. The cost of a one-row forage harvester is approximately $16,200 and the cost of the separator was taken to be $3,300; therefore, a value of $20,000 was used for the total cost of the pith combine. The expected life was 2,000 hours and the lifetime repair costs are taken as 80% of purchase price based on the values given for a silage harvester in ASAE Standard D230.4 (1988). A 79 kW tractor is required to operate the pith combine. This tractor was expected to cost $35,000 and have a service life of 10,000 hours.

4.5.1.3 System C Equipment

System C utilizes the same harvester, screw press, and juice handling equipment as System A. It uses the same silage wagons as System B. The only new item in System C is the mobile processor unit. The processor is the same as in System A except that the power unit is replaced by a PTO driveline, and a knuckle-boom loader has been added to load the stalks into the processor. The drive system, which includes a PTO drive shaft, a gear box, and a hydraulic drive package, was expected to cost $5,000. The knuckle-boom loader was valued at $12,000. The trailer cost was approximately $10,000 as in System A. Summing all these costs, the total cost of the System C processor was $50,100. Since the mobile processor will be used in the field, it was assumed to have a service life similar to that of a combine. A service life of 2,000 hours and a lifetime repair cost of 90% of purchase price were used based on values in ASAE Standard D230.4 for a combine.

4.5.1.4 Summary of Equipment Costs

All of the equipment was estimated to have a salvage value of 10% of the purchase price at the end of the service life, except for the harvester, the pith combine, and the processor. These highly specialized machines would have little value for other uses and were assumed to have a salvage value of 5% of purchase price. Information on the cost, expected life, assumed repair cost, and power and labor requirements for each of the three systems is summarized in Table 6.

4.5.2 Fixed Costs

The capital cost recovery method of calculating depreciation and interest recommended by Boehlje and Eidman (1984) was used. The expected life of each machine in hours was divided by the number of hours the machine was used for a given simulated year. The result was the expected lifetime of that machine in years, and this was used as the service life to calculate the capital cost recovery expense for that machine for that simulated year using Equations [2.2] and [2.3].

Since the submodel is not attempting to model 100 successive years, but rather the probability distribution for one year, inflation was not considered. Equipment cost figures were based on present value, and real interest rate was used rather than nominal, or charged, interest as recommended by Boehlje and Eidman (1984). The real interest rate was determined as follows. The National Agricultural Statistics Service (1989) gave price deflators for various farm equipment categories based on 1977 prices. Tractors and self-propelled machinery had a deflator of 178 in 1985 and 181 in 1988. These figures show inflation of 3% in three years or a current inflation rate of approximately 1% per year. Other farm machinery had a deflator of 183 in 1985 and 197 in 1988 indicating a much higher inflation of 14% over three years or approximately 4.67% per year. The Board of Governors of the Federal Reserve System (1990) showed the current nominal rate of interest on 1-year U.S. Treasury Bills as approximately 7.9% during the last half of 1989. The real

Table 6. Estimated cost factors for three harvest systems

Item	Cost/Unit ($)	Service Life (h)	Other Usage (h)	Maintenance (% of Purchase)	Number of Operators	Number of Units
		System A				
Harvester	13,200	2,000	0	70	0	1
40 kW Tractor (Harvester)	16,000	10,000	500	120	1	1
42 kW Field Loader	25,000	10,000	400	120	1	1
Dump Trailer	9,000	3,000	100	80	0	2
34 kW Tractor (Trailer)	14,000	10,000	500	120	2	2
32 kW Loader	24,000	10,000	400	120	1	1
Processor	33,100	5,000	0	90	1	1
45 kW Power Unit (Processor)	10,000	10,000	0	120	0	1
Screw Press	60,000	15,000	0	100	0	1
30 kW Power Unit (Press)	4,000	10,000	0	120	0	1
Juice Equipment	6,000	10,000	0	100	0	1
Total Equipment Cost	237,300			Crew Size	6	
		System B				
Pith Combine	20,000	2,000	0	80	0	1
79 kW Tractor (Combine)	35,000	10,000	500	120	1	1
Silage Wagon	8,500	3,000	300	80	0	3
34kW Tractor (Wagon)	14,000	10,000	500	120	2	2
Screw Press	60,000	15,000	0	100	1	1
30 kW Power Unit (Press)	4,000	10,000	0	120	0	1
Juice Equipment	6,000	10,000	0	100	0	1
Total Equipment Cost	178,500			Crew Size	4	
		System C				
Harvester	13,200	2,000	0	70	0	1
40 kW Tractor (Harvester)	16,000	10,000	500	120	1	1
Mobile Processor	50,100	2,000	0	90	1	1
79 kW Tractor (Processor)	35,000	10,000	500	120	1	1
Silage Wagon	8,500	3,000	300	80	0	3
34 kW Tractor (Wagon)	14,000	10,000	500	120	2	2
Screw Press	60,000	15,000	0	100	1	1
30 kW Power Unit (Press)	4,000	10,000	0	120	0	1
Juice Equipment	6,000	10,000	0	100	0	1
Total Equipment Cost	237,800			Crew Size	6	

rate of interest was calculated using 7.9% as the nominal interest rate and 2.8% as the average inflation rate. Using these values in Equation [2.1], a value of 5% was obtained. This figure might be somewhat low since the Treasury Bill rate is a "no risk" interest rate, and a higher rate would probably be charged on a business loan. However, a strong possibility exists for government incentives for an operation of this type. Such incentives could lower the effective real interest rate to 5% or lower. Given these uncertainties, the rate of 5% was used in the analyses.

Other fixed costs include taxes, insurance, and housing for the equipment. The cost of these expenses was estimated as 2% of the purchase price as recommended by ASAE Engineering Practice EP391.1 (1988).

4.5.3 Operating Costs

Operating costs include repairs, maintenance, and fuel. Repairs and maintenance cost was calculated by

$$\mathrm{CRM} = \mathrm{EMAINT} \times \mathrm{PURCH} \times \frac{\mathrm{USE}}{\mathrm{YRSLIFE}}, \tag{4.11}$$

where CRM = cost of repairs and maintenance for a given year ($),

EMAINT = lifetime repair and maintenance cost (% of purchase price),

PURCH = purchase price of machine ($),

USE = fraction of total use assigned to harvesting operation, and

YRSLIFE = estimated life of machine (yrs).

Powered equipment was expected to operate at an average of 75% of rated power. The Nebraska Tractor Tests (1982) were consulted to determine the fuel consumption rates for several tractors with power ratings similar to those required for the three harvesting systems. An average consumption rate of 0.4615 L/kW • h was determined for tractors operated at 75% of rated power. The yearly cost of fuel was calculated by

$$\mathrm{FUEL} = 0.75 \times \mathrm{POWER} \times \mathrm{C} \times \mathrm{HOURS} \times \mathrm{FCOST}, \qquad [4.12]$$

where FUEL = cost of fuel ($/yr),

POWER = rated power of machine (kW),

C = fuel consumption constant (L/kW • h),

HOURS = number of hours machine is used in a year, and

FCOST = cost of fuel ($/L).

The cost of labor was $5.50/h, including benefits, based on information from VASS (1988). Two shifts (16 hours) were worked each day that work occurred, including moving days.

4.5.4 Juice Transportation Cost

The cost of transporting juice to a central plant was calculated by

$$\mathrm{TRANS} = \frac{\mathrm{DIST} \times \mathrm{RATE} \times \mathrm{JUICE}}{\mathrm{LOAD}}, \qquad [4.13]$$

where TRANS = cost of juice transportation ($/yr),

DIST = average distance transported (km),

RATE = freight rate ($/km),

JUICE = mass of juice to be transported during year (Mg), and

LOAD = capacity of truck (Mg).

The capacity of the truck, LOAD, was assumed to be 20.4 Mg. The cost of transporting the juice from the field to a central plant would be somewhat analogous to the cost of delivering feed from a feed mill to local farms, and also to the cost of hauling logs to a saw mill. A cost of $1.50 per loaded km was obtained from a proprietary source for the cost of delivering feed, and a cost of $1.55 per loaded km was given by Stuart (1990) as the cost of delivering logs to a saw mill. Based on an estimated fuel consumption of 0.535 L/km, and assuming that the rate charged must pay for travel in both directions, loaded and empty, the freight rate was given by

$$\mathrm{RATE} = \mathrm{NFC} + 0.535 \times 2 \times \mathrm{FCOST}, \qquad [4.14]$$

where RATE = freight rate ($/km),

NFC = nonfuel costs of trucking ($/km), and

FCOST = fuel cost ($/L).

The fuel cost used was $0.27/L, and solving Equation [4.14] for a freight rate of $1.50 per loaded km, the nonfuel trucking costs were found to be $1.21 per loaded km. Fuel cost was separated out so that the freight rate would increase with fuel cost increases, and the model would be more sensitive to changes in fuel cost.

4.5.5 Crop Production Cost

The expected cost of producing the sweet sorghum was estimated as $365/ha for each hectare planted, regardless of whether or not it was harvested. This production cost was based on the work by Maxey et al. (1989a) and includes all direct expenses incurred by the farmer up to harvest. A return to labor is included, but, like all other costs in this study, no profit for the farmer is included.

4.5.6 Value of By-products

The value of the by-products (rind-leaf hay, pith presscake silage, combination silage, and/or whole-stalk silage) was subtracted from the total cost figure. The by-product values are given in

Table 5. The value of any whole-stalk silage produced, minus the cost of harvesting it, was also subtracted from the total cost. Whole-stalk silage was produced only when weather conditions made harvesting the entire planted area with the Piedmont System impossible.

4.5.7 Projected Ethanol Yield

Meade and Chen (1985) state that each Mg of sugar will produce 576 L of ethanol using conventional fermentation methods. Each Mg of sugar in the juice was multiplied by 576 to obtain the expected ethanol yield. Mean cost per liter of ethanol was determined by dividing the total cost to deliver juice to the evaporation plant by the expected ethanol yield. The necessary statistics were collected for calculating the standard deviation and a confidence interval for the mean cost per liter of ethanol. It is emphasized that this cost per liter figure is a feedstock cost only. The cost of evaporating juice to syrup, transporting the syrup to a distillation plant, and fermentation/distillation must still be added, but these further processing costs are the same for all three harvest systems and are considered beyond the scope of this economic study.

4.6 Analysis of Model Output

4.6.1 Statistical Comparison of Three Systems

Law and Kelton (1982) describe the method used to compare the output of the models. The goal was to select the system with the smallest expected cost. The selection can never be made with absolute certainty because of the randomness of the data, but a probability, P*, that the correct selection will be made can be prespecified. Also, an "indifference" amount, d*, must be selected to prevent a large number of replications from being required to decide between two systems that have unimportant differences in their expected costs. For instance, if the cost per liter of ethanol for System A is less than \$0.02 different from the cost for System B, no strong conclusions can be drawn as to the superiority of one system over the other. For this reason, d* was set at 0.02 for the analysis. Also, P* was set at 0.95 so that the correct selection can be made with 95% certainty, given the condition that differences less than \$0.02 are insignificant. Using this procedure, the true mean of the selected system will be no larger than $\mu_{i1} + 0.02$, where μ_{i1} is the true mean of the lowest cost system. The procedure requires that each set of simulations be run independently; therefore an independent set of weather data was generated by WGEN for each of the three system models, and different random number streams were used in the harvest simulation models. Initially, 40 years of data were generated and the cost per liter of ethanol predicted by each model. These data were analyzed to determine the sample mean ($\overline{X}_i^{(1)}$) and standard deviation (s_i^2) for each model. The resulting parameters were then used to determine how many additional simulations were needed to reach a decision. The total number of simulations required for each system was calculated by

$$N_i = \max\{n_0 + 1, [\frac{h_1^2 s_i^2(n_0)}{(d^*)^2}]\}, \qquad [4.15]$$

where N_i = total number of replications required,

n_0 = number of replications in initial run,

h_1 = constant from Table 9.7, p 329 (Law and Kelton, 1982),

s_i^2 = sample variance of initial run, and

d^* = indifference amount ($d^* = 0.02$).

The notation [z] indicates that the real number, z, inside the brackets is rounded up to the next integer (i.e. [63.15] = 64). Once N_i had been established, $(N_i - n_0)$ more replications were run and the second-stage sample mean ($\overline{X}_i^{(2)}$) was obtained. The weights for each sample mean were then obtained by

$$W_{i1} = \frac{n_o}{N_i}(1 + \{1 - \frac{N_i}{n_0}[1 - \frac{(N_i - n_0)(d^*)^2}{h_1^2 s_1^2(n_0)}]\}^{1/2}), \qquad [4.16]$$

and

$$W_{i2} = 1 - W_{i1}, \qquad [4.17]$$

where W_{i1} = weight of the first stage sample mean, and

W_{i2} = weight of the second stage sample mean.

Finally, the weighted sample mean for each system is defined by

$$\hat{X}_i(N_i) = W_{i1}\overline{X}_i^{(1)}(n_0) + W_{i2}\overline{X}_i^{(2)}(N_i - n_0), \qquad [4.18]$$

where $\hat{X}_i$ = weighted sample mean for the ith system.

The system with the smallest weighted sample mean was then chosen as the best system.

4.6.2 Response to Increased Fuel Price

In order to determine the response of each of the systems to a major increase in fuel prices, the assumed cost of fuel was increased in the economic submodel from $0.27/L to $0.54/L and then to $1.08/L. All other inputs were held constant and the models were run for 100 years.

4.6.3 Response to Increased Sugar Content

If the average sugar content could be raised through development of improved varieties, the cost per liter of ethanol would be reduced. The harvest simulation submodels were altered by increasing the juice sugar content at the beginning of harvest from 12.5° Brix to 15.5° Brix. The models were run for 100-year simulations and the mean feedstock cost per liter recorded.

4.6.4 Response to Increased Whole-stalk Yield

If the mean yield of whole-stalks can be increased by improving varieties and/or improving agronomic methods, the cost per liter would be reduced. To determine the extent of this reduction for each system, the harvest simulation models were changed by increasing the yearly mean yield of whole-stalks from 42 Mg/ha to 60 Mg/ha. The distribution of this new yearly mean yield had a standard deviation of 6.666 and end points at 40 and 80 Mg/ha. The models were again run for 100 year simulations and the mean cost per liter recorded.

4.7 Energy Analysis

The Piedmont System is being proposed as a possible way to extend U.S. petroleum supplies; therefore, it is helpful to determine whether or not the production of ethanol in this manner will indeed result in a net gain of energy, and more importantly, a net gain of liquid fuel. An energy balance of a sweet sorghum for ethanol industry was done for System A, the harvesting/processing system described in Section 4.1. A comparison was made between sweet sorghum and corn as feedstocks since 85% of the fuel ethanol currently being produced in the United States is produced from corn. Since the most efficient corn producing area in the United States is the Midwest, the analysis was based upon corn being produced and processed into ethanol in Indiana, and then shipped via rail to Virginia, where it would be used. The issue to be resolved was whether ethanol could be produced from sweet sorghum in Virginia and compete, on an energy efficiency basis, with ethanol produced from corn in the Midwest.

In the analysis, an attempt was made to separate the energy inputs which must practically be supplied by liquid fuels from those which can be supplied by solid fuels such as coal or biomass. Liquid fuels include gasoline, diesel fuel, alcohol fuels, LP gas, and natural gas, which is used to produce LP gas, since all of these fuels can be used to power tractors, automobiles, and other mobile power units. The distinction between energy from liquid fuels and other sources is important since liquid fuels are now produced almost exclusively from petroleum, and petroleum reserves are being rapidly depleted in this country and worldwide. If energy from solid fuels (coal, biomass) can be used to make liquid fuels (ethanol), an advantage will be gained even though the net energy gain might be near zero.

The Piedmont System processes stalks into juice, a rind-leaf fraction, and a pith presscake fraction. For the energy analysis, the yields used were 42.0 Mg/ha of whole-stalks, 11.35 Mg/ha of rind-leaf fraction, 11.35 Mg/ha of pith presscake, and 16.8 Mg/ha of juice containing 2.5 Mg/ha of sugar. The pith presscake and rind-leaf fractions are ensiled together at or near the farm where they are produced. The figures in Table 7 represent expected yields and physical properties of sweet sorghum juice at varying concentrations (Meade and Chen, 1985). Sugar concentrations are given in ° Brix which is a common expression in the sugar industry and is defined as the mass of solids as a percentage of the total mass of the solution. The juice sugar concentration at the beginning of harvest is approximately 12.5° Brix and it increases as the plants mature to approximately 17° or 18° Brix, so the average sugar concentration is approximately 15° Brix.

Two options have been proposed for the operation of an ethanol plant using sweet sorghum as a feedstock. In Option 1, the juice would be transported to an evaporation plant located an average of 16 km from the field, where it is evaporated to 60° Brix syrup, the concentration needed for safe storage. Fermentation and distillation of the ethanol would occur at a larger plant centrally located an average distance of 48 km from the smaller evaporation plants which are scattered throughout the production area. Under Option 1, the by-products would be fed to cattle on the farm where they were produced, and the fermentation/distillation plant would use syrup produced in the fall as a feedstock for operation throughout the year.

Table 7. Expected yields and physical properties of sweet sorghum juice (Meade and Chen, 1985)

	Juice Density (kg/L)	Sugar Density (kg/L of Juice)	Yield (L/ha)
15° Brix Juice	1.06	0.1588	15,850
30° Brix Juice	1.126	0.3378	7,450
60° Brix Syrup	1.285	0.7712	3,260
75° Brix Syrup	1.346	0.9424	2,670

Option 2 assumes that the technology for economical conversion of cellulose to sugar for the production of ethanol is available. In this option, the juice would be fermented as it is produced during the harvest season, thus avoiding the high energy cost of evaporation. The central plant would then use the by-product silage, as well as other cellulose materials, as feedstock for the remainder of the year. It is assumed that the cellulose conversion to sugar would occur at the fermentation/distillation plant since simultaneous saccharification and fermentation (SSF) appears to be the most efficient method of cellullose conversion (Wright, 1988). Consequently, both the whole juice and the by-product silage would be transported an average distance of 48 km to a central plant under Option 2.

The energy balances for the two options are dependent on the choice of transportation distances. For Option 1, the evaporation plants are assumed to be an average of 16 km from the production site. Transporting the juice this distance would require approximately 2% of the energy which would ultimately be derived from the juice in the form of ethanol. An additional 1.5% of the energy produced would be required to transport the syrup 48 km to the fermentation/distillation plant. Additionally, approximately 2% of the energy produced would be required to transport the stalks from the field to the crossroads processing site. Total energy invested in transportation would then be 2% (field) + 2% (juice) + 1.5% (syrup) = 5.5%. For comparison, approximately 2% of the energy in coal is used for its transportation from the extraction point (mine) to the utilization point, and the average energy invested in the transportation of petroleum from the well head to a retail outlet is 4% of the energy in the fuel (Tillman, 1978). The 5.5% of expected ethanol yield for transportation in Option 1 does not include transportation from the fermentation/distillation plant to the retail outlet, however it is hoped this transportation will be minimal, perhaps as little as 0.5%. Total energy for transportation in Option 1 would then be 6% of expected ethanol yield, compared to 4% for petroleum fuels.

In Option 2, transporting the juice 48 km to the central processing plant would require approximately 6% of the energy in the ethanol produced. When whole-stalk transportation is included, the total energy for transportation is 2% (field) + 6% (juice) = 8% of the energy produced. Assuming a yield of 129 L of ethanol per Mg of 66% M.C. silage, the energy required to transport the by-product silage 48 km to the central plant represents approximately 23% of the energy in the ethanol produced from it. The high cost (both in energy and dollars) of transporting feedstock is a recognized limitation on the production of ethanol from cellulosic materials. If the net energy balance is positive, however, an advantage still exists for using these by-products as an energy source.

4.7.1 Energy for Crop Production

Estimated energy inputs for corn production in the midwest were obtained from Pimentel (1980). Specifically, the values used were for corn production in Indiana. Since sweet sorghum is currently a minor crop, no information specific to this crop was found in the literature, so the values for nonirrigated grain sorghum in Nebraska (Pimentel, 1980) were used with adjustments for the amount of fertilizer and lime recommended for sweet sorghum production in the Piedmont of Virginia. The energy required to harvest the crop was subtracted from the values given by Pimentel (1980) since this energy requirement is included in the next section of the analysis. Doering and Peart (1977) estimated that 561 MJ/ha of diesel fuel energy is required to harvest grain crops, so this figure was subtracted from the total diesel fuel required to produce grain sorghum given by Pimentel (1980). Also, it was estimated that 1/3 of the machinery used to produce the crop was harvesting equipment, therefore the estimate given by Pimentel for the machinery energy was reduced by 1/3.

Values used for the portion of energy which must come from liquid fuels are based on information from Pimentel (1980). Although some electrical energy now uses liquid fuels as an energy source, all electricity could be generated using solid fuels if a world or national liquid fuels crisis were to make this necessary, therefore electrical energy was not included in liquid fuel requirements. All transportation inputs were assumed to be from liquid fuels, since the vast majority of energy for transportation is supplied by liquid fuels. Approximately 67 kg/ha of nitrogen, phosphorous, and potassium, and 560 kg/ha of lime would be required each year to grow sweet sorghum in the Virginia Piedmont (Harrison, 1985). Pimentel (1980) showed that approximately 99% of the energy in nitrogen is derived from liquid fuels. Transportation of raw materials and final product represent 27% of the energy in phosphorous (Pimentel,1980), therefore 27% of the total energy in phosphorous was considered to be liquid fuel energy. Potassium and lime are materials which are not processed except for mining and grinding, therefore it was expected that all energy in these materials came from liquid fuels. Pimentel (1980) reported that approximately 42% of the energy in pesticides comes from oil, so that figure was used in the analysis as the percentage of energy from liquid fuel. Approximately 50% of the energy to produce grain (seed) crops comes from liquid fuels (Pimentel, 1980), so 50% of the energy embodied in the seed was considered to be liquid fuel energy. The embodied energy in machinery is made up mostly of electric and steam energy for molding and machining steel (Pimentel, 1980). Since these energy forms can be produced from solid fuels, it was estimated that 85% of the embodied energy in machinery could be supplied by solid fuels. Using the above described values, the energy requirements for tasks and materials used to produce sweet sorghum in the Virginia Piedmont and corn in the midwest are summarized in Table 8.

4.7.2 Energy for Local Processing

The energy required to transport corn to a local grain bin and dry it (in Indiana) were taken from Pimentel (1980). Estimates were also made for the energy required to harvest sweet sorghum stalks, transport them to the processor, process them, and extract the juice. These estimates were developed using the methods described by Pimentel (1980) and are described in the following discussion. As a review, System A consisted of a whole-stalk harvester, which could harvest approximately 0.3 ha/h, a chopper/processor which was capable of processing approximately 8 Mg/h, and a 30-cm diameter screw press which could press approximately 5.6 Mg/h of pith fraction, the estimated output from the separator if 70% of the stalk mass were in the pith fraction. System A was ex-

Table 8. Energy requirements for crop production (MJ/ha)

Item	Sweet Sorghum		Corn	
	Liquid Fuel	Total	Liquid Fuel	Total
Fertilizer				
Nitrogen	3,343	3,377	5,976	6,036
Phosphorous	228	844	221	817
Potassium	450	450	639	639
Lime	740	740	468	468
Pesticides	587	1,398	1,281	3,049
Seed	99	197	1,245	2,490
Equipment				
Gasoline	1,960	1,960	1,141	1,141
Diesel	1,482	1,482	3,749	3,749
Machinery	83	555	622	4,145
Total	8,972	11,003	15,342	22,534

pected to harvest and process approximately 170 hectares per year. (See Section 5.2.2 for performance results for Systems A, B, and C.)

4.7.2.1 Embodied Energy Calculations

Embodied energy is defined as the energy sequestered in a piece of machinery or repair part as manufactured and delivered to the user, and was calculated using the method described by Pimentel (1980). A value of 62.8 MJ/kg was given by Pimentel (1980) as the embodied energy in steel, rubber, and other materials used to manufacture the machinery. Fabrication energy was 8.63 MJ/kg of assembled mass for a total of 71.43 MJ/kg (Pimentel, 1980). Embodied energy in repair parts over the life of the machine was based on the estimated Total Accumulated Repair (TAR) for the service life of the machine. The service life was defined by Pimentel (1980) as 82% of the total life of the machine. Since the TAR is based on dollar cost of total repairs, 1/3 of this value was taken as representing parts exclusive of labor and other maintenance costs (Pimentel, 1980). The embodied energy for parts is then computed by

$$EE_p = EE_{am} \times 1/3 \times M_{TAR}, \qquad [4.19]$$

where EE_p = embodied energy in parts (MJ),

EE_{am} = embodied energy in assembled machine (MJ), and

M_{TAR} = multiplier for Class 1, 2, 4, or 5.

The different classes of machinery are described and their multipliers given by Pimentel (1980). The multiplier for Classes 1, 2, 4, and 5 are 0.7425, 0.891, 0.6069, and 0.7598, respectively. Total embodied energy required for the various pieces of machinery on a per hectare harvested basis is given by

$$EE = \frac{EE_{am} + EE_p}{YRSLIF \times HAYR}, \qquad [4.20]$$

where EE = total embodied energy (MJ/ha processed),

YRSLIF = expected service life (yrs), and

HAYR = expected hectares processed per year.

The embodied energy of each component of System A is shown in Table 9 along with the values of the parameters used to calculate these figures. The service life in years (YRSLIF) was estimated based on the average annual hours of operation from the simulation of System A (1000 h for processing equipment and 715 h for harvesting equipment) and on the service life, in hours, used for the economic submodel (Table 6).

4.7.2.2 Other Energy Calculations

Energy required to operate the equipment per hectare harvested is given by

$$EO = POW \times RATE \times 3.6, \qquad [4.21]$$

where EO = operating energy required (MJ/ha),

POW = power required (kW),

RATE = processing/harvesting rate (h/ha), and

3.6 = conversion from kWh to MJ.

The processing rate was calculated to be 5.25 h/ha based on a processor capacity of 8 Mg/h (Crandell et al., 1989) and the expected mean yield of 42 Mg/ha. The harvesting rate used was 3.33 h/ha (Rains, 1989). Equation [4.21] was used to calculate the energy required to operate the harvester tractor, processor loader, the chopper/separator, and the screw press. The tractor and loader were expected to operate at an average of 75% of rated power, while the chopper/separator and screw press operated at 100% of rated power. The energy required to haul sugar cane from the field and load it onto road trucks in Florida was given as 880 MJ/ha by Eiland (1990). This operation is similar to the hauling of whole sorghum stalks to the storage pile in System A, and the value

Table 9. Embodied energy and parameter values for components of System A

Item	Mass (kg)	Class (for Repair Parts)	Service Life (yrs)	Embodied Energy in Machine	Embodied Energy in Parts
Harvester	2,000	4	3	142,860	28,901
40 kW Tractor (Harvester)	2,500	2	14	178,575	53,037
42 kW Field Loader	2,500	2	14	178,575	53,037
34 kW Tractors (Trailer)	2,000	2	14	285,720	84,859
Dump Trailers	2,000	5	4	285,720	84,859
32 kW Loader (Processor)	2,000	2	10	142,860	42,429
45 kW Chopper/Separator	5,000	2	5	357,150	106,074
30 kW Screw Press	5,000	1	15	357,150	88,395

of 880 MJ/ha was used as the energy required to operate the field loader and the tractors pulling the dump trailers.

Energy requirements for transportation of corn and sweet sorghum from the field and for local processing (drying of corn and juice expression from sorghum) are summarized in Table 10. As in the previous section, 15% of embodied energy and 100% of transportation energy were taken to be derived from liquid fuels.

4.7.3 Energy for Juice Transportation and Evaporation (Option 1)

Energy requirements for the transportation of juice to an evaporation plant located an average distance of 16 km from the processing site, and the evaporation of the 15° Brix juice to 60° Brix syrup were determined and are summarized in Table 11. Energy to transport the juice was calculated by

$$ET = MTR \times DTR \times TF, \qquad [4.22]$$

where ET = transportation energy required (MJ/ha),
MTR = mass to be transported (kg),
DTR = average distance traveled (km), and
TF = transportation energy factor.

The transportation energy factor is the estimated average energy required to transport one kg of material a distance of one km. The factor used for truck transport was $3.475\text{x}10^{-3} \ \frac{\text{MJ}}{\text{kg} \cdot \text{km}}$ (Pimentel, 1980).

Edible sorghum syrup is made almost exclusively in open pan evaporators in order to remove the heat coagulatable materials that float to the surface during the early part of the evaporation process.

Table 10. Energy requirements for local processing and transportation (MJ/ha)

Item	Sweet Sorghum		Corn	
	Liquid Fuel	Total	Liquid Fuel	Total
Local Transport				
Whole-stalks to Processor	879	879		
Corn to Farm Bin			200	200
Drying (Corn)				
LP Gas	0	0	1,114	1,114
Electricity	0	0	0	379
Harvester				
Embodied Energy	51	337	0	0
Harvester Tractor				
Embodied Energy	15	97	0	0
Operating Energy	360	360	0	0
Field Loader				
Embodied Energy	15	97	0	0
2 Tractors (Dump Trailers)				
Embodied Energy	23	156	0	0
2 Dump Trailers				
Embodied Energy	79	527	0	0
Processor Loader				
Embodied Energy	16	109	0	0
Operating Energy	454	454	0	0
Chopper/Separator				
Embodied Energy	41	272	0	0
Operating Energy	851	851	0	0
Screw Press				
Embodied Energy	26	175	0	0
Operating Energy	567	567	0	0
Total	3,377	4,881	1,314	1,693

Table 11. Energy requirements for juice transportation and evaporation in Option 1 (MJ/ha)

Item	Liquid Fuel	Total
Juice Transportation	934	934
Evaporation	0	9,774
Total	934	10,708

Open pan evaporators are the least efficient evaporators available. If the syrup is to be used for ethanol production, more efficient evaporators would be used. Multiple-effect tube or plate evaporators operate much more efficiently and therefore are used in the hypothetical evaporation plant. According to APV (1980), a triple effect evaporator will requires approximately 0.775 MJ/kg of water evaporated. The amount of water to be evaporated on a per hectare basis is the difference between the mass of 15° Brix juice produced on a hectare and the mass of 60° Brix syrup produced from that juice. From Table 7, the yield of 15° Brix juice was 15,850 L/ha with a density of 1.06 kg/L, so the total mass of juice was $1.06 \times 15{,}850 = 16{,}801$ kg. After evaporation to 60° Brix syrup, the mass was $1.285\ \mathrm{kg/L} \times 3{,}260\ \mathrm{L} = 4{,}189\ \mathrm{kg}$, and the amount of water evaporated from the juice was then $16{,}801 - 4{,}189 = 12{,}612\ \mathrm{kg/ha}$.

4.7.4 Energy for Fermentation and Distillation

The energy required to transport 60° Brix syrup from the evaporation plant to the distillery (Option 1) or to transport raw juice and by-product silage an average distance of 48 km to the distillery (Option 2) was determined using Equation [4.22]. The distance and method of transportation of corn varies widely, but the assumption was made that corn was transported the same distance (48 km) and by the same method (truck) as was the sweet sorghum products. The area required to grow corn to supply a distillery would be similar to the area required to grow sweet sorghum, so the transportation distances would be similar.

Most ethanol feedstocks must undergo preparation before they can be fermented. In the case of the dry milling process for corn, it is ground, saccharified (starch converted to sugars), fermented (sugars converted to ethanol), and distilled (water and other impurities removed from the ethanol). Using present technology, the fermentation/distillation stage is by far the most energy intensive process in ethanol production; however, most of the energy can be supplied by sources other than liquid fuels. Scheller and Mohr (1976) estimated that 30.10 MJ of energy are required at this stage to produce one liter of ethanol from corn. Of this amount, 11.15 MJ are used in grinding and cooking the feedstock and for drying the distiller's grains (an animal feed by-product). None of these operations will be necessary with sweet sorghum syrup; therefore, a good estimate of energy required to ferment and distill sweet sorghum syrup is 30.10 - 11.15 = 18.95 MJ/L of ethanol produced.

No commercial plants for converting cellulose to ethanol are presently in operation, so no reliable data on the energy required for this process is available. Hinman (1990) estimated that the energy required to produce ethanol from cellulose would be approximately equal to that required to produce ethanol from corn using the dry milling process. He further stated that future technologies were expected to lower the energy requirement significantly. The value of 30.10 MJ/L of ethanol was therefore used in the analysis as the energy required to produce ethanol from by-product silage.

The energy required to transport the feedstock to the distillery, and to convert it to ethanol (Table 12) are based on the following :

1. Corn will yield 6.24 Mg/ha and produce 0.389 L of ethanol per kg of corn (SERI, 1980). The expected yield of ethanol from corn is then 2427 L/ha.
2. Under Option 1, sweet sorghum will yield 2500 kg of sugars per hectare and one kg of sugar will produce 0.576 liters of ethanol at 90% conversion efficiency (Meade and Chen, 1985). The expected yield of ethanol from sweet sorghum syrup is then 1440 L/ha.
3. Under Option 2, expected by-product silage yield is 22.7 Mg/ha at 66% moisture, which is equivalent to 7.7 Mg of dry matter. Two thirds of the dry matter can be converted to sugar (Wright, 1988), and the resultant sugar yield is then 5100 kg. Total yield of fermentables from Option 2 is 2500 kg (juice) + 5100 kg (silage) = 7600 kg. Using the 0.576 L/kg figure, the expected yield of ethanol is then 4,378 L/ha.

As stated at the beginning of this energy analysis, the fuel produced was to be used in Virginia. Since corn can be produced more efficiently in the Midwest, the ethanol from corn was produced

Table 12. Energy requirements for transportation, fermentation, and distillation (MJ/ha)

Item	Sweet Sorghum (Option 1)		Sweet Sorghum (Option 2)		Corn	
	Liquid Fuel	Total	Liquid Fuel	Total	Liquid Fuel	Total
Feedstock Transportation	699	699	6,588	6,588	1,034	1,034
Feedstock Preparation	0	0	0	32,759	0	27,061
Fermentation/Distillation	0	27,288	0	82,963	0	45,992
Ethanol Transportation	0	0	0	0	750	750
Total	699	27,987	6,588	122,310	1,784	74,837

in Indiana and then transported via rail to Virginia. The transportation factor for rail transport is given by Pimentel (1980) as $0.502 \times 10^{-3} \frac{\mathrm{MJ}}{\mathrm{kg} \bullet \mathrm{km}}$. The transportation distance was 800 km, the distance from Indianapolis, Indiana to Roanoke, Virginia. With a density of 0.7439 kg/L, the energy required to transport the ethanol from one hectare of corn 800 km is 725 MJ.

5.0 Results and Discussion

5.1 Soil Trafficability Model

The results of the verification test for the soil trafficability model showed close agreement between the predicted and "actual" workdays. The model incorrectly predicted only four non-workdays and two workdays when simulation results were compared with actual work records for seven three-month harvest seasons. It was not possible to reconstruct exactly which days the soil was trafficable, so the "actual" workdays were subjectively estimated from work records, as explained in Section 4.3. If records had been available for days when the fields were dry enough for different classes of equipment to operate, the results would probably not have been as good as reported here, however the trafficability submodel has an acceptable level of accuracy for the purpose of this study. The trafficability of one field may be different from that of the field located next to it depending on slope and soil type. Since the actual fields where sweet sorghum will be grown is unknown at this point, it is impossible to make more accurate predictions concerning available workdays. The aim of this study is to generate a reasonable estimate of what might occur in the designated area, and the submodel accomplishes that purpose.

5.2 Sensitivity Analyses for Input Parameters

5.2.1 Low-Yield Cutoff

The results of the sensitivity analysis to determine the minimum yield for economical harvesting is shown in Table 13. For this test, it was assumed that only enough hectares were planted for each system so that all of the area could be harvested 90% of the years. The yield distributions used in this test had a medium standard deviation (7.33 for yearly mean and 6.67 for within-year mean). The results indicate that the mean feedstock cost per liter rises if the low-yield cutoff is set above 20 Mg/ha. (The low-yield cutoff is the yield below which a field will not be harvested by the Piedmont System.) The analysis did not include low-yield cutoffs below 20 Mg/ha, since yields below this level are not considered economical, even for a conventional forage harvester. Also, fields yielding less than 20 Mg/ha tend to experience excessive weed growth, since not enough sweet sorghum exists to shade out late season weeds. These large weed populations tend to clog harvesting equipment, as well as lowering the quality of the harvested product. The costs rise at cutoffs over 20 Mg/ha even though the rejected fields are not completely wasted. In the analysis, fields producing over 20 Mg/ha, but less than the low-yield cutoff were assumed to be chopped by a conventional forage harvester and the resulting silage valued as cattle feed. As a result of this analysis, all subsequent simulations used 20 Mg/ha as the low-yield cutoff.

5.2.2 Planted Area

The response of the three systems to planted area is shown in Table 14. The same yield distributions (standard deviation = 7.33 for yearly mean and 6.67 for within-year mean) were used as in

Table 13. Feedstock cost for three systems with different low-yield cutoffs

Assumptions: 90% confidence level planting area (150, 95, and 130 ha for Systems A, B, and C, respectively). Within-year and yearly mean yield distributions both have medium standard deviations (approximately 7).

	Mean Feedstock Cost ($/L)		
Low Yield Cutoff	**System A**	**System B**	**System C**
20 Mg/ha	0.57 0.39-0.75*	0.66 0.51-0.80	0.86 0.76-0.97
25 Mg/ha	0.60 0.35-0.84	0.67 0.47-0.88	0.87 0.73-1.02
30 Mg/ha	0.70 0.24-1.15	0.75 0.37-1.13	0.92 0.65-1.19

* 90% confidence interval

Table 14. Feedstock cost for three systems with different planted areas

Assumptions: 20 Mg/ha low-yield cutoff. Within-year and yearly mean yield distributions both have medium standard deviations (approximately 7).

	System A	System B	System C
		---90% Confidence Level---	
Hectares Planted	150	95	130*
Mean Cost ($/L)	0.57	0.66	0.86
90% confidence interval	0.39-0.75	0.51-0.80	0.76-0.97
		---80% Confidence Level---	
Hectares Planted	160	100	140
Mean Cost ($/L)	0.57	0.65	0.86
90% confidence interval	0.39-0.74	0.51-0.79	0.75-0.97
		---70% Confidence Level---	
Hectares Planted	165	105	145
Mean Cost ($/L)	0.57	0.65	0.86
90% confidence interval	0.39-0.74	0.51-0.78	0.75-0.96
		---60% Confidence Level---	
Hectares Planted	170*	110	155
Mean Cost ($/L)	0.56	0.64	0.86
90% confidence interval	0.39-0.74	0.51-0.75	0.75-0.97
		---50% Confidence Level---	
Hectares Planted	175	120*	165
Mean Cost ($/L)	0.56	0.63	0.86
90% confidence interval	0.39-0.74	0.51-0.75	0.75-0.97
		---40% Confidence Level---	
Hectares Planted	180	125	170
Mean Cost ($/L)	0.56	0.64	0.86
90% confidence interval	0.39-0.74	0.51-0.76	0.75-0.97

* Recommended planting area for each system

the previous test, and the 20 Mg/ha low-yield cutoff was assumed. Within the bounds of the sensitivity analysis, the models are somewhat unresponsive to changes in planted area. In bad years, when fewer hectares can be harvested than were planted, a lower planted area yields a lower cost. In good years, when more hectares can be harvested than were planted, a higher planted area yields a lower cost. Thus, when 100 years are simulated, these two effects partially offset each other causing the model to appear more insensitive than might be expected. The results clearly show, however, that the area which should be planted for each system is different. The confidence level in Table 14 is the confidence that all of the planted area can be harvested in any given year. If the crop is planted at the 60% confidence level (170 hectares planted for System A), then all of the crop would be expected to be harvested 60% of the years. The area which was not harvested the remaining 40% of the years was assumed to be harvested by a conventional silage harvester and ensiled as whole-stalk silage.

The results indicate that if System A were to be used, the area which should be planted each year is approximately 170 hectares for each unit of System A employed. Planting more than 170 hectares does not reduce the mean feedstock cost per liter, but does result in more whole-stalk silage in the years when weather prevents harvesting the whole crop with the Piedmont System. The mean cost for System B declines with increased planted area until 120 hectares are planted for each unit, therefore 120 hectares would be the recommended planting level for System B. The cost per liter using System C is unresponsive to planted area, therefore the recommended planting area for this system is 130 hectares per unit, the smallest area tested. The systems were not tested at a confidence level higher than 90% since these values are in the tail of the distribution and it becomes necessary to greatly reduce the planted area to significantly improve the confidence level of a complete harvest.

5.2.3 Estimated Yield Distributions

The response of the three systems to variations in the estimated yearly mean and within-year yield distributions are shown in Table 15. The simulations were run with the assumption that the optimum area for each system (determined in Section 5.2.2) was planted each year. The first three lines of Table 15 show the response to variations in the yearly mean yield distribution, narrow, medium, and wide, with the within-year distribution held constant at the medium level. As the assumed yearly mean distribution is varied from a narrow to a wide distribution, the mean cost per liter for System A increases by $0.04 from $0.55 to $0.59. The cost for System B increases similarly by $0.05 from $0.62 to $0.67, and the cost of System C increases $0.10 from $0.79 to $0.89. The spread of the 90% confidence interval for System A increases by $0.44 from $0.15 to $0.59. The spread for System B increases by $0.34 from $0.13 to $0.47, and that for System C increases by $0.26 from $0.14 to $0.40. It is apparent that an error in the estimation of the shape of this distribution can cause a significant error in the estimated cost per liter. However, it is also evident that the potential error will be similar for all three systems, and especially for Systems A and B. The yearly mean distributions with medium standard deviations (7.33) were used in subsequent simulations since this was estimated to be the "best guess." The fact that the shape of this distribution cannot be supported by data is reason to suspect a specific value in the cost-per-liter results, but the comparison between the three systems should not be seriously affected even if this assumption is inaccurate.

The effects of varying the within-year yield distribution, with the yearly mean distribution held constant at the medium shape, is also given in Table 15. This variation has very little effect on the results. The mean cost per liter for Systems B and C varied by only $0.01 and the mean cost of System A was not affected at all. Likewise, the spread of the 90% confidence interval varies by only

Table 15. Feedstock cost with different shapes for the assumed yield distributions

Assumptions: Optimum planted area (170, 120, and 130 ha for Systems A, B, and C, respectively).

Standard Deviation		Mean Feedstock Cost ($/L)		
Yearly Mean	**Within-Year**	**System A**	**System B**	**System C**
Narrow (3.53)	Medium (6.67)	0.55 0.47-0.62*	0.62 0.56-0.69	0.79 0.72-0.86
Medium (7.33)	Medium (6.67)	0.56 0.39-0.74	0.63 0.51-0.75	0.86 0.76-0.97
Wide (10.42)	Medium (6.67)	0.59 0.30-0.89	0.67 0.43-0.90	0.89 0.69-1.09
Medium (7.33)	Narrow (3.21)	0.56 0.39-0.73	0.64 0.52-0.75	0.86 0.76-0.96
Medium (7.33)	Medium (6.67)	0.56 0.39-0.74	0.63 0.51-0.75	0.86 0.75-0.99
Medium (7.33)	Wide (9.47)	0.57 0.39-0.75	0.64 0.50-0.78	0.87 0.75-0.99

* 90% confidence Interval

$0.02, $0.03, and $0.03 for System A, B, and C, respectively. The distribution with the medium standard deviation (6.67) was used in subsequent simulations.

5.3 System Cost Comparisons

5.3.1 Statistical Comparison of Three Systems

The results of the statistical test to compare the three systems, given by Law and Kelton (1982) and described in Section 4.6, are given in Table 16. In the top section, it was assumed that all of the by-products will be fed locally to cattle (Option 1 as described in Section 4.7), and the values of these by-products were taken from (Table 5). The number of years which had to be simulated for System A (216) was much higher than the number required for System B (154) or System C (100). Because of the lower variance for Systems B and C, fewer additional simulations were required to gain the desired level of confidence in the result. The cost for System A was low in the majority of years because of the large volume of sweet sorghum harvested, but in a year when yields were low and/or harvest time was limited by weather, the System A cost was very high because of the large investment requirement. System B was less able to take advantage of good harvest years, but in bad years, the cost was reduced due to lower investment requirements. System C was unable to fully take advantage of good years, and it required large investment, so the cost for System C tended to be consistently high. The mean of the first 40 years (replications) was only $0.01 different from that of the subsequent series of replications in each case. The weighted means for Systems A, B, and C were $0.56, $0.63, and $0.87, respectively.

The assumption that the by-products were all used for making ethanol by converting cellulose to sugars (Option 2 as described in Section 4.7) was used for the bottom section of Table 16. The

Table 16. Weighted means of feedstock costs ($/L) for three systems

Item	System A	System B	System C
By-products Used as Cattle Feed			
Number of Years in First Stage (n_1)	40	40	40
Mean Cost for First Stage ($\bar{x}_1$)	0.55	0.64	0.88
Variance of First Stage (s^2)	0.01110	0.007896	0.005141
Total Number of Years Required (N) (Equation [4.15])	216	154	100
Number of Years in Second Stage (n_2)	176	114	60
Mean of Second Stage ($\bar{x}_2$)	0.56	0.63	0.87
Weight of First Stage Mean (W_1) (Equation [4.16])	0.2059	0.2911	0.4241
Weight of Second Stage Mean (W_2) (Equation [4.17])	0.7941	0.7089	0.5759
Weighted Mean Cost ($\hat{x}$) (Equation [4.18])	**0.56**	**0.63**	**0.87**
By-products Used for Cellulose Conversion to Ethanol			
Number of Years in First Stage (n_1)	40	40	40
Mean Cost for First Stage ($\bar{x}_1$)	0.67	0.73	0.95
Variance of First Stage (s^2)	0.009729	0.006971	0.004968
Total Number of Years Required (N) (Equation [4.15])	189	135	97
Number of Years in Second Stage (n_2)	149	95	57
Mean Cost for Second Stage ($\bar{x}_2$)	0.68	0.71	0.95
Weight for First Stage Mean (W_1) (Equation [4.16])	0.2254	0.3166	0.4512
Weight for Second Stage Mean (W_2) (Equation [4.17])	0.7746	0.6833	0.5488
Weighted Mean Cost ($\hat{x}$) (Equation [4.18])	**0.68**	**0.72**	**0.95**

figures are based on the number of liters of ethanol produced from the juice only. The economic analysis considered the cellulose conversion to be a separate operation and only considered the dollar value of the by-products as if they were being sold to this separate operation. The resulting lower values of the by-products when used for cellulose conversion and the longer transportation distance of the juice (48 instead of 16 km) raised the feedstock cost for all three systems as expected, but the weighted average of System A was raised more than that for Systems B and C ($0.12 for System A, $0.09 for System B, and $0.08 for System C). Consequently, it is more difficult to determine, with confidence, whether System A or B is the better system when the by-products are used for cellulose conversion.

In comparing Options 1 and 2, the feedstock cost per liter of ethanol for Option 1 only includes the cost of transporting the juice to the evaporator and not the cost of evaporation and transporting the resulting syrup to the fermentation/distillation plant. The cost for Option 2 includes transporting the juice and the by-product silage to the fermentation/distillation plant. The cost of juice evaporation is saved with this option, consequently the advantage of Option 2 relative to Option 1 is not fully revealed in the comparison. The focus of this part of the study is on cost of fermentables delivered to the first step of off-farm processing. The reader is directed to the discussion of the energy balance in Section 5.4 to gain additional insight on the advantages and disadvantages of Options 1 and 2.

Regardless of the assumed value of the by-products, it is apparent that System C is too costly, as compared to the other systems. At least two factors contribute to this high cost. (1) While the overall investment for System C is approximately the same as that for System A, more of the equipment is operated in the field, which reduces the service life. (2) The processor in System C is only able to operate when the soil moisture is at or below 95% of field capacity. This limitation significantly reduces the available processor operating days as compared to System A, which operates at a hardened pad and can process stalks from the storage pile on any day when rainfall is less than 2.54 cm.

Weibull distributions were fit to feedstock-cost-per-liter data for Systems A, B, and C, and the results are shown in Figures 13 through 15, respectively. The data used for these curves were taken from 100-year simulations of the three systems under Option 1 (by-products fed to cattle). The mean per-liter costs were \$0.56, \$0.63, and \$0.86 for Systems A, B, and C, respectively. These results are not identical to the weighted averages given in Table 16. The differences between the costs in Table 16 and the 100-year simulations result from the random differences expected in any probabilistic model. Figures 13 through 15 were generated by a distribution fitting program called GDA (Worley et al., 1990). They show the histogram of the actual data with the density function of the Weibull distribution superimposed. The "skewness" of the curves, especially for System A, indicates that the possibility exists that the cost for a given year will be well above the mean, but little probability exists for a cost very far below the mean. For instance, the minimum cost predicted for System A is approximately \$0.38/L, \$0.18 below the mean cost of \$0.56. The maximum predicted cost is above \$1.05/L, or more than \$0.50 above the mean. Although the probability of either of these occurrences is low, it is important to recognize these possibilities and consider the effect of a catastrophic year on the financial condition of an enterprise engaged in the fuel-ethanol-from-sweet-sorghum business. A catastrophic year is one where yields are extremely low due to drought during the growing season, the harvest season is shortened by persistent rain or early freezing temperatures, or some combination of these factors which result in a feedstock cost in the upper tail of the distribution.

The cost distribution for all three systems is shown in Figure 16. This figure confirms the results of the statistical analysis. The cost of System C is significantly higher than that of the other two. The mean cost of System B is slightly higher than that of System A, but the differences between Systems A and B are so small that changes in assumptions or slight modifications to the systems could reverse the results. The "skewness" of the cost curve for System B is much less than that of System A, consequently the upper tails of the two distributions fall on top of each other indicating that the cost of a catastrophic year for System B is approximately the same as that for System A.

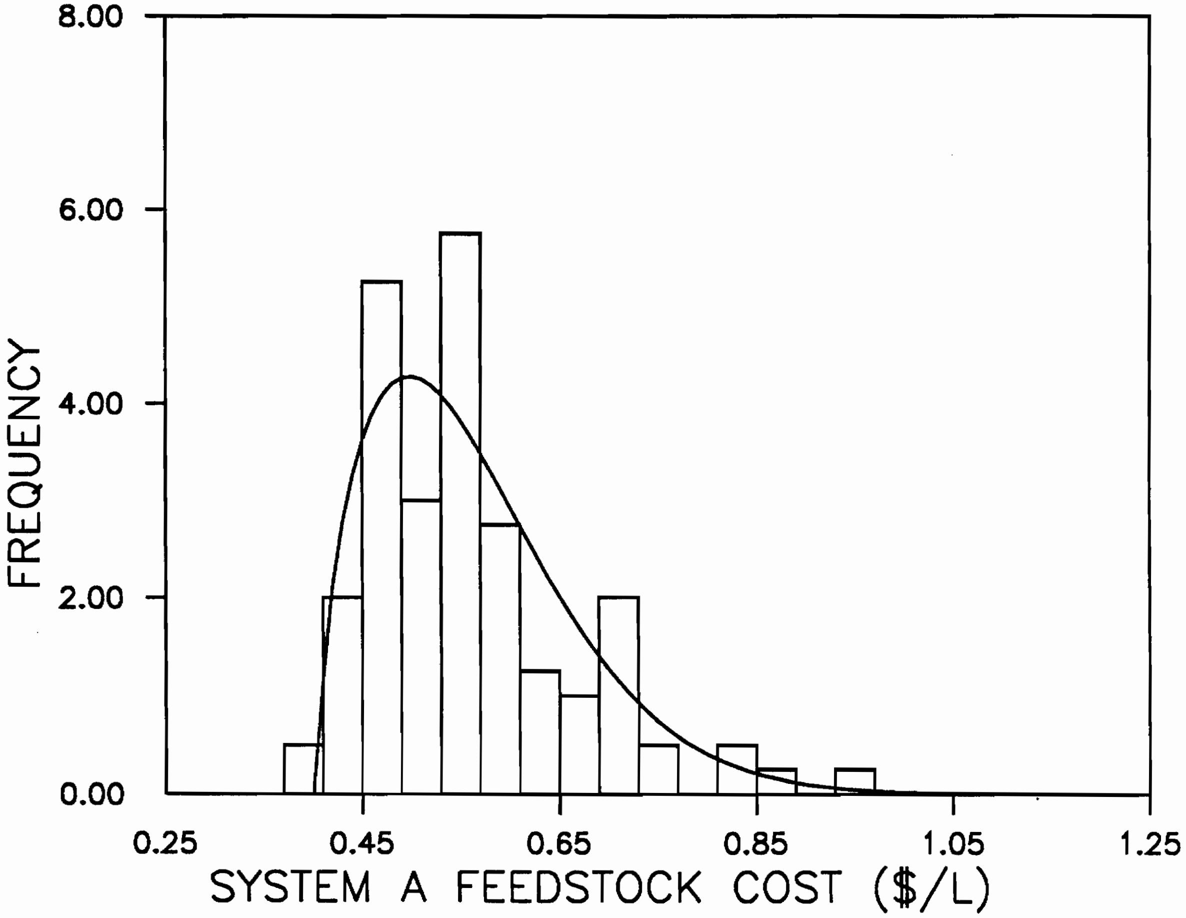

Figure 13. Distribution of feedstock cost per liter for System A

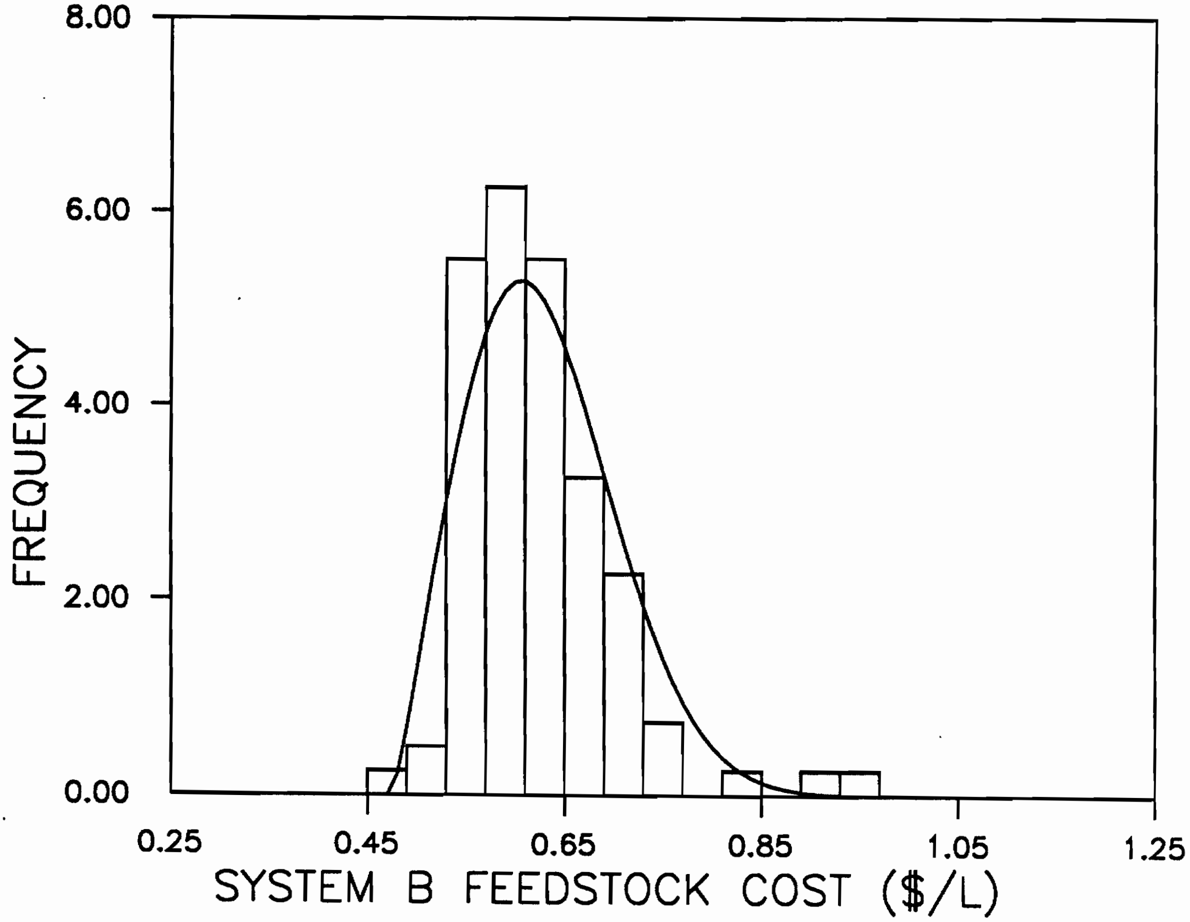

Figure 14. Distribution of feedstock cost per liter for System B

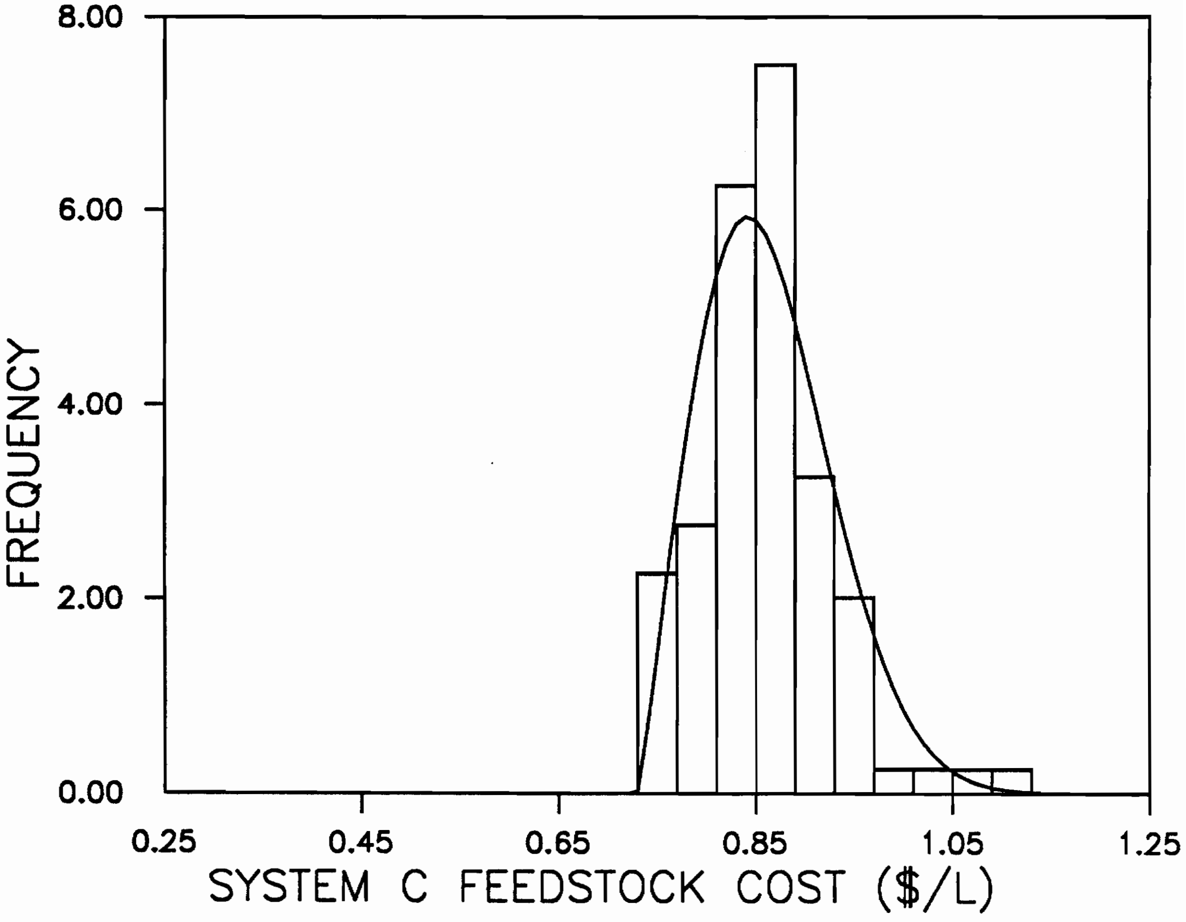

Figure 15. Distribution of feedstock cost per liter for System C

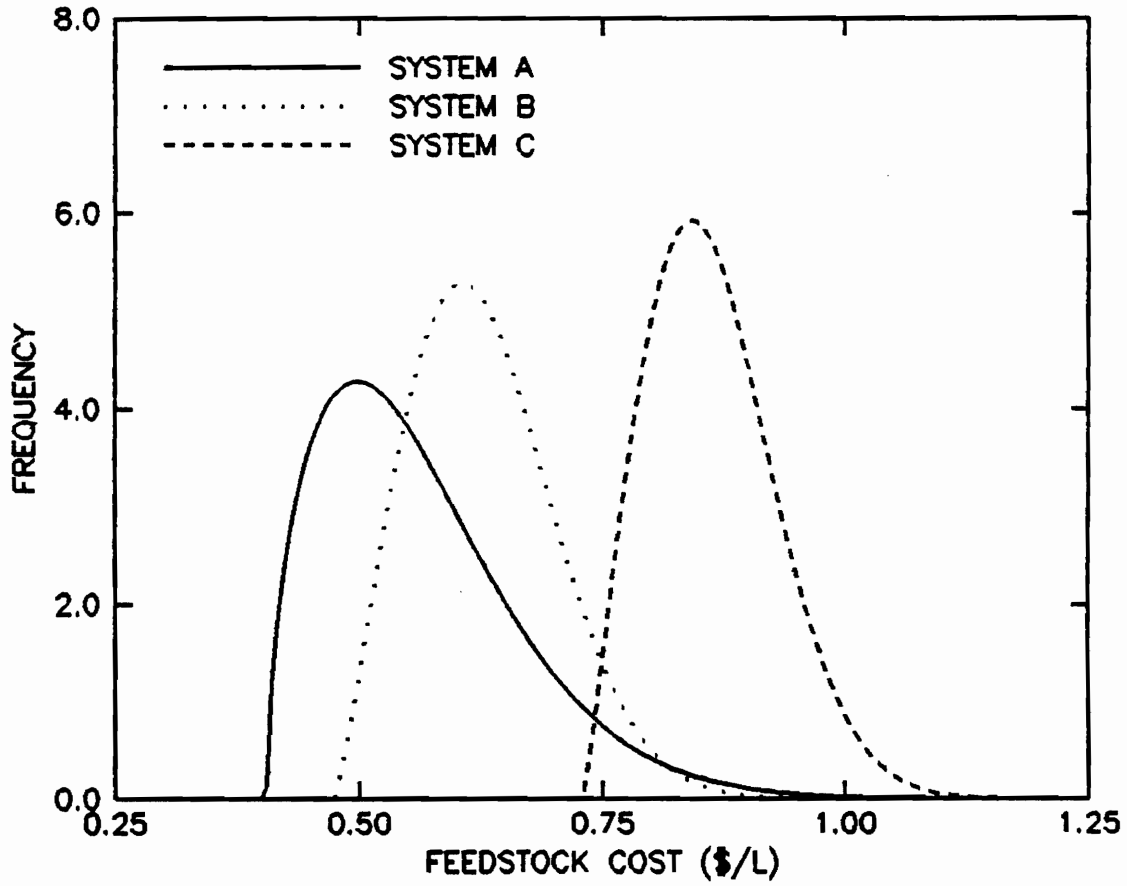

Figure 16. Distribution of feedstock cost per liter for Systems A, B, and C

The yearly-average costs and the cost per liter of ethanol for each system; A, B, and C; are categorized in Table 17. The data used for this analysis was the same as that used for the curve fitting procedure in the previous section. The cost of growing the crop is approximately the same for each system ($0.28/L). Harvesting cost for System A includes the cost of harvesting and hauling the stalks to a stock-pile near the processor. Processing includes stalk processing and juice removal. For System B, the pith fraction must be pressed within a few hours after harvesting to prevent early fermentation, consequently the hours of operation of the screw press occur at approximately the same time as those for the pith combine. The entire harvesting/processing operation can therefore be considered as one operation for System B. All of the costs for harvesting and processing are therefore included in harvesting cost for System B with the exception of the cost of moving the operation from one site to another, which is reported under processing cost. Harvesting cost for System C only includes the cost of harvesting and windrowing. Since the processor travels through the field, all other activities are included in processing cost. With these differences, it is hard to compare harvesting and processing expenses between one system and another. If harvesting and processing expenses are combined, the per-liter costs are $0.50, $0.48, and $0.72 for Systems A, B, and C, respectively. Juice transportation cost is minimal ($0.01/L) for each system. The total average per-liter cost for Systems A and B are equal at $0.79/L and the cost for System C is $1.00/L. The value of the by-products (including whole-stalk silage) is the factor responsible for the cost of System A being lower than that of System B. The by-product values are $0.23, $0.17, and $0.14 for Systems A, B, and C, respectively. The primary economic advantage, then, of System A over System B is based on the results of the by-product analysis in Section 3.0 which indicate that the by-product silage produced by System A has a higher value than the rind-leaf hay and pith presscake silage produced by System B. Without production-scale experience on the cost of handling the by-products and their subsequent value, the conclusion that System A is definitely better than System B is premature.

Table 17. Cost breakdown for three systems (mean of 100-year simulation)

Item	System A Cost ($/yr)	System A Cost ($/L)[1]	System B Cost ($/yr)	System B Cost ($/L)[2]	System C Cost ($/yr)	System C Cost ($/L)[3]
Crop Production	62,050	0.28	43,800	0.29	47,450	0.27
Harvesting						
Fixed	16,286	0.07	26,813	0.18	41,227	0.24
Operating	20,753	0.09	29,633	0.20	46,001	0.27
Labor	15,691	0.07	15,563	0.10	22,596	0.13
Total Harvesting	52,730	0.24	72,009	0.48	109,824	0.64
Processing						
Fixed	20,202	0.09	0	0	5,303	0.03
Operating	25,790	0.12	435	< 0.00	5,299	0.03
Labor	11,464	0.05	0	0	3,103	0.02
Total Processing	57,456	0.26	435	< 0.00	13,705	0.08
Transportation	3,170	0.01	2,112	0.01	2,499	0.01
Total Cost	175,406	0.79	118,356	0.79	173,478	1.00
By-product Value	-49,942	-0.22	-20,638	-0.14	-24,404	-0.14
Whole-stalk Silage Value	-2,216	-0.01	-3,969	-0.03	-387	-0
Net Cost	123,248	0.56	93,749	0.63	148,687	0.86

[1] System A cost based on 222,400 L/yr production.

[2] System B cost based on 149,500 L/yr production.

[3] System C cost based on 172,800 L/yr production.

5.3.2 Response to Increased Fuel Cost

The results of a dramatic increase in fuel price, as might be expected in a world oil embargo or similar crisis, are shown in Table 18. These results do not give the complete picture, since they do not include the effect of the increases in other input costs that would accompany such large fuel price increases. Labor costs as well as the purchase price of equipment would likely increase. However, the results are useful in showing a trend. A quadrupling (300% increase)of the price of fuel causes an increase for System A of 51%, and increases of 41% and 23% for Systems B and C, respectively. These increases would be higher if the effects of inflation in other input costs were considered, but would almost certainly be less than the 300% increase in the value of the fuel produced. Since the cost of production increases at a lower rate than the value of the ethanol produced, the competitive position of sweet sorghum will improve as the cost of fuel rises. Another interesting result is that System A is affected more by the increase in fuel cost than System B. If the effects of inflation in other input costs were included, this difference would probably be more pronounced, since System B requires less equipment and less labor than System A.

5.3.3 Response to Increased Sugar Content

An increase in the average juice sugar content of only 3° Brix dramatically reduced the cost per liter for each system (Table 19). The cost for Systems A and B are reduced by $0.10/L and the cost for System C is reduced by $0.13/L, which is still not enough to make System C competitive with the other two systems. This is an indication that improvements in plant breeding, including, perhaps, a contribution from biotechnology, could significantly improve the competitive position of sweet sorghum as a feedstock for ethanol. Juice sugar concentrations in excess of 20° Brix are achievable now in temperate climates where growing seasons are longer than in Virginia.

Table 18. Feedstock cost response to increased fuel price

Fuel Cost ($/L)	Mean Feedstock Cost ($/L)		
	System A	System B	System C
0.27	0.56	0.63	0.86
0.54	0.67	0.72	0.97
1.04	0.86	0.89	1.16

Table 19. Feedstock cost response to increased sugar content

Initial Sugar Level (° Brix)	Mean Feedstock Cost ($/L)		
	System A	System B	System C
12.5	0.56	0.63	0.86
15.5	0.47	0.53	0.73

As the sugar level increases, more sugar will be left in the presscake because of the limitations of the screw press. The yield of sugar can also be improved by washing the presscake (adding water to the pith fraction as it enters the press), however the added water must then be evaporated if the juice is to be stored in the form of syrup. Also, if too much of the sugar is removed from the presscake, it will not ensile properly since the sugar is used by the anaerobic bacteria in the ensiling process.

5.3.4 Response to Increased Whole-stalk Yield

An increase in the yearly-mean yield of whole-stalks reduced the System A cost per liter by \$0.19 (Table 20). The mean costs for Systems B and C were also greatly reduced, \$0.13 and \$0.11, respectively. System B was reduced less than System A because System B is limited mainly by the Mg/h capacity of the pith combine. If the mass yield per hectare is increased, the pith combine must travel at a slower rate and consequently can cover less hectares in a given time period. The principal advantage of higher yields for System B is that the production cost would be reduced because fewer hectares are planted to achieve a given annual Mg production and there would be fewer hectares rejected because of yields below the 20 Mg/ha yield cutoff. System A can take advantage of the higher yields because the whole-stalk harvester can travel at approximately the same field speed regardless of yield, thus the per Mg cost of harvesting is reduced. Also, more material can be harvested and stockpiled on the acceptable harvest days so that the processor can continue to operate without delay even if there are prolonged periods of rain when the whole-stalk harvester cannot operate. System C is limited by the fact that the soil must be at or less than 95% of field capacity for processing to take place, therefore it cannot take the same advantage of the increased yields as System A.

Table 20. Feedstock cost response to increased yearly mean whole-stalk yield

Yearly Mean Whole-stalk Yield (Mg/ha)	Mean Feedstock Cost ($/L)		
	System A	System B	System C
42.0	0.56	0.63	0.86
60.0	0.38	0.50	0.75

Table 20. Feedstock cost response to increased yearly mean whole-stalk yield

Yearly Mean Whole-stalk Yield (Mg/ha)	**Mean Feedstock Cost ($/L)**		
	System A	**System B**	**System C**
42.0	0.56	0.63	0.86
60.0	0.38	0.50	0.75

Yields greater than 60 Mg/ha are being achieved now in areas with more favorable growing conditions. Yields can be increased by increasing the seeding rate, increasing the application of fertilizer, and/or irrigation; however, with currently available varieties of sweet sorghum, increasing yields by the above methods tends to promote rapid growth of stalks with small cross-sections. These small stalks tend to lodge more readily than larger stalks, rendering them largely unharvestable. Significant increases in yields will probably have to come from improvements in varieties. Very little research has been devoted to improving varieties of sweet sorghum over the past several years, and if yields of sweet sorghum can be improved by a factor similar to the improvement in corn yields over the past 40 years, an increase to a yearly mean yield of 60 Mg/ha, or greater, is certainly realistic.

The response of System A feedstock cost per liter of ethanol to an increase in whole-stalk yields at two juice sugar concentrations and based on two assumed values for fuel cost are shown in Figure 17. An increase in the juice sugar concentration is more effective in lowering cost at the higher fuel price, than at the lower fuel price, while the effect of increased whole-stalk yield (the slope of the curves) is approximately the same for both levels of fuel price. All of the curves are bowed slightly downward, implying that, as whole-stalk yields continue to increase above 60 Mg/ha, the rate of cost reduction will decrease.

5.4 Energy Balance

The total energy requirements for ethanol from corn, sweet sorghum syrup (Option 1), and sweet sorghum juice and by-products (Option 2) are given in Table 21. For ethanol from sweet sorghum syrup (Option 1), transportation and evaporation of juice requires approximately 2/3 as much energy (10,700 MJ/ha) as is required to grow, harvest, and process the juice (15,900 MJ/ha), and

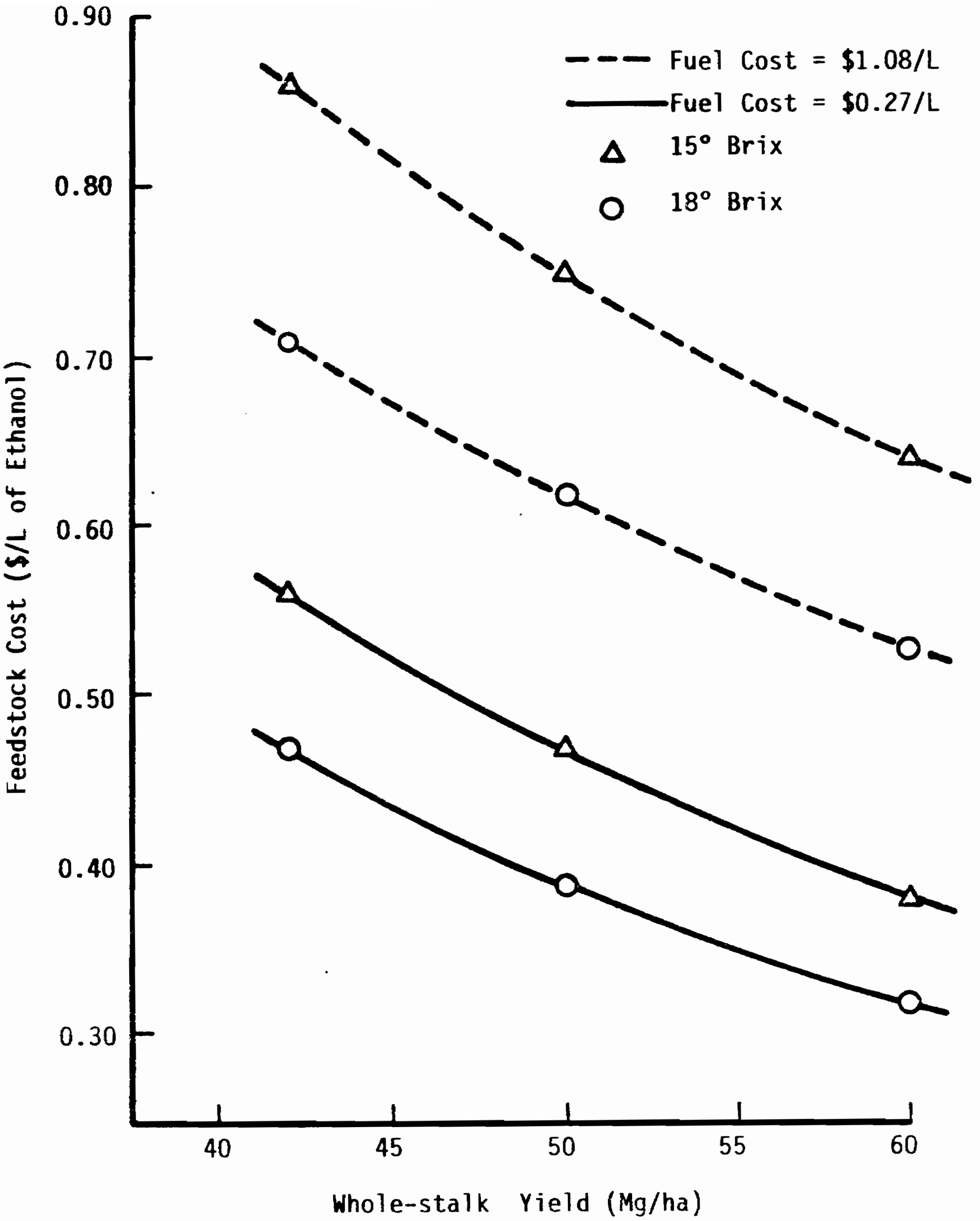

Figure 17. Influence of increase in sugar content, whole-stalk yield, and fuel cost on System A cost per liter of ethanol

Table 21. Energy balance for sweet sorghum and corn

Item	Sweet Sorghum (Option 1)		Sweet Sorghum (Option 2)		Corn	
	Liquid Fuel	Total	Liquid Fuel	Total	Liquid Fuel	Total
Energy Inputs (MJ/ha)						
Crop Production	8,972	11,003	8,972	11,003	15,342	22,534
Local Proccessing	3,377	4,881	3,377	4,881	1,314	1,693
Evaporation	934	10,708	0	0	0	0
Ferm/Distillation	699	27,987	6,588	122,310	1,784	74,837
Total Inputs	13,982	54,579	18,937	138,194	18,440	99,064
Energy Outputs						
Ethanol Produced (L/ha)	1,440	1,440	4,378	4,378	2,427	2,427
Total Output (MJ/ha)	49,450	49,450	150,341	150,341	83,343	83,343
Energy Ratio	3.54	0.91	7.94	1.09	4.52	0.84

fermentation and distillation requires more energy (28,000 MJ/ha) than is required for all operations up to that point. It is obvious that evaporation and fermentation/distillation are areas of research that have great potential for improving the energy balance in ethanol production. According to Hinman (1990), significant improvements in the fermentation/distillation area are expected in the near future.

The expected energy output and energy ratio (output divided by input) for each crop are also compared in Table 21. Based on the discussion in Section 2.4, the effective energy of one liter of ethanol when used in a 90% gasoline blend is equal to that from one liter of gasoline (34.34 MJ/L). If all energy inputs are considered, the energy ratio for sweet sorghum syrup (Option 1) is 0.91 and for sweet sorghum juice and by-products (Option 2) is 1.09. These figures represent an improvement over corn which has a ratio of 0.84. Corn does have by-products, such as distiller's dried grains from the dry milling process or corn gluten feed and corn oil from the wet milling process, which would increase its energy ratio to near 1.0 if considered; however, these products are not used as a direct energy source and are therefore not included in the energy balance. The argument can be made that corn by-products will replace other feed ingredients and thus save energy. The energy saved by not having to produce these other feed ingredients should then be credited to corn in the energy balance. However, the feed ingredients that would probably be replaced are protein sources like soybean meal and cottonseed meal. These products are themselves by-products of oil extraciton processes, so it is not clear how much, if any energy would be saved overall.

The energy ratio, if only liquid fuel inputs is considered, is 3.5 for sweet sorghum (Option 1), 7.9 for sweet sorghum (Option 2) and 4.5 for corn. A liquid fuel energy ratio of 7.9 means that 7.9 units of liquid fuel would be produced from sweet sorghum for every unit of liquid fuel invested. These figures indicate that it is profitable, from an energy standpoint, to produce liquid fuel from either corn or sweet sorghum, using nonliquid fuel inputs whenever possible. Perhaps the most important result of this energy analysis is that sweet sorghum (under Option 2) has a significant advantage over corn. The improved energy ratio for sweet sorghum indicates that, as the price of liquid fuel rises with all other variables held constant, sweet sorghum will gain an economic advantage over corn. If the price of liquid fuel increases, the feedstock cost for corn would be affected almost twice as much as the feedstock cost for sweet sorghum (Option 2) because twice as much liquid fuel is required to produce a unit of ethanol from corn as from sweet sorghum.

Hinman (1990) predicted that significant improvements in the fermentation/distillation phase will be achieved. If this prediction proves true, energy ratios would also be significantly improved. The effect of a 30% reduction in the energy required for the fermentation/distillation phase is shown in Table 22, along with the effect of a 30% improvement in the other phases of ethanol production. The 30% figure is not based on any specific expected improvements in technology, but is simply used to illustrate the effect of a major breakthrough in any one or more areas of the ethanol production process. As expected, the phase with the greatest potential contribution is the fermentation/distillation phase. The total energy ratio for sweet sorghum Option 2 improves by 36%, and improvements of 18% and 30% are seen in sweet sorghum Option 1 and corn, respectively.

Table 22. Effect of 30% reduction in energy inputs on total energy ratio

Phase of Production Experiencing 30% Reduction in Energy Inputs	Total Energy Ratio Sweet Sorghum (Option 1)	Sweet Sorghum (Option 2)	Corn
None	0.91	1.09	0.84
Crop Production	0.96	1.11	0.90
Local Processing	0.93	1.10	0.85
Evaporation	0.96	1.09	0.84
Fermentation/Distillation	1.07	1.48	1.09
All Phases	1.29	1.45	1.20

6.0 Summary and Conclusions

The Piedmont System is a collection of equipment for efficiently removing the juice from sweet sorghum stalks for the production of ethanol. The concept is to separate the whole stalks into pith and rind-leaf fractions, pass only the pith fraction through a screw press, and thus achieve an improvement in juice expression efficiency and press capacity. This research concentrated on determining the most efficient organization of the harvesting and processing equipment to achieve the lowest feedstock cost per liter of ethanol produced.

The operation of three alternative harvesting/processing systems for the Piedmont System were modeled and compared using computer simulation. The specific objective was to determine which system could produce sweet sorghum juice and deliver it to a central plant at the lowest cost per liter of potential ethanol produced. This target value was called the "feedstock" cost per liter of ethanol because the model only predicts the cost of producing the juice (feedstock) and does not include the cost of evaporating the juice to syrup, transporting the syrup to the fermentation/distillation plant, or fermentation to and distillation of ethanol.

6.1 Description of System Models

System A used a light-weight whole-stalk harvester to cut and collect bundles of whole stalks which were loaded on trailers and transported to a storage pile at a nearby "crossroads" location. The stalks were processed (at the time of harvest or up to 30 days later) and separated into three fractions: juice, pith presscake, and rind-leaf. The rind-leaf and pith presscake were ensiled together and used for cattle feed or as a feedstock for additional ethanol production through conversion of cellulose to sugar. The juice was transported to an off-farm plant and either fermented directly or evaporated into a syrup and stored for later conversion to ethanol.

System B used a "pith combine" to separate the whole-stalks into the pith fraction and the rind-leaf fraction in the field as the stalks were harvested. The rind-leaf fraction was left in the field to dry, and was later baled and handled as hay. Like the combination silage produced by System A, the hay could be either fed to cattle, or used as feedstock for ethanol production. The pith fraction was put through a screw press to produce juice and pith presscake. The juice was transported and the pith presscake ensiled, just as in System A. System B required less investment in equipment, less operating cost, and less labor than System A, but the harvest season for System B was limited to approximately 60 days compared to 90 days for System A. With System B, processing of the pith fraction (juice removal) had to occur within a few hours of harvest in order to prevent premature fermentation. With System A, the harvested stalks could be stored up to 30 days before processing. If a hard freeze occurred, stalks standing in the field would be severely damaged and begin to rapidly lose sugar, whereas stalks stored in the System A stockpile were better protected from the cold and received much less damage. The capability with System A to postpone processing effectively extended the harvest season by up to 30 days relative to System B. Another advantage of System A was that the light-weight whole-stalk harvester could operate in fields with a higher soil moisture content than could the pith combine of System B. Also, the processor of

System A could operate from stockpiled stalks even when the ground was too wet for field operations.

System C was a combination of Systems A and B. The whole-stalk harvester of System A was used so the ability to store stalks, and thus extend the harvest season, was maintained. The processor, however, moved through the field picking up bundles of stalks and separating the rind-leaf from the pith fraction. Once this separation occurred, System C operated like System B, with the pith fraction being hauled to a nearby screw press for juice removal and the rind-leaf fraction being left on the field for drying. While System C had the ability to extend the harvest season like System A, the processor in System C was more limited by wet field conditions than that of System A. Required investment for System C was found to be approximately equal to that of System A.

To compare these three systems based on the expected field conditions under which they would operate, a weather generator (WGEN) was employed to generate a large number of years of maximum and minimum temperatures, rainfall, and evaporation. This generator used historical data collected at Orange, located in the northern Virginia Piedmont, as a basis for generating the weather data. The weather data was used by a soil trafficability model ("WKDAY") to predict which days during each simulated year would be suitable for harvesting and/or processing by the different machines of Systems A, B, and C.

To compare the three systems on an impartial basis, it was necessary to determine the optimum operating parameters for each individual system; consequently sensitivity analyses were conducted to determine the effect of varying certain parameters on the feedstock cost per liter of ethanol for each of the three systems. It was determined that any field yielding less than 20 Mg/ha should not be harvested, since yields below 20 Mg/ha would not return enough value to pay for the cost of harvesting. It was also determined that the area which should be planted was 170, 120, and 130 ha for Systems A, B, and C, respectively. Simulations to select these planted areas incorporated the ability of the different systems to harvest different amounts of material during an average season, and considered the economic cost of a failure to harvest the expected amount. For instance, System

B can not harvest 120 hectares as often as System A can harvest 170 hectares, but the lower operating and investment cost of System B makes the failure to harvest all planted hectares less costly on a per-liter-of-ethanol basis. It was assumed that any fields which could not be harvested by the Piedmont System due to bad weather, would be harvested by a conventional forage harvester and ensiled. The value of the resulting silage, less the cost of harvesting it, was credited against the production cost.

The distribution of the yearly-mean whole-stalk yield for the production area served by a given harvesting/processing unit (System A, B, or C) had a mean of 42 Mg/ha based on the input of experts and a standard deviation of 7.33. It was determined that, if an error was made in estimating this standard deviation, the feedstock cost estimate would be affected, but the cost would be affected approximately equally for all three systems, and therefore, the choice of the best system would not be affected. The experts consulted were not as confident of the shape of the distribution as they were of the mean and endpoints, so caution should be exercised in drawing conclusions about the actual cost of producing juice based on the three system models. The confidence level is much higher when comparisons are made between the three systems. In general, computer models are much better at making comparisons between alternatives, than at predicting the results of a single system. The standard deviation of a within-year variation of yields, defined as the distribution of yields from all fields harvested in a given year, was chosen to be 6.67. The same arguments hold for the within-year yield distribution as for the yearly-mean yield, but the effect of varying the within-year distribution was much less than the effect of varying the yearly-mean yield distribution.

Certainly, one way to improve the models used in this study would be to more accurately identify the yearly-mean and within-year yield distributions. The only viable method of accomplishing this improvement would be by adding a crop growth submodel. If such a submodel were added, the yield for a given year would be determined by the weather experienced during that year's growing season. Without the development of a model, large quantities of actual yield data for the varieties and the locations of interest would need to be gathered and analyzed. Collection of data for distribution fitting would be expensive and prohibitively time consuming, as approximately 100 years of data would be required to gain confidence in the distribution derived from the data.

6.2 Economic Results

6.2.1 Comparison of System Costs

A comparison of the feedstock cost per liter for the three systems was done using a statistical analysis which predicted the least cost system with a 95% confidence level, given that a difference of less than $0.02/L was insignificant. If the by-products were used as cattle feed and valued as such, the weighted average feedstock cost per liter of ethanol was $0.56, $0.63, and $0.87 for Systems A, B, and C, respectively. If the by-products were used for the production of ethanol through cellulose conversion, the value of the by-products was lower, due primarily to the relatively high cost for transporting this biomass to a central processing plant. The lower value of the by-products for cellulose conversion effectively raised the feedstock cost for each system to $0.68, $0.72, and $0.95 per liter of ethanol for Systems A, B, and C, respectively. These costs are based on the number of liters of ethanol produced from the juice only. The economic analysis considered the cellulose conversion to be a separate operation and only considered the dollar value of the by-products as if they were being sold to this separate operation.

Based on this analysis, System A was the system which would be chosen as the least cost system of the three. System B was slightly higher, and System C was much higher than Systems A and B. It was found, however, that the primary difference between Systems A and B was the higher value of the by-product silage (combination rind-leaf and pith presscake) produced by System A as compared to the rind-leaf hay and pith presscake silage produced by System B. Considering the fact that production-scale tests have not been done, and therefore the expected yields and values of these by-products have not been thoroughly established, the "true" difference between Systems A and B is questionable. The cost of System C, however, is sufficiently higher than the other systems to eliminate it from consideration for further research.

One feature of the System B pith combine, which was not included in the model, is it's ability to at least partially harvest stalks which have lodged. As presently envisioned, the whole-stalk harvester could not harvest these stalks at all. Considering the benefit gained by the pith combine's ability to harvest lodged stalks and the uncertainty concerning the exact value of by-products, neither System A nor System B should be eliminated from future research. It is possible that a combination of the two systems might be employed when a commercial industry is established. System A might be mainly used to harvest and stockpile stalks to be processed after the harvest season, and System B might be used for harvesting stalks during the season. Alternatively, System B might be used primarily to harvest fields that have been lodged by high winds and System A would harvest the standing crop.

6.2.2 Sensitivity to Expected Future Changes

One of the areas of research which holds great potential for lowering the cost of ethanol feedstock is the improvement of varieties through plant breeding techniques and, perhaps, genetic manipulation. It is highly desirable to develop varieties which will produce higher juice sugar levels, higher yields, and less tendency to lodge. To determine how much these improvements might lower the cost of feedstock, a series of sensitivity analyses were done. It was determined that both an increase in the juice sugar content and an increase in whole-stalk yield would significantly reduce the feedstock cost per liter of ethanol for all three systems. Reductions of approximately 17% were seen in each system by increasing the juice sugar level by 3° Brix, and reductions of up to 33% were forecast as a result of an increase in whole-stalk yield from 42 to 60 Mg/ha. An increase in juice sugar content caused a greater reduction in cost when the price of the fuel used to harvest and process the crop was increased. This response indicated that improved varieties of sweet sorghum would make a greater contribution as fuel prices rise. An increase in fuel price would increase the feedstock cost for all three systems, but the increase would be less for System B than for Systems A and C, because of the lower energy requirement of System B. This lower response to increased fuel cost by System B supports the conclusion that System B should not be eliminated from future research, since future market conditions might make System B more economical than System A.

6.3 Energy Analysis

The response of feedstock cost to increases in fuel prices is strongly influenced by the amount of energy required to produce ethanol from a given feedstock. For this reason, an energy analysis of the production of ethanol from sweet sorghum was done and compared to the production of ethanol from corn. Two options were analyzed for production from sweet sorghum. Under Option 1, the by-products were fed to cattle, and the juice was concentrated to a syrup, stored, and used throughout the year as the feedstock for the ethanol plant. Under Option 2, the juice was used for the production of ethanol during the harvest season, and was not concentrated into syrup and stored. The by-product silage was used the remainder of the year as feedstock for cellulose conversion to sugar and subsequent fermentation and distillation. Comparisons among the two sweet sorghum options and corn were made on the basis of energy ratios (energy output divided by energy input). The total energy ratios were found to be 0.9, 1.1, and 0.8 for sweet sorghum Option 1, sweet sorghum Option 2, and corn, respectively. These ratios indicate that approximately as much energy is required to make ethanol as is derived from it. However, much of the energy required to make ethanol can be supplied by coal, biomass, or other forms of energy which are not suitable for operating automobiles, farm tractors, and other mobile power units. If only liquid fuels were considered in the energy balance, the ratios improved to 3.5, 7.9, and 4.5 for sweet sorghum Option

1, sweet sorghum Option 2, and corn, respectively. In other words, approximately eight liters of liquid fuel could be produced under sweet sorghum Option 2 for each liter used in the process. In addition, it is expected that new technologies presently being studied in the area of fermentation and distillation will significantly reduce the energy requirements for this phase of ethanol production, which presently accounts for over 50% of the required energy in the ethanol production process. Total energy ratio could be improved to approximately 1.5 if this research is successful. As energy prices increase, processes with higher energy ratios will gain an economic advantage over processes with low ratios. If the expected increases in energy prices occur, sweet sorghum Option 2 is expected to gain an economic advantage over sweet sorghum Option 1 or corn as a feedstock for ethanol production. This advantage is revealed by both the total energy ratio and the liquid fuel energy ratio.

6.4 Research Needs

An industry which produces ethanol from sweet sorghum will be viable only if a number of technological advances are made. The following is a list of research areas which are perceived to be vital to the development of such an industry:

1. Sugar and whole-stalk yields need to be increased. To accomplish these increases, improved varieties will be required, as well as improvements in pest management strategies and other agronomic practices.
2. Improvements in fermentation/distillation technology are also necessary. Although this stage of the process only costs approximately $0.12/L at the present time (USDA, 1988), the process is the most energy intensive portion of ethanol production, and as energy prices rise, efficiency in this step will be much more crucial. Included in this area is the need for economical conversion of cellulose to sugar for the production of ethanol on a commercial scale.

3. Much work remains in the development of efficient machines to harvest and process sweet sorghum stalks. In addition to refining existing machines, the stalk feeding mechanism needs to be completed, and a pith combine should be developed.
4. As more information is gathered, the simulation models used in this study need to be improved.
    - A crop growth model should be added to the model to more accurately predict the yield of each hectare of sweet sorghum. This model might be enhanced by the incorporation of information from a geographic information system (GIS) to predict yields based on actual geographic information.
    - The value of by-products could be better established if data were available from large-scale tests. These tests would include production tests to determine field and storage losses, feeding trials to establish the value for cattle feed, and tests to establish the value of the by-products as a feedstock for cellulose conversion.
    - Additional work is needed to determine the storability of bundled stalks in the field at varying times during the harvest season. Tests should be done with leaves still attached, and ambient temperatures should be recorded to determine the effect of temperature on storability. Since storing of stalks is the primary advantage of System A, the storability of this material needs to be firmly established in order to raise the level of confidence in the model.

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Appendix A. Hay Equipment Cost Estimations

31 kW Tractor with Loader

Expenses $/y

Fuel 8.42 l/h × $.26/l × 744 h/y = **1629**

Labor $5.50/h × 694 h/y = **3817**

Depreciation

$15,900 − 10% salvage = $14,310 to be depreciated

$$\frac{10{,}000 \text{ h life}}{694 \text{ h/y}} = 14 \text{ y life}$$

$$\frac{\$14{,}310}{14 \text{ yr}} = \mathbf{1022}$$

Interest

$$\frac{\$15{,}900 + 10\% \text{ salvage}}{2} \times 5\% \text{ real interest} = \mathbf{437}$$

Repairs and Maintenance (120% of Purchase Price over Machine Life)

$$\frac{\$15{,}900 \times 1.2}{14 \text{ y}} = \mathbf{1363}$$

Taxes, Insurance, and Housing (2% of Purchase Price per Year)

$15,900 × .02 = **318**

Total Expenses **8586**

% Attributable to Rind-leaf Hay Operation

$$\frac{187 \text{ h}}{694 \text{ h}} = 26.9\%$$

.269 × 8586 = **2310**

Cost per Productive Hour

$$\frac{2310}{164 \text{ h/y}} = \mathbf{\$14.09}$$

Cost per Mg of Hay

$$\frac{2310}{410 \text{ Mg}} = \mathbf{\$5.63}$$

Side Delivery Hay Rake (2.44m wide)

Expenses $/y

Depreciation

$2,500 – 10% salvage = $2,250 to be depreciated

$$\frac{2{,}000 \text{ h life}}{333 \text{ h/y}} = 6 \text{ y life}$$

$$\frac{\$2{,}250}{6 \text{ y}} \qquad = \mathbf{375}$$

Interest

$$\frac{\$2{,}500 + 10\% \text{ salvage}}{2} \times 5\% \text{ real interest} \qquad = \mathbf{69}$$

Repairs and Maintenance (100% of Purchase Price over Machine Life)

$$\frac{\$2{,}500}{6 \text{ y}} \qquad = \mathbf{417}$$

Taxes, Insurance, and Housing (2% of Purchase Price per Year)

$2,500 × .02 = **50**

Total Expenses **911**

% Attributable to Rind-leaf Hay Operation

$$\frac{105 \text{ h}}{133 \text{ h}} = 31.5\%$$

.315 × 911 = **287**

Cost per Productive Hour

$$\frac{287}{105 \text{ h/y}} \qquad = \mathbf{\$2.73}$$

Cost per Mg of Hay

$$\frac{287}{410 \text{ Mg}} \qquad = \mathbf{\$.70}$$

48 kW Tractor (Baler)

Expenses $/y

Fuel 15.92 l/h × $.26/l × 744 h/y = **3080**

Labor $5.50/h × 694 h/y = **3817**

Depreciation

$19,800 – 10% salvage = $17,820 to be depreciated

$$\frac{10{,}000\text{ h life}}{694\text{ h/y}} = 14\text{ y life}$$

$$\frac{\$17{,}820}{14\text{ y}}$$ = **1273**

Interest

$$\frac{\$19{,}800 + 10\%\text{ salvage}}{2} \times 5\%\text{ real interest}$$ = **545**

Repairs and Maintenance (120% of Purchase Price over Machine Life)

$$\frac{\$19{,}800 \times 1.2}{14\text{ yr}}$$ = **1697**

Taxes, Insurance, and Housing (2% of Purchase Price per Year)

$19,800 × .02 = **396**

Total Expenses **10808**

% Attributable to Rind-leaf Hay Operation

$$\frac{187\text{ h}}{694\text{ h}} = 26.9\%$$

.269 × 10808 = **2907**

Cost per Productive Hour

$$\frac{2907}{164\text{ h/y}}$$ = **$17.73**

Cost per Mg of Hay

$$\frac{2907}{410\text{ Mg}}$$ = **$7.09**

Round Bale Hay Baler

Expenses $/y

Twine

$$\frac{\$25/\text{roll}}{75\text{bales/roll}} \times 840\text{bales/y} \qquad = 280$$

Depreciation

$12,000 – 10% salvage = $10,800 to be depreciated

$$\frac{2{,}000\ \text{h life}}{520\ \text{h/y}} = 4\ \text{y life}$$

$$\frac{\$10{,}800}{4\ \text{y}} \qquad = 2700$$

Interest

$$\frac{\$12{,}000 + 10\%\ \text{salvage}}{2} \times 5\%\ \text{real interest} \qquad = 330$$

Repairs and Maintenance (80% of Purchase Price over Machine Life)

$$\frac{\$12{,}000 \times 0.8}{4\ \text{y}} \qquad = 2400$$

Taxes, Insurance, and Housing (2% of Purchase Price per Year)

$$\$12{,}000 \times .02 \qquad = 240$$

Total Expenses 5950

% Attributable to Rind-leaf Hay Operation

$$\frac{164\ \text{h}}{520\ \text{h}} = 31.5\%$$

$$.315 \times 5950 \qquad = 1874$$

Cost per Productive Hour

$$\frac{1874}{164\ \text{h/y}} \qquad = \$11.43$$

Cost per Mg of Hay

$$\frac{1874}{410\ \text{Mg}} \qquad = \$4.57$$

Appendix B. Dairy Ration Formulae

This appendix contains a listing of the dairy ration formulae used to estimate the value of sweet sorghum by-products when used as livestock feed. Each table is a copy of the screen display which is used in the interactive program, DAIR4, to balance dry matter, crude protein, and net energy requirements for dairy rations. The abbreviations used in the table headings are defined as follows: DM = Dry Matter, CP = Crude Protein, NE = Net Energy, and ADF = Acid Detergent Fiber. The feed ingredient descriptions shown at the bottom of the first table are only shown once for each type of ration since this material is the same for all rations of the same type. Each type ration; dry cow, lactating cow, or growing heifer; was formulated first with conventional ingredients; corn silage, fescue hay, alfalfa hay, corn, and soybean meal. It was then reformulated by substituting either sorghum by-product silage (presscake or combination presscake and rind-leaf), rind-leaf hay, or whole-stalk silage for corn silage or hay and adjusting supplemental ingredients as necessary. In each case, an attempt was made to equalize the cost per cow of all rations of the same type by adjusting the cost of the substituted ingredient used in that ration. The resultant cost is taken as the market value of that ingredient.

Dry Cow Rations

Table B1. Dry cow ration formulated with reference ingredients, fescue and alfalfa hay

		DM		CP		NE		ADF		COST	
Feed	lbs	%	lb	%	lb	Mcal/lb	Mcal	%	lb	$/ton	$/cow
313	0.00	38.0	0.0	7.5	0.0	0.68	0.0	30.0	0.0	20	0.00
114	21.4	92.0	19.7	9.5	1.9	0.46	9.1	39.0	7.7	50	0.53
537	0.00	89.0	0.0	49.9	0.0	0.85	0.0	10.0	0.0	250	0.00
115	0.00	90.0	0.0	5.0	0.0	0.55	0.0	41.0	0.0	40	0.00
324	0.00	40.0	0.0	7.0	0.0	0.45	0.0	30.0	0.0	0	0.00
409	0.00	88.0	0.0	10.1	0.0	0.92	0.0	4.0	0.0	111	0.00
103	5.00	90.0	4.5	17.0	0.8	0.57	2.6	35.0	1.6	100	0.25
323	0.00	30.0	0.0	7.5	0.0	0.56	0.0	42.0	0.0	0	0.00
Total	26.40		24.2		2.6		11.6		9.3		0.78
Dry Cow Requirements											
		101%	24.0	107%	2.5	100%	11.6				

NE (MCALS/LB)	0.48	313	CORN SILAGE 32-40%DM
PERCENT FIBER	38.3	114	FESCUE HAY, BL
PERCENT PROTEIN	10.9	537	SOYBEAN OIL MEAL,44%
DM INTAKE (% BWT)	2.0	115	SORG RL HAY
BODY WEIGHT	1200.	324	SORG BYPROD SILAGE
DAILY LBS MILK	0.	409	CORN, GND
FAT TEST	3.5	103	ALFALFA, HAY, MB
LACTATION NO. =	3.	323	SORGHUM SILAGE

Table B2. Dry cow ration formulated with sorghum by-product silage substituted for fescue hay

		DM		CP		NE		ADF		COST	
Feed	lbs	%	lb	%	lb	Mcal/lb	Mcal	%	lb	$/ton	$/cow
113	0.00	38.0	0.0	7.5	0.0	0.68	0.0	30.0	0.0	20	0.00
114	0.00	92.0	0.0	9.5	0.0	0.46	0.0	39.0	0.0	50	0.00
537	0.00	89.0	0.0	49.9	0.0	0.85	0.0	10.0	0.0	250	0.00
115	0.00	90.0	0.0	5.0	0.0	0.55	0.0	41.0	0.0	0	0.00
324	40.00	40.0	16.0	6.6	1.1	0.54	8.6	35.0	5.6	16	0.32
409	0.00	88.0	0.0	10.1	0.0	0.92	0.0	4.0	0.0	111	0.00
103	9.00	90.0	8.1	17.0	1.4	0.57	4.6	35.0	2.8	100	0.45
323	0.00	30.0	0.0	7.5	0.0	0.56	0.0	42.0	0.0	0	0.00
Total	49.00		24.1		2.4		13.3		8.4		0.77
Dry Cow Requirements											
		100%	24.0	99%	2.5	114%	11.6				

Table B3. Dry cow ration formulated with rind-leaf hay substituted for fescue hay

		DM		CP		NE		ADF		COST	
Feed	lbs	%	lb	%	lb	Mcal/lb	Mcal	%	lb	$/ton	$/cow
313	0.00	38.0	0.0	7.5	0.0	0.68	0.0	30.0	0.0	20	0.00
114	0.00	92.0	0.0	9.5	0.0	0.46	0.0	39.0	0.0	50	0.00
537	0.00	89.0	0.0	49.9	0.0	0.85	0.0	10.0	0.0	250	0.00
115	16.00	90.0	14.4	5.7	0.8	0.54	7.8	41.0	5.9	32	0.26
324	0.00	40.0	0.0	7.0	0.0	0.45	0.0	30.0	0.0	19	0.00
409	0.00	88.0	0.0	10.1	0.0	0.92	0.0	4.0	0.0	111	0.00
103	10.50	90.0	9.4	17.0	1.6	0.57	5.4	35.0	3.3	100	0.52
323	0.00	30.0	0.0	7.5	0.0	0.56	0.0	42.0	0.0	0	0.00
Total	26.50		23.8		2.4		13.2		9.2		0.78
Dry Cow Requirements											
		99%	24.0	99%	2.5	113%	11.6				

Table B4. Dry cow ration formulated with whole-stalk silage substituted for fescue hay

		DM		CP		NE		ADF		COST	
Feed	lbs	%	lb	%	lb	Mcal/lb	Mcal	%	lb	$/ton	$/cow
313	0.00	38.0	0.0	7.5	0.0	0.68	0.0	30.0	0.0	20	0.00
114	0.00	92.0	0.0	9.5	0.0	0.46	0.0	39.0	0.0	50	0.00
537	0.00	89.0	0.0	49.9	0.0	0.85	0.0	10.0	0.0	250	0.00
115	0.00	90.0	0.0	5.0	0.0	0.54	0.0	41.0	0.0	25	0.00
324	0.00	40.0	0.0	7.0	0.0	0.45	0.0	30.0	0.0	19	0.00
409	0.00	88.0	0.0	10.1	0.0	0.92	0.0	4.0	0.0	111	0.00
103	8.00	90.0	7.2	17.0	1.2	0.57	4.1	35.0	2.5	100	0.40
323	55.00	30.0	16.5	7.5	1.2	0.56	9.2	42.0	6.9	14	0.38
Total	63.00		23.7		2.5		13.3		9.4		0.78
Dry Cow Requirements											
		99%	24.0	100%	2.5	115%	11.6				

Lactating Cow Rations

Table B5. Lactating cow ration formulated with reference ingredients; corn silage, fescue hay, and soybean meal

		DM		CP		NE		ADF		COST	
Feed	lbs	%	lb	%	lb	Mcal/lb	Mcal	%	lb	$/ton	$/cow
313	75.00	38.0	28.5	7.5	2.1	0.68	19.4	30.0	8.5	20	0.75
114	5.00	92.0	4.6	9.5	0.4	0.46	2.1	39.0	1.8	50	0.13
537	5.50	89.0	4.9	49.9	2.4	0.85	4.2	10.0	0.5	250	0.69
324	0.00	40.0	0.0	7.0	0.0	0.45	0.0	30.0	0.0	30	0.00
115	0.00	90.0	0.0	5.0	0.0	0.55	0.0	41.0	0.0	0	0.00
409	0.00	88.0	0.0	10.1	0.0	0.92	0.0	4.0	0.0	0	0.00
103	0.00	90.0	0.0	17.0	0.0	0.57	0.0	35.0	0.0	0	0.00
323	0.00	30.0	0.0	7.5	0.0	0.56	0.0	42.0	0.0	0	0.00
Total	85.50		38.0		5.0		25.7		10.8		1.56
Lactating Requirements											
		100%	38.0	100%	5.0	104%	24.6				

NE (MCALS/LB)	0.68
PERCENT FIBER	28.5
PERCENT PROTEIN	13.2
DM INTAKE (% BWT)	3.2
BODY WEIGHT	1200
DAILY LBS MILK	50
FAT TEST	3.5
LACTATION NO. =	3

313 CORN SILAGE 32-40%DM
114 FESCUE HAY, BL
537 SOYBEAN OIL MEAL,44%
324 SORG BYPROD SILAGE
115 SORG RL HAY
409 CORN, GND
103 ALFALFA, HAY, MB
323 SORGHUM SILAGE

Table B6. Lactating cow ration formulated with by-product silage substituted for corn silage and fescue hay

		DM		CP		NE		ADF		COST	
Feed	lbs	%	lb	%	lb	Mcal/lb	Mcal	%	lb	$/ton	$/cow
313	0.00	38.0	0.0	7.5	0.0	0.68	0.0	30.0	0.0	20	0.00
114	0.00	92.0	0.0	9.5	0.0	0.46	0.0	39.0	0.0	50	0.00
537	5.75	89.0	5.1	49.9	2.6	0.85	4.3	10.0	0.5	250	0.72
324	63.00	40.0	25.2	6.6	1.7	0.54	13.6	35.0	8.8	10	0.31
115	0.00	90.0	0.0	5.0	0.0	0.55	0.0	41.0	0.0	0	0.00
409	9.50	88.0	8.4	10.1	0.8	0.92	7.7	4.0	0.3	111	0.53
0	0.00	0.0	0.0	0.0	0.0	0.00	0.0	0.0	0.0	0	0.00
0	0.00	0.0	0.0	0.0	0.0	0.00	0.0	0.0	0.0	0	0.00
Total	78.25		38.7		5.1		25.6		9.7		1.56
Lactating Requirements											
		100%	38.6	100%	5.0	104%	24.6				

Table B7. Lactating cow ration formulated with rind-leaf hay substituted for corn silage and fescue hay

		DM		CP		NE		ADF		COST	
Feed	lbs	%	lb	%	lb	Mcal/lb	Mcal	%	lb	$/ton	$/cow
313	0.00	38.0	0.0	7.5	0.0	0.68	0.0	30.0	0.0	20	0.00
114	0.00	92.0	0.0	9.5	0.0	0.46	0.0	39.0	0.0	50	0.00
537	6.50	89.0	5.8	49.9	2.9	0.85	4.9	10.0	0.6	250	0.81
324	0.00	40.0	0.0	7.0	0.0	0.55	0.0	41.0	0.0	11	0.00
115	28.00	90.0	25.2	5.7	1.4	0.54	13.6	41.0	10.3	22	0.31
409	8.00	88.0	7.0	10.1	0.7	0.92	6.5	4.0	0.3	111	0.44
0	0.00	0.0	0.0	0.0	0.0	0.00	0.0	0.0	0.0	0	0.00
0	0.00	0.0	0.0	0.0	0.0	0.00	0.0	0.0	0.0	0	0.00
Total	42.50		38.0		5.0		25.0		11.2		1.56
Lactating Requirements											
		100%	37.8	100%	5.0	102%	24.6				

Table B8. Lactating cow ration formulated with whole-stalk silage substituted for corn silage and fescue hay

		DM		CP		NE		ADF		COST	
Feed	lbs	%	lb	%	lb	Mcal/lb	Mcal	%	lb	$/ton	$/cow
113	0.00	38.0	0.0	7.5	0.0	0.68	0.0	30.0	0.0	20	0.00
114	0.00	92.0	0.0	9.5	0.0	0.46	0.0	39.0	0.0	50	0.00
537	5.50	89.0	4.9	49.9	2.4	0.85	4.2	10.0	0.5	250	0.69
324	0.00	40.0	0.0	7.0	0.0	0.55	0.0	41.0	0.0	11	0.00
115	0.00	90.0	0.0	5.0	0.0	0.54	0.0	41.0	0.0	11	0.00
409	7.00	88.0	6.2	10.1	0.6	0.92	5.7	4.0	0.2	111	0.39
323	87.00	30.0	26.1	7.5	2.0	0.56	14.6	42.0	11.0	11	0.48
0	0.00	0.0	0.0	0.0	0.0	0.00	0.0	0.0	0.0	0	0.00
Total	99.50		37.2		5.0		24.4		11.7		1.55
Lactating Requirements											
		100%	37.3	100%	5.0	99%	24.6				

Heifer Rations

Table B9. Heifer ration formulated with reference ingredients; fescue hay, soybean meal, and corn

		DM		CP		NE		ADF		COST	
Feed	lbs	%	lb	%	lb	Mcal/lb	Mcal	%	lb	$/ton	$/cow
113	0.00	38.0	0.0	7.5	0.0	65.0	0.0	30.0	0.0	20	0.00
114	10.00	92.0	9.2	9.5	0.9	48.0	4.4	39.0	3.6	50	0.25
115	0.00	90.0	0.0	5.0	0.0	55.0	0.0	41.0	0.0	0	0.00
537	1.00	89.0	0.9	49.9	0.4	84.0	0.7	10.0	0.1	250	0.13
324	0.00	40.0	0.0	7.0	0.0	55.0	0.0	41.0	0.0	0	0.00
409	5.00	88.0	4.4	10.1	0.4	88.0	3.9	4.0	0.2	111	0.28
103	0.00	90.0	0.0	17.0	0.0	58.0	0.0	35.0	0.0	0	0.00
323	0.00	30.0	0.0	7.5	0.0	60.0	0.0	42.0	0.0	0	0.00
Total	16.00		14.5		1.8		9.0		3.9		0.65
Heifer Requirements											
		99%	14.6	99%	1.8	104%	8.7				

PERCENT TDN	62
PERCENT FIBER	26.6
PERCENT PROTEIN	12.2
DM INTAKE (% BWT)	2.4
BODY WEIGHT	600
DAILY LBS GAIN	1.5
BREED : LARGE (L) OR SMALL (S)	L

313 CORN SILAGE 32-40%DM
114 FESCUE HAY, BL
115 SORG RL HAY
537 SOYBEAN OIL MEAL,44%
324 SORG BYPROD SILAGE
409 CORN, GND
103 ALFALFA, HAY, MB
323 SORGHUM SILAGE

Table B10. Heifer ration formulated with sorghum by-product silage substituted for fescue hay

		DM		CP		NE		ADF		COST	
Feed	lbs	%	lb	%	lb	Mcal/lb	Mcal	%	lb	$/ton	$/cow
313	0.00	38.0	0.0	7.5	0.0	65.0	0.0	30.0	0.0	20	0.00
114	0.00	92.0	0.0	9.5	0.0	48.0	0.0	39.0	0.0	50	0.00
115	0.00	90.0	0.0	5.0	0.0	55.0	0.0	41.0	0.0	40	0.00
537	2.10	89.0	1.9	49.9	0.9	84.0	1.6	10.0	0.2	250	0.26
324	28.50	40.0	11.4	6.6	0.8	55.0	6.3	35.0	4.0	23	0.33
409	1.00	88.0	0.9	10.1	0.1	88.0	0.8	4.0	0.0	111	0.06
103	0.00	90.0	0.0	17.0	0.0	58.0	0.0	35.0	0.0	0	0.00
323	0.00	30.0	0.0	7.5	0.0	60.0	0.0	42.0	0.0	0	0.00
Total	31.60		14.1		1.8		8.6		4.2		0.65
Heifer Requirements											
		100%	14.2	100%	1.8	99%	8.7				

Table B11. Heifer ration formulated with rind-leaf hay substituted for fescue hay

		DM		CP		NE		ADF		COST	
Feed	lbs	%	lb	%	lb	Mcal/lb	Mcal	%	lb	$/ton	$/cow
313	0.00	38.0	0.0	7.5	0.0	65.0	0.0	30.0	0.0	20	0.00
114	0.00	92.0	0.0	9.5	0.0	48.0	0.0	39.0	0.0	50	0.00
115	12.50	90.0	11.2	5.7	0.6	55.0	6.2	41.0	4.6	47	0.29
537	2.40	89.0	2.1	49.9	1.1	84.0	1.8	10.0	0.2	250	0.30
324	0.00	40.0	0.0	7.0	0.0	55.0	0.0	41.0	0.0	24	0.00
409	1.00	88.0	0.9	10.1	0.1	88.0	0.8	4.0	0.0	111	0.06
103	0.00	90.0	0.0	17.0	0.0	58.0	0.0	35.0	0.0	0	0.00
323	0.00	30.0	0.0	7.5	0.0	60.0	0.0	42.0	0.0	0	0.00
Total	15.90		14.3		1.8		8.8		4.9		0.65
Heifer Requirements											
		100%	14.3	101%	1.8	101%	8.7				

Table B12. Heifer ration formulated with whole stalk silage substituted for fescue hay

		DM		CP		NE		ADF		COST	
Feed	lbs	%	lb	%	lb	Mcal/lb	Mcal	%	lb	$/ton	$/cow
313	0.00	38.0	0.0	7.5	0.0	65.0	0.0	30.0	0.0	20	0.00
114	0.00	92.0	0.0	9.5	0.0	48.0	0.0	39.0	0.0	50	0.00
115	0.00	90.0	0.0	5.0	0.0	55.0	0.0	41.0	0.0	45	0.00
537	1.80	89.0	1.6	49.9	0.8	84.0	1.3	10.0	0.2	250	0.22
324	0.00	40.0	0.0	7.0	0.0	55.0	0.0	41.0	0.0	24	0.00
409	0.00	88.0	0.0	10.1	0.0	88.0	0.0	4.0	0.0	111	0.00
323	43.50	30.0	13.0	7.5	1.0	60.0	7.8	42.0	5.5	19	0.41
103	0.00	90.0	0.0	17.0	0.0	58.0	0.0	35.0	0.0	0	0.00
Total	45.30		14.7		1.8		9.2		5.6		0.64
Heifer Requirements											
		100%	14.6	100%	1.8	106%	8.7				

Appendix C. Listing of Soil Trafficability Subprogram

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C*********************************************************************
C
C WKDAY IS AN ADAPTATION OF THE PROGRAM, FALL WORKDAY ESTIMATOR,
BY
C J. DYER.  IT IS ADAPTED SPECIFICALLY FOR ESTIMATING WORKDAYS FOR
C HARVESTING SWEET SORGHUM IN SEPTEMBER AND OCTOBER.  AUGUST
WEATHER
C RECORDS ARE USED TO PROVIDE A MORE REALISTIC STARTING CONDITION
CFOR THE SIMULATIONS.  THE SOIL IS ASSUMED TO START AT A RANDOM
MOISTURE
C CONTENT BETWEEN 0% AND 100% OF FIELD CAPACITY ON AUGUST 1 OF
EACH
CYEAR.  THE MOISTURE CONTENT ON SEPTEMBER 1 (BEGINNING OF HARVEST
SEASON)
C IS THEN DEPENDENT ON THE WEATHER EXPERIENCED IN AUGUST.
C THE PROGRAM RUNS TWO TIMES ALLOWING THE USER TO INPUT TWO DIF-
FERENT
C CRITICAL MOISTURE LEVELS.  THE OUTPUT INCLUDES THE RESULTS FOR
BOTH
C RUNS.
C
C THE ADAPTATION WAS WRITTEN BY JOHN W. WORLEY      JANUARY, 1990
C
C*********************************************************************
      REAL TMAX(100,122),TMIN(100,122),P(100,122),PE(100,122),Z(100)
      REAL STMOIST(100)
      INTEGER WORK(2,100,122),NODAYS(100)
      J=80
C*********************************************************************
C TMAX=MAXIMUM TEMPERATURE FOR EACH DAY (DEG. C)
C TMIN=MINIMUM TEMPERATURE FOR EACH DAY (DEG. C)
C P=DAILY PRECIPITATION (CM)
C PE=DAILY PAN EVAPORATION (CM)
C WORK=1 IF A WORK DAY, 0 IF TOO WET TO WORK
C J=NUMBER OF YEARS OF DATA
C*********************************************************************
C
C READ WEATHER DATA
      READ(10,100)((IM,ID,IY,TMAX(IY,I),TMIN(IY,I),
```

```
     $P(IY,I),PE(IY,I),I=1,122),K=1,J)
 100  FORMAT(3I5,4F7.2)
 C  READ IN Z-TABLE
      READ(15,120)(Z(I),I=1,100)
 120  FORMAT(10F6.2)
      IRUN=1
 C GET CRITICAL SOIL MOISTURE LEVEL FROM USER
 122  WRITE(*,123)
 123  FORMAT(' INPUT CRITICAL MOISTURE LEVEL (FRACTION)')
      READ(*,*)CMOIST
 C**********************************************************************
 C CONSTANTS AND SYMBOLS USED IN SOIL MOISTURE BUDGET
 C**********************************************************************
 C DRS=DRAINAGE PER DAY (CM)
 C RDS=ZONAL EXCHANGE COEFFICIENT
 C RTX=ROOT EXTRACTION COEFFICIENT
 C C1,C2=FIELD CAPACITY OF TWO SOIL LAYERS (CM)
 C V1,V2=TOTAL VOID SPACE OF TWO SOIL LAYERS (CM)
 C S1,S2=AMOUNT OF MOISTURE HELD IN EACH LAYER ON A GIVEN DAY (CM)
 CSTMOIST=STARTING MOISTURE CONTENT OF SOIL ON AUGUST 1 (FRACITON
OF C1,C2)
 C CMOIST=CRITICAL MOIST CONTENT ABOVE WHICH FIELD WORK CANNOT
BE DONE (FRACTION )
 C PDL=AMOUNT OF WATER PUDDLED ON TOP OF SOIL (CM)
 C DRN1,DRN2=DOWNWARD DRAINAGE OF WATER FROM EACH LAYER ON A
GIVEN DAY (CM)
 C DF=WATER DIFFUSED BETWEEN ZONES (CM)
 C ASE=ACTUAL SURFACE EVAPORATION (CM)
 C AERT=ROOT EXTRACTED WATER (CM)
 C PE=PAN (POTENTIAL) EVAPORATION (CM)
 C P=DAILY PRECIPITATION (CM)
 C Z=Z TABLE VALUE BASED ON (ACTUAL MOISTURE/MOISTURE CAPACITY)
 C IFREEZE=INDICATOR THAT ROOTS ARE NO LONGER EXTRACTING WATER
DUE TO
 C        EXTENDED COLD WEATHER
 C
 C**********************************************************************
 C
      ISEED=529838
      CALL RNSET(ISEED)
      DRS=0.7
      RDS=0.2
      RTX=0.1
      C1=2.54
      C2=12.70
      V1=4.06
      V2=20.32
      DO 150 IY=1,J
 C SET INITIAL CONDITIONS FOR EACH YEAR
       STMOIST(IY)=RNUNF()
       NODAYS(IY)=0
       S1=STMOIST(IY)*C1
       S2=STMOIST(IY)*C2
       DRN1=0.
       DRN2=0.
       DF=0.
```

```
      IFREEZE=0
      PDL=0.
      TN=TMIN(IY,1)
      DO 140 I=1,122
C INITIALLY ASSUME THAT DAY IS A WORK DAY
        WORK(IRUN,IY,I)=1
C IF MORE THAN 0.5 CM OF RAIN FALLS, ASSUME NONWORKDAY
        IF(P(IY,I).GT.0.5)WORK(IRUN,IY,I)=0
C
C LOWER ZONE MOISTURE CONTENT CALCULATIONS
C   LOWER ZONE MOISTURE CONTENT CANNOT BE MORE THAN TOTAL VOID
SPACE
        IF(S2.GT.V2)S2=V2
C   GRAVITY WATER WILL DRAIN TO FIELD CAPACITY
        IF(S2.GT.C2.AND.DRN2.GT.(S2-C2))DRN2=S2-C2
        IF(S2.GT.C2)S2=S2-DRN2
C
C UPPER ZONE MOISTURE CONTENT CALCULATIONS
C   INITIAL ESTIMATE = INITIAL + RAIN + YESSTERDAY'S SURFACE WATER
        S1=S1+P(IY,I)+PDL
C   ESTIMATION OF ACTUAL SURFACE EVAPORATION
        M=S1/C1*100
        IF(M.GT.100)M=100
        ASE=Z(M)*PE(IY,I)*S1/C1
        IF(ASE.GT.PE(IY,I))ASE=PE(IY,I)
        IF(ASE.LE.0.)ASE=0.005
C   ESTIMATION OF ROOT ZONE EXTRACTION
        M=S2/C2*100
        IF(M.GT.100)M=100
        AERT=RTX*Z(M)*PE(IY,I)*S2/C2
        IF(IFREEZE.EQ.1)AERT=0.
C   ADJUSTMENT OF SURFACE EVAPORATION FOR ROOT EXTRACTION
        ASE=ASE-AERT
C   ADJUSTMENT OF ZONE 1 MOISTURE CONTENT FOR EVAPORATION
        S1=S1-ASE
        IF(S1.LT.0.)S1=0.
C   CALCULATION OF PUDDLING
        PDL=0.
        IF(S1.GT.V1)PDL=S1-V1
C   SUBTRACT YESTERDAY'S DRAINAGE AND ADD YESTERDAY'S DIFFUSION
FROM ZONE
C   2 TO ZONE 1 MOISTURE CONTENT
        S1=S1-DRN1+DF
C   ADJUST ZONE 2 MOISTURE CONTENT
        S2=S2+DRN1-DF-AERT
C   FINAL CALCULATION OF S1
        S1=S1-PDL
C IF MORE THAN 0.5 CM OF PUDDLING, ASSUME THE EXCESS RUNS OFF
        IF(PDL.GT.0.5)PDL=0.5
C CALCULATION OF DRAINAGE FROM ZONES FOR TODAY
C   DRAINAGE FROM ZONE 2 TODAY = DRAINAGE FROM ZONE 1 YESTERDAY
        DRN2=DRN1
        IF(DRN2.GT.(V2-C2))DRN2=V2-C2
        DRN1=(S1-C1)*DRS
        IF(S1.GT.V1)DRN1=(V1-C1)*DRS
        IF(S2.GT.V2)DRN1=0.
```

```
        IF(DRN1.LT.0.)DRN1=0.
 C CALCULATION OF WATER DIFFUSED BETWEEN ZONES (POSITIVE INDICATES
ZONE 2 TO 1)
        DF=((S2/C2)-(S1/C1))*C1*RDC
        IF(DF.GT.C1)DF=C1
        IF(DF.LT.0.)DF=DF*(C1/C2)
        IF(S1.GE.C1.AND.S2.GE.C2)DF=0.
 C IF MOISTURE CONTENT OF TOP LAYER IS TOO HIGH, DAY IS NONWORKDAY
        IF(S1.GT.(CMOIST*C1))WORK(IRUN,IY,I)=0
 C ADD UP NUMBER OF WORKDAYS AVAILABLE IN SEPTEMBER AND OCTOBER
        IF(I.LT.32.OR.I.GT.92) GOTO 129
         NODAYS(IY)=NODAYS(IY)+WORK(IRUN,IY,I)
 C CALCULATE 5 DAY SMOOTHED MINIMUM TEMPERATURE
 C CANNOT SMOOTH FIRST 2 OR LAST 2 DAYS, SO USE THE MIN TEMP FOR
THESE DAYS
 129     IF(I.LT.3.OR.I.GT.90)THEN
         TN=TMIN(IY,I)
         GOTO 130
        ENDIF
        TN=(TMIN(IY,I-2)+(4*TMIN(IY,I-1))+(6*TMIN(IY,I))+
    $     (4*TMIN(IY,I+1))+TMIN(IY,I+2))/16.
 C ONCE AN EXTENDED FREEZE OCCURS, PLANTS ARE CONSIDERED DEAD AND
IT IS
 C ASSUMED THAT NO MORE WATER WILL BE EXTRACTED BY ROOTS
 130     IF(TN.LE.0.)IFREEZE=1
 140    CONTINUE
 150   CONTINUE
 C RERUN THE PROGRAM USING ANOTHER CRITICAL MOISTURE LEVEL
      IF(IRUN.LT.2) THEN
       IRUN=2
       GOTO 122
      ENDIF
 C WRITE OUTPUT TO FILE
 C     WRITE(20,165)CMOIST
 165   FORMAT(' CRITICAL MOISTURE LEVEL=  ',F4.2)
      DO 180 IY=1,J
 C      WRITE(20,166)IY,STMOIST(IY)
 166    FORMAT(' STARTING MOISTURE CONTENT FOR YEAR ',I4,'  =  ',F4.2,' OF
     $ FIELD CAPACITY')
       DO 170 I=32,122
        WRITE(20,200)IY,I,TMIN(IY,I),P(IY,I),WORK(1,IY,I),WORK(2,IY,I)
 170    CONTINUE
 C     WRITE(20,210)NODAYS(IY)
 180   CONTINUE
 200   FORMAT(2I5,2F7.2,2I5)
 210   FORMAT(' NO. OF AVAILABLE DAYS IN SEPT, OCT. ',I5)
      END
```

Appendix D. Listings of Harvest Simulation Subprograms

Crossroads Processing System (System A)

```
 //SYSAJW JOB 21C04,JWW,TIME=9,REGION=2M
 /*PRIORITY IDLE
 /*ROUTE PRINT VTVM1.AGENGS13
 /*JOBPARM LINES=2
 //STEP1 EXEC SLAMCG
 //FORT.SYSIN DD *
      PROGRAM MAIN
      DIMENSION NSET(30000)

COMMON/SCOM1/ATRIB(100),DD(100),DDL(100),DTNOW,II,MFA,MSTOP,NCLNR,
     1NCRDR,NPRNT,NNRUN,NNSET,NTAPE,SS(100),SSL(100),TNEXT,TNOW,XX(100)
       COMMON QSET(30000)
      EQUIVALENCE(NSET(1),QSET(1))
      NNSET=30000
      NCRDR=5
      NPRNT=6
      NTAPE=7
      CALL SLAM
      STOP
      END
 C***********************************************************************
      SUBROUTINE INTLC
      INCLUDE(SLMSCOM1)
      EQUIVALENCE (HDAY,XX(1)),(FRZE,XX(2)),(FRST,XX(3)),(BRIX,XX(4))
      EQUIVALENCE (WDAY,XX(5)),(NMOVE,XX(6)),(YMEAN,XX(7))
 C CALCULATE THE YEARLY MEAN YIELD (MG/HA) OF WHOLE-STALKS
      Z=-(RNORM(0.,1.,1)-0.0)/1.338
      YMEAN=20.+44./(1.+EXP(Z))
      HDAY=0
      FRZE=0
      FRST=0
      BRIX=12.5
      WDAY=0
      NMOVE=0
      RETURN
      END
```

```
C*************************************************************************
      SUBROUTINE EVENT(I)
      GOTO(1,2),I
1     CALL YLD
      RETURN
2     CALL NEWDAY
      RETURN
      END
C*************************************************************************
      SUBROUTINE YLD
      INCLUDE(SLMSCOM1)
      EQUIVALENCE (HDAY,XX(1)),(FRZE,XX(2)),(FRST,XX(3)),(BRIX,XX(4))
      EQUIVALENCE (YMEAN,XX(7))
C CALCULATE THE YIELD OF EACH HECTARE OF SORGHUM
      Z=-(RNORM(0.,1.,2)-0.0)/1.338
      ATRIB(2)=YMEAN-20.+40./(1.+EXP(Z))
C ASSIGN MASS (MG PER MG OF STALKS) OF BY-PRODUCT SILAGE AND
C JUICE TO ATTRIBUTES 3 AND 4 RESPECTIVELY
      ATRIB(3)=0.54
      ATRIB(4)=0.40
      RETURN
      END
C*************************************************************************
      SUBROUTINE NEWDAY
      INCLUDE(SLMSCOM1)
      EQUIVALENCE (HDAY,XX(1)),(FRZE,XX(2)),(FRST,XX(3)),(BRIX,XX(4))
      EQUIVALENCE (WDAY,XX(5)),(NMOVE,XX(6))
C READ IN VALUES OF MINIMUM TEMP,RAIN, AND WORK DAY
      READ(10,100)IY,ID,TMIN,RAIN,IHARV,IHARV95
100   FORMAT(I4,I5,2F7.2,2I5)
C
C CHANGE DAY NUMBER
      HDAY=HDAY+1
C
C OPERATION MOVES EVERY 10 PROCESSING DAYS
      MOVE=0
C PROCESSING DAY OCCURS WHEN LESS THAN 2.54 CM RAIN AND STALKS ARE
C READY TO BE PROCESSED
      IF(RAIN.LT.2.54.AND.NNQ(2).GT.0)WDAY=WDAY+1
      IF(WDAY.GE.10)THEN
        MOVE=1
        WDAY=0
C NMOVE COUNTS THE NUMBER OF MOVES DURING THE SEASON
        NMOVE=NMOVE+1
      ENDIF
C
C HARVESTING ENDS ON OCT.31
      IF(HDAY.GT.62)IHARV=0
C
C IF BRIX DROPS BELOW 10 DUE TO EARLY FROST OR FREEZE, HARVESTING
ENDS
      IF(BRIX.LT.10)IHARV=0
C
C STOP HARVESTING IF SOIL IS TOO WET (IHARV=0)OR PROCESSOR HAS A 20
DAY
C SUPPLY OF STALKS (APPROX. 1800 T) OR IT IS A MOVING DAY (MOVE=1)
```

```
      ATRIB(1)=0
      IF(IHARV.EQ.1.AND.NNQ(2).LT.1800.AND.MOVE.EQ.0)GOTO 110
      IF(NNACT(3).GE.1)GOTO 120
      ATRIB(1)=1
      GOTO 120
 110  CALL STOPA(1)
 120  CONTINUE
 C
 C CHECK TO SEE IF PROCESSOR CAN BE OPERATED (LESS THAN 2.54 CM OF
RAIN
 C AND NOT A MOVING DAY)
      IF(RAIN.LT.2.54.AND.MOVE.EQ.0)GOTO 160
      IF(NNRSC(2).LT.1.AND.NRUSE(2).LT.1)GOTO 170
      CALL ALTER(2,-1)
      GOTO 170
 160  IF(NNRSC(2).GE.1.OR.NRUSE(2).GE.1)GOTO 170
      CALL ALTER(2,1)
 170  CONTINUE
 C
 C CHECK TO SEE IF FROST OR FREEZE HAS OCCURRED
      IF(FRZE.EQ.1.)GOTO 180
      IF(TMIN.LE.2.)FRST=1.
      IF(TMIN.LE.-2.)THEN
        FRST=0.
        FRZE=1.
      ENDIF
 180  CONTINUE
 C
 C BRIX STARTS AT 12.5 ON SEPT.1 AND INCREASES AT .1 PER DAY UNTIL
 C MATURITY ON OCT.15. THEN DROPS AT .1 PER DAY UNTIL THE END OF THE
 C HARVEST SEASON ON OCT.31.  IF FROST OCCURS, BRIX BEGINS DROPPING
 C AT .05 PER DAY AND IF A FREEZE OCCURS, BRIX DROPS AT .2 PER DAY.
 C BRIX IS XX(4) AND THE DAY OF HARVEST SEASON (HDAY) IS XX(1)
 C FRZE (XX(2) INDICATES THAT A HARD FREEZE HAS OCCURRED
 C FRST (XX(3) INDICATES THAT A KILLING FROST HAS OCCURRED
 C
      IF(FRST.GT.0.)GOTO 200
      IF(FRZE.GT.0.)GOTO 210
      IF(HDAY.GT.46.)GOTO 220
      BRIX=BRIX+.1
      RETURN
 200  IF(HDAY.GT.46.)GOTO 220
      BRIX=BRIX-.05
      RETURN
 210  BRIX=BRIX-.2
      RETURN
 220  BRIX=BRIX-.1
 C
 C ADJUST THE AMOUNT OF BYPRODUCTS AND THE JUICE BRIX IN EACH TON
OF
 C STALKS WAITING TO BE PROCESSED TO ACCOUNT FOR STORAGE LOSSES
 C   LOCATE POINTER TO FIRST ENTRY IN FILE 2 (PROCQ), THEN INCREMENT
 C   THROUGH EACH ENTRY IN FILE
      NEXT=MMFE(2)
 250  IF(NEXT.EQ.0)RETURN
 C   REDUCE ATRIBUTE 3 (BY-PRODUCT SILAGE) BY .5% EACH DAY
```

```
       QSET(NEXT + 3) = 0.995*QSET(NEXT + 3)
 C    REDUCE ATRIBUTE 1 (JUICE SUGAR CONTENT) BY .05 BRIX EACH DAY
       QSET(NEXT + 1) = QSET(NEXT + 1)-.05
       NEXT = NSUCR(NEXT)
      GOTO 250
      END
C***********************************************************************
      SUBROUTINE OTPUT
      INCLUDE(SLMSCOM1)
      EQUIVALENCE (HDAY,XX(1)),(FRZE,XX(2)),(FRST,XX(3)),(BRIX,XX(4))
      EQUIVALENCE (WDAY,XX(5)),(NMOVE,XX(6)),(YMEAN,XX(7))
 C REMHA = NUMBER OF UNHARVESTED HECTARES (NUMBER IN HARVQ)
      REMHA = NNQ(1) + NNQ(4)
 C REMMG = NUMBER OF UNHARVESTED MEGAGRAMS (SUM 0F YIELDS (AT-
TRIBUTE 2) FOR
 C ALL HECTARES REMAINING IN HARVQ
      REMMG = 0
      NEXT = MMFE(1)
 50   IF(NEXT.EQ.0)GOTO 80
      REMMG = REMMG + QSET(NEXT + 2)
      NEXT = NSUCR(NEXT)
      GOTO 50
 80   CONTINUE
      NEXT = MMFE(4)
 85   IF(NEXT.EQ.0)GOTO 88
      REMMG = REMMG + QSET(NEXT + 2)
      NEXT = NSUCR(NEXT)
      GOTO 85
 88   CONTINUE
 C TO MAINTAIN COMMON RANDOM NUMBERS, CALL SUBROUTINE YLD AN
EQUAL NUMBER
 C OF TIMES FOR EACH SYSTEM.  THIS IS NECESSARY ONLY FOR SENSITIVITY
 C ANALYSES WHERE COMMON RANDOM NUMBERS ARE DESIRED.
      DO 90 I = 1,30
        CALL EVENT(1)
 90   CONTINUE
 C AVERAGE YIELD (MG/HA)
      YLD = CCAVG(1)
 C NUMBER OF HECTARES HARVESTED
      HEC = CCNUM(3)
 C NUMBER OF HECTARES REJECTED
      REJ = CCNUM(2)
 C MASS OF WHOLE-STALKS PROCESSED (MG)
      TNS = CCNUM(4)
 C YIELD OF BY-PRODUCT SILAGE (MG)
      YSL = CCAVG(4)*TNS
 C YIELD OF JUICE (MG)
      YJU = CCAVG(5)*TNS
 C YIELD OF SUGAR (MG)
      YSU = CCAVG(6)*TNS
 C NUMBER OF DAYS HARVESTER OPERATED
      HARDY = AAAVG(1)*90.
 C NUMBER OF DAYS PROCESSOR OPERATED
      PRODY = AAAVG(2)*90.

WRITE(6,100)YMEAN,YLD,HEC,REJ,REMHA,REMMG,YHA,YSL,YJU,YSU,HARDY,
```

```
     $PRODY,NMOVE
100  FORMAT(2F5.1,3F5.0,4F6.0,F5.0,2F5.1,I3)
     RETURN
     END
C**********************************************************************
//GO.SYSIN DD *
GEN,WORLEY,HARVEST SYSTEM A,01/18/1990,100,N,N,,N,Y/S,72;
LIM,4,5,2300;
TIMST,XX(2),FREEZE TIME;
TIMST,XX(3),FROST TIME;
TIMST,XX(4),AVG. BRIX;
EQUIVALENCE/XX(4),BRIX/;
NETWORK;
;
; MAIN PROCESSING NETWORK;
;
     RESOURCE/1,HARVESTER(1),1;
     RESOURCE/2,PROCESSOR(1),2;
     CREATE,0,,,170;
;ASSIGN YIELD OF STALKS,JUICE, AND BYPRODUCT
     EVENT,1;
;COLLECT STATISTICS ON AVERAGE YIELD OF STALKS (MG/HA)
     COLCT(1),ATRIB(2),YIELD,,1;
;IF YIELD IS LESS THAN 20 MG/HA, DO NOT HARVEST;
     ACT,,ATRIB(2).LT.20,T1;
;OTHERWISE, PUT IN QUEUE FOR HARVESTER
     ACT,,,HARVQ;
;COLLECT STATISTICS ON HOW MANY HECTARES WERE REJECTED
T1   COLCT(2),ATRIB(2),REJECT,,1;
     TERM;
HARVQ AWAIT(1),HARVESTER/1;
     ACT/1,.24;HARVESTING
     FREE,HARVESTER/1;
;COLLECT STATISTICS ON THE NUMBER OF HECTARES HARVESTED
     COLCT(3),ATRIB(2),HARV AREA;
;ASSIGN BRIX OF STANDING STALKS TO CUT STALKS AT TIME OF HARVESTING
     ASSIGN,ATRIB(1)=BRIX;
;CHANGE 1 HECTARE OF STALKS TO THE NUMBER OF TONS OF STALKS
YIELDED BY
;THIS HECTARE AND PLACE IN QUEUE TO BE PROCESSED (STORED IN BUN-
DLES)
     UNBATCH,2;
PROCQ AWAIT(2),PROCESSOR/1;
     ACT/2,.009;PROCESSING
     FREE,PROCESSOR/1;
;CALCULATE THE YIELD OF SUGAR IN MG
;(MG OF JUICE TIMES BRIX AT TIME OF PROCESSING)
     ASSIGN,ATRIB(5)=ATRIB(4)*ATRIB(1)/100;
;COLLECT STATISTICS ON SUGAR AND BYPRODUCT YIELDS
     COLCT(4),ATRIB(3),SILAGE;
     COLCT(5),ATRIB(4),JUICE;
     COLCT(6),ATRIB(5),SUGAR;
     COLCT(7),ATRIB(1),PRBRIX;
     TERM;
;
;DAILY UPDATE NETWORK
```

```
;
     CREATE,1;
;CALL SUBROUTINE NEWDAY
     EVENT,2,2;
     ACT,.99,,T2;
     ACT,,ATRIB(1).EQ.1,P1;
P1   PREEMPT(3),HARVESTER;
     ACT/3,STOPA(1);
     FREE,HARVESTER;
     TERM;
;TERMINATE THE SIMULATION AT END OF NOVEMBER
T2   TERM,91;
     ENDNETWORK;
FIN;
/*
//FT10F001 DD *
 1  32  12.78  0.00  1  1
 1  33  12.78  0.53  0  0
```

Pith Combine System (System B)

```
//SYSBJW JOB 21C04,JWW,TIME=9,REGION=2M
/*PRIORITY IDLE
/*ROUTE PRINT VTVM1.AGENGS13
/*JOBPARM LINES=2
//STEP1 EXEC SLAMCG
//FORT.SYSIN DD *
      PROGRAM MAIN
      DIMENSION NSET(30000)
COMMON/SCOM1/ATRIB(100),DD(100),DDL(100),DTNOW,II,MFA,MSTOP,NCLNR,
     1NCRDR,NPRNT,NNRUN,NNSET,NTAPE,SS(100),SSL(100),TNEXT,TNOW,XX(100)
      COMMON QSET(30000)
      EQUIVALENCE(NSET(1),QSET(1))
      NNSET=30000
      NCRDR=5
      NPRNT=6
      NTAPE=7
      CALL SLAM
      STOP
      END
C***********************************************************************
      SUBROUTINE INTLC
      INCLUDE(SLMSCOM1)
      EQUIVALENCE (HDAY,XX(1)),(FRZE,XX(2)),(FRST,XX(3)),(BRIX,XX(4))
      EQUIVALENCE (WDAY,XX(5)),(NMOVE,XX(6)),(YMEAN,XX(7))
C CALCULATE THE YEARLY MEAN YIELD (MG/HA) OF WHOLE-STALKS
      Z=-(RNORM(0.,1.,1)-0.0)/1.338
      YMEAN=20.+44./(1.+EXP(Z))
      HDAY=0
      FRZE=0
      FRST=0
      BRIX=12.5
      WDAY=0
```

```
      NMOVE=0
      RETURN
      END
C*********************************************************************
      SUBROUTINE EVENT(I)
      GOTO(1,2,3),I
1      CALL YLD
      RETURN
2      CALL NEXT
      RETURN
3      CALL NEWDAY
      RETURN
      END
C*********************************************************************
      SUBROUTINE YLD
      INCLUDE(SLMSCOM1)
      EQUIVALENCE (HDAY,XX(1)),(FRZE,XX(2)),(FRST,XX(3)),(BRIX,XX(4))
      EQUIVALENCE (YMEAN,XX(7))
C CALCULATE THE YIELD OF EACH HECTARE OF SORGHUM USING
      Z=-(RNORM(0.,1.,1)-0.0)/1.338
      ATRIB(2)=YMEAN-20.+40./(1.+EXP(Z))
C ASSIGN MASS (MG PER MG OF STALKS) OF HAY, SILAGE AND
C JUICE TO ATTRIBUTES 3,4, AND 5 RESPECTIVELY
      ATRIB(3)=0.07
      ATRIB(4)=0.27
      ATRIB(5)=0.40
      RETURN
      END
C*********************************************************************
      SUBROUTINE NEXT
      INCLUDE(SLMSCOM1)
C RELEASE THE NEXT HECTARE TO BE HARVESTED WHEN HARVESTER HAS 1
MG
C REMAINING ON THE PRESENT HECTARE
      IF(NNQ(2).LE.1)CALL STOPA(1)
      RETURN
      END
C*********************************************************************
      SUBROUTINE NEWDAY
      INCLUDE(SLMSCOM1)
      EQUIVALENCE (HDAY,XX(1)),(FRZE,XX(2)),(FRST,XX(3)),(BRIX,XX(4))
      EQUIVALENCE (WDAY,XX(5)),(NMOVE,XX(6))
C READ IN VALUES OF MINIMUM TEMP,RAIN, AND WORK DAY
      READ(10,100)IY,ID,TMIN,RAIN,IHARV,IHARV95
100   FORMAT(I4,I5,2F7.2,2I5)
C
C CHANGE DAY NUMBER
      HDAY=HDAY+1
C
C RELEASE THE FIRST HECTARE FOR PROCESSING.  SUBSEQUENT
C RELEASES WILL OCCUR IN EVENT 2 (NEXT)
      IF(NNQ(2).LE.1)CALL STOPA(1)
C
C HARVESTING ENDS ON OCT.31
      IF(HDAY.GT.62)IHARV95=0
C
```

```
C IF BRIX DROPS BELOW 10 DUE TO EARLY FROST OR FREEZE, HARVEST ENDS
      IF(BRIX.LT.10)IHARV95=0
C
C OPERATION MOVES EVERY 10 HARVESTING DAYS
      MOVE=0
      IF(IHARV95.EQ.1)WDAY=WDAY+1
      IF(WDAY.GE.10)THEN
        MOVE=1
        WDAY=0
        NMOVE=NMOVE+1
      ENDIF
C
C CHECK TO SEE IF COMBINE CAN BE OPERATED (IHARV95=1)
C AND NOT A MOVING DAY)
      IF(IHARV95.EQ.1.AND.MOVE.EQ.0)GOTO 160
      IF(NNRSC(1).LT.1.AND.NRUSE(1).LT.1)GOTO 170
      CALL ALTER(1,-1)
      GOTO 170
160   IF(NNRSC(1).GE.1.OR.NRUSE(1).GE.1)GOTO 170
      CALL ALTER(1,1)
170   CONTINUE
C
C CHECK TO SEE IF FROST OR FREEZE HAS OCCURRED
      IF(FRZE.EQ.1.)GOTO 180
      IF(TMIN.LE.2.)FRST=1.
      IF(TMIN.LE.-2.)THEN
        FRST=0.
        FRZE=1.
      ENDIF
180   CONTINUE
C
C BRIX STARTS AT 12.5 ON SEPT.1 AND INCREASES AT .1 PER DAY UNTIL
C MATURITY ON OCT.15. THEN DROPS AT .1 PER DAY UNTIL THE END OF THE
C HARVEST SEASON ON OCT.31.  IF FROST OCCURS, BRIX BEGINS DROPPING
C AT .05 PER DAY AND IF A FREEZE OCCURS, BRIX DROPS AT .2 PER DAY.
C BRIX IS XX(4) AND THE DAY OF HARVEST SEASON (HDAY) IS XX(1)
C FRZE (XX(2) INDICATES THAT A HARD FREEZE HAS OCCURRED
C FRST (XX(3) INDICATES THAT A KILLING FROST HAS OCCURRED
C
      IF(FRST.GT.0.)GOTO 200
      IF(FRZE.GT.0.)GOTO 210
      IF(HDAY.GT.46.)GOTO 220
      BRIX=BRIX+.1
      RETURN
200   IF(HDAY.GT.46.)GOTO 220
      BRIX=BRIX-.05
      RETURN
210   BRIX=BRIX-.2
      RETURN
220   BRIX=BRIX-.1
      END
C*********************************************************************
      SUBROUTINE OTPUT
      INCLUDE(SLMSCOM1)
      EQUIVALENCE (HDAY,XX(1)),(FRZE,XX(2)),(FRST,XX(3)),(BRIX,XX(4))
      EQUIVALENCE (WDAY,XX(5)),(NMOVE,XX(6)),(YMEAN,XX(7))
```

```
 C REMHA=NUMBER OF UNHARVESTED HECTARES (NUMBER IN HARVQ)
      REMHA=NNQ(1)+NNQ(4)
 C REMMG=NUMBER OF UNHARVESTED MEGAGRAMS (SUM OF YIELDS (AT-
TRIBUTE 2)
 C FOR ALL HECTARES REMAINING IN HARVQ
      REMMG=0
      NEXT=MMFE(1)
 50    IF(NEXT.EQ.0)GOTO 80
      REMMG=REMMG+QSET(NEXT+2)
      NEXT=NSUCR(NEXT)
      GOTO 50
 80    CONTINUE
      NEXT=MMFE(4)
 85    IF(NEXT.EQ.0)GOTO 88
      REMMG=REMMG+QSET(NEXT+2)
      NEXT=NSUCR(NEXT)
      GOTO 85
 88    CONTINUE
 C TO MAINTAIN COMMON RANDOM NUMBERS, CALL SUBROUTINE YLD AN
EQUAL NUMBER
 C OF TIMES FOR EACH SYSTEM.  THIS IS NECESSARY ONLY FOR SENSITIVITY
 C ANALYSES WHERE COMMON RANDOM NUMBERS ARE DESIRED.
      DO 90 I=1,80
        CALL EVENT(1)
 90    CONTINUE
 C AVERAGE YIELD (MG/HA)
      YLD=CCAVG(1)
 C NUMBER OF HECTARES HARVESTED
      HEC=CCNUM(3)
 C NUMBER OF HECTARES REJECTED
      REJ=CCNUM(2)
 C MASS OF WHOLE-STALKS PROCESSED (MG)
      TNS=CCNUM(4)
 C YIELD OF BY-PRODUCT HAY (MG)
      YHA=CCAVG(4)*TNS
 C YIELD OF BY-PRODUCT SILAGE (MG)
      YSL=CCAVG(5)*TNS
 C YIELD OF JUICE (MG)
      YJU=CCAVG(6)*TNS
 C YIELD OF SUGAR (MG)
      YSU=CCAVG(7)*TNS
 C NUMBER OF DAYS COMBINE OPERATED
      COMDY=AAAVG(2)*91.

WRITE(6,100)YMEAN,YLD,HEC,REJ,REMHA,REMMG;YHA,YSL,YJU,YSU,COMDY,
     $PRODY,NMOVE
 100   FORMAT(2F5.1,3F5.0,4F6.0,F5.0,2F5.1,I3).
      RETURN
      END
 C***********************************************************************
 //GO.SYSIN DD *
 GEN,WORLEY,HARVEST SYSTEM B,02/12/1990,100,N,N,,N,Y/S,72;
 LIM,4,5,2300;
 TIMST,XX(2),FREEZE TIME;
 TIMST,XX(3),FROST TIME;
 TIMST,XX(4),AVG. BRIX;
```

```
EQUIVALENCE/XX(4),BRIX/;
NETWORK;
;
; MAIN PROCESSING NETWORK;
;
    RESOURCE/1,COMBINE(1),2;
    CREATE,0,,,120;
;ASSIGN YIELD OF STALKS,JUICE, AND BYPRODUCTS
    EVENT,1;
;COLLECT STATISTICS ON AVERAGE YIELD OF STALKS (MG/HA)
    COLCT(1),ATRIB(2),YIELD,,1;
;IF YIELD IS LESS THAN 20 MG/HA, DO NOT HARVEST;
    ACT,,ATRIB(2).LT.20,T1;
;OTHERWISE, PUT IN QUEUE FOR HARVEST
    ACT,,,HARVQ;
;COLLECT STATISTICS ON HOW MANY HECTARES WERE REJECTED
T1  COLCT(2),ATRIB(2),REJECT,,1;
    TERM;
HARVQ QUEUE(1);
    ACT/1,STOPA(1),;HARVWAIT;
;COLLECT STATISTICS ON THE NUMBER OF HECTARES HARVESTED
    COLCT(3),ATRIB(2),HARV AREA;
;CHANGE 1 HECTARE OF STALKS TO THE NUMBER OF TONS OF STALKS
YIELDED BY
;THIS HECTARE AND PLACE IN QUEUE TO BE HARVESTED BY COMBINE
    UNBATCH,2;
COMBQ AWAIT(2),COMBINE/1;
    ACT/2,.009;COMBINING
    FREE,COMBINE/1;
;PUT NEXT HECTARE IN QUEUE TO BE HARVESTED WHEN 1 MG OF PRESENT
;HECTARE REMAINS TO BE HARVESTED
    EVENT,2;
;ESTIMATE THE SUGAR RECOVERED AT THE TIME OF PROCESSING
    ASSIGN,ATRIB(1)=ATRIB(5)*BRIX/100;
;COLLECT STATISTICS ON SUGAR AND BYPRODUCT YIELDS
    COLCT(4),ATRIB(3),HAY;
    COLCT(5),ATRIB(4),SILAGE;
    COLCT(6),ATRIB(5),JUICE;
    COLCT(7),ATRIB(1),SUGAR;
    TERM;
;
;DAILY UPDATE NETWORK
;
    CREATE,1;
;CALL SUBROUTINE NEWDAY
    EVENT,3;
    ACT,.99;
;TERMINATE THE SIMULATION AT END OF NOVEMBER
    TERM,91;
    ENDNETWORK;
FIN;
/*
//FT10F001 DD *
  1  32  12.78  0.00  1  1
  1  33  12.78  0.53  0  0
```

Combined System (System C)

```
//SYSCJW JOB 21C04,JWW,TIME=9,REGION=2M
/*PRIORITY IDLE
/*ROUTE PRINT VTVM1.AGENGS13
/*JOBPARM LINES=2
//STEP1 EXEC SLAMCG
//FORT.SYSIN DD *
      PROGRAM MAIN
      DIMENSION NSET(30000)

COMMON/SCOM1/ATRIB(100),DD(100),DDL(100),DTNOW,II,MFA,MSTOP,NCLNR,
     1NCRDR,NPRNT,NNRUN,NNSET,NTAPE,SS(100),SSL(100),TNEXT,TNOW,XX(100)
      COMMON QSET(30000)
      EQUIVALENCE(NSET(1),QSET(1))
      NNSET=30000
      NCRDR=5
      NPRNT=6
      NTAPE=7
      CALL SLAM
      STOP
      END
C************************************************************************
      SUBROUTINE INTLC
      INCLUDE(SLMSCOM1)
      EQUIVALENCE (HDAY,XX(1)),(FRZE,XX(2)),(FRST,XX(3)),(BRIX,XX(4))
      EQUIVALENCE (WDAY,XX(5)),(NMOVE,XX(6)),(YMEAN,XX(7))
C CALCULATE THE YEARLY MEAN YIELD (MG/HA) OF WHOLE-STALKS
      Z=-(RNORM(0.,1.,1)-0.0)/1.338
      YMEAN=20.+44./(1.+EXP(Z))
      HDAY=0
      FRZE=0
      FRST=0
      BRIX=12.5
      WDAY=0
      NMOVE=0
      RETURN
      END
C************************************************************************
      SUBROUTINE EVENT(I)
      GOTO(1,2),I
1     CALL YLD
      RETURN
2     CALL NEWDAY
      RETURN
      END
C************************************************************************
      SUBROUTINE YLD
      INCLUDE(SLMSCOM1)
      EQUIVALENCE (HDAY,XX(1)),(FRZE,XX(2)),(FRST,XX(3)),(BRIX,XX(4))
      EQUIVALENCE (YMEAN,XX(7))
C CALCULATE THE YIELD OF EACH HECTARE OF SORGHUM
      Z=-(RNORM(0.,1.,1)-0.0)/1.338
      ATRIB(2)=YMEAN-20.+40./(1.+EXP(Z))
C ASSIGN MASS (MG PER MG OF STALKS) OF HAY, SILAGE AND
```

```
C JUICE TO ATTRIBUTES 3, 4, AND 5 RESPECTIVELY
      ATRIB(3)=0.07
      ATRIB(4)=0.27
      ATRIB(5)=0.40
      RETURN
      END
C*********************************************************************
      SUBROUTINE NEWDAY
      INCLUDE(SLMSCOM1)
      EQUIVALENCE (HDAY,XX(1)),(FRZE,XX(2)),(FRST,XX(3)),(BRIX,XX(4))
      EQUIVALENCE (WDAY,XX(5)),(NMOVE,XX(6)),(YMEAN,XX(7))
C READ IN VALUES OF MINIMUM TEMP,RAIN, AND WORK DAY
      READ(10,100)IY,ID,TMIN,RAIN,IHARV,IHARV95
100   FORMAT(I4,I5,2F7.2,2I5)
C
C CHANGE DAY NUMBER
      HDAY=HDAY+1
C
C HARVESTING ENDS ON OCT.31
      IF(HDAY.GT.62)IHARV=0
C
C IF BRIX DROPS BELOW 10 DUE TO EARLY FROST OR FREEZE, HARVESTING
ENDS
      IF(BRIX.LT.10)IHARV=0
C
C OPERATION MOVES EVERY 10 PROCESSING DAYS
      MOVE=0
C PROCESSING DAY OCCURS WHEN SOIL IS DRY ENOUGH AND STALKS ARE
READY
C TO BE PROCESSED
      IF(IHARV95.EQ.1.AND.NNQ(2).GT.0)WDAY=WDAY+1
      IF(WDAY.GE.10)THEN
        MOVE=1
        WDAY=0
C NMOVE COUNTS THE NUMBER OF MOVES DURING THE SEASON
        NMOVE=NMOVE+1
      ENDIF
C
C STOP HARVESTING IF SOIL IS TOO WET (IHARV=0)OR PROCESSOR HAS A 20
DAY
C SUPPLY OF STALKS (APPROX. 1800 T) OR IT IS A MOVING DAY (MOVE=1)
      ATRIB(1)=0
      IF(IHARV.EQ.1.AND.NNQ(2).LT.1800.AND.MOVE.EQ.0)GOTO 110
      IF(NNACT(3).GE.1)GOTO 120
      ATRIB(1)=1
      GOTO 120
110   CALL STOPA(1)
120   CONTINUE
C
C CHECK TO SEE IF PROCESSOR CAN BE OPERATED (IHARV95=1
C AND NOT A MOVING DAY)
      IF(IHARV95.EQ.1.AND.MOVE.EQ.0)GOTO 160
      IF(NNRSC(2).LT.1.AND.NRUSE(2).LT.1)GOTO 170
      CALL ALTER(2,-1)
      GOTO 170
160   IF(NNRSC(2).GE.1.OR.NRUSE(2).GE.1)GOTO 170
```

```
      CALL ALTER(2,1)
 170  CONTINUE
 C
 C CHECK TO SEE IF FROST OR FREEZE HAS OCCURRED
      IF(FRZE.EQ.1.)GOTO 180
      IF(TMIN.LE.2.)FRST=1.
      IF(TMIN.LE.-2.)THEN
        FRST=0.
        FRZE=1.
      ENDIF
 180  CONTINUE
 C
 C BRIX STARTS AT 12.5 ON SEPT.1 AND INCREASES AT .1 PER DAY UNTIL
 C MATURITY ON OCT.15. THEN DROPS AT .1 PER DAY UNTIL THE END OF THE
 C HARVEST SEASON ON OCT.31.  IF FROST OCCURS, BRIX BEGINS DROPPING
 C AT .05 PER DAY AND IF A FREEZE OCCURS, BRIX DROPS AT .2 PER DAY.
 C BRIX IS XX(4) AND THE DAY OF HARVEST SEASON (HDAY) IS XX(1)
 C FRZE (XX(2) INDICATES THAT A HARD FREEZE HAS OCCURRED
 C FRST (XX(3) INDICATES THAT A KILLING FROST HAS OCCURRED
 C
      IF(FRST.GT.0.)GOTO 200
      IF(FRZE.GT.0.)GOTO 210
      IF(HDAY.GT.46.)GOTO 220
      BRIX=BRIX+.1
      RETURN
 200  IF(HDAY.GT.46.)GOTO 220
      BRIX=BRIX-.05
      RETURN
 210  BRIX=BRIX-.2
      RETURN
 220  BRIX=BRIX-.1
 C
 C ADJUST THE AMOUNT OF BYPRODUCTS AND THE JUICE BRIX IN EACH TON
OF
 C STALKS WAITING TO BE PROCESSED TO ACCOUNT FOR STORAGE LOSSES
 C    LOCATE POINTER TO FIRST ENTRY IN FILE 2 (PROCQ), THEN INCREMENT
 C    THROUGH EACH ENTRY IN FILE
      NEXT=MMFE(2)
 250  IF(NEXT.EQ.0)RETURN
 C    REDUCE ATRIBUTE 3 (BY-PRODUCT SILAGE) BY .5% EACH DAY
        QSET(NEXT+3)=0.995*QSET(NEXT+3)
 C    REDUCE ATRIBUTE 1 (JUICE SUGAR CONTENT) BY .05 BRIX EACH DAY
       QSET(NEXT+1)=QSET(NEXT+1)-.05
      NEXT=NSUCR(NEXT)
      GOTO 250
      END
 C************************************************************************
      SUBROUTINE OTPUT
      INCLUDE(SLMSCOM1)
      EQUIVALENCE (HDAY,XX(1)),(FRZE,XX(2)),(FRST,XX(3)),(BRIX,XX(4))
      EQUIVALENCE (WDAY,XX(5)),(NMOVE,XX(6)),(YMEAN,XX(7))
 C REMHA=NUMBER OF UNHARVESTED HECTARES (NUMBER IN HARVQ)
      REMHA=NNQ(1)+NNQ(4)
 C REMMG=NUMBER OF UNHARVESTED MEGAGRAMS(SUM OF YIELDS (AT-
TRIBUTE 2) FOR
 C ALL HECTARES REMAINING IN HARVQ
```

```
      REMMG=0
      NEXT=MMFE(1)
 50   IF(NEXT.EQ.0)GOTO 80
      REMMG=REMMG+QSET(NEXT+2)
      NEXT=NSUCR(NEXT)
      GOTO 50
 80   CONTINUE
      NEXT=MMFE(4)
 85   IF(NEXT.EQ.0)GOTO 88
      REMMG=REMMG+QSET(NEXT+2)
      NEXT=NSUCR(NEXT)
      GOTO 85
 88   CONTINUE
 C TO MAINTAIN COMMON RANDOM NUMBERS, CALL SUBROUTINE YLD AN
EQUAL NUMBER
 C OF TIMES FOR EACH SYSTEM.  THIS IS NECESSARY ONLY FOR SENSITIVITY
 C ANALYSES WHERE COMMON RANDOM NUMBERS ARE DESIRED.
      DO 90 I=1,70
        CALL EVENT(1)
 90   CONTINUE
 C AVERAGE YIELD (MG/HA)
      YLD=CCAVG(1)
 C NUMBER OF HECTARES HARVESTED
      HEC=CCNUM(3)
 C NUMBER OF HECTARES REJECTED
      REJ=CCNUM(2)
 C MASS OF WHOLE-STALKS PROCESSED (MG)
      TNS=CCNUM(4)
 C YIELD OF RIND-LEAF HAY (MG)
      YHA=CCAVG(4)*TNS
 C YIELD OF PRESSCAKE SILAGE (MG)
      YSL=CCAVG(5)*TNS
 C YIELD OF JUICE (MG)
      YJU=CCAVG(6)*TNS
 C YIELD OF SUGAR (MG)
      YSU=CCAVG(7)*TNS
 C NUMBER OF DAYS HARVESTER OPERATED
      HARDY=AAAVG(1)*90.
 C NUMBER OF DAYS PROCESSOR OPERATED
      PRODY=AAAVG(2)*90.

WRITE(6,100)YMEAN,YLD,HEC,REJ,REMHA,REMMG,YHA,YSL,YJU,YSU,HARDY,
     $PRODY,NMOVE
 100  FORMAT(2F5.1,3F5.0,4F6.0,F5.0,2F5.1,I3)
      RETURN
      END
 C***********************************************************************
 //GO.SYSIN DD *
 GEN,WORLEY,HARVEST SYSTEM C,02/12/1990,100,N,N,,N,Y/S,72;
 LIM,4,6,2300;
 TIMST,XX(2),FREEZE TIME;
 TIMST,XX(3),FROST TIME;
 TIMST,XX(4),AVG. BRIX;
 EQUIVALENCE/XX(4),BRIX/;
 NETWORK;
 ;
```

```
; MAIN PROCESSING NETWORK;
;
    RESOURCE/1,HARVESTER(1),1;
    RESOURCE/2,PROCESSOR(1),2;
    CREATE,0,,,130;
;ASSIGN YIELD OF STALKS,JUICE, AND BYPRODUCT
    EVENT,1;
;COLLECT STATISTICS ON AVERAGE YIELD OF STALKS (MG/HA)
    COLCT(1),ATRIB(2),YIELD,,1;
;IF YIELD IS LESS THAN 20 MG/HA, DO NOT HARVEST;
    ACT,,ATRIB(2).LT.20,T1;
;OTHERWISE, PUT IN QUEUE FOR HARVESTER
    ACT,,,HARVQ;
;COLLECT STATISTICS ON HOW MANY HECTARES WERE REJECTED
T1   COLCT(2),ATRIB(2),REJECT,,1;
    TERM;
HARVQ AWAIT(1),HARVESTER/1;
    ACT/1,.24;HARVESTING
    FREE,HARVESTER/1;
;COLLECT STATISTICS ON THE NUMBER OF HECTARES HARVESTED
    COLCT(3),ATRIB(2),HARV AREA;
;ASSIGN BRIX OF STANDING STALKS TO CUT STALKS AT TIME OF HARVESTING
    ASSIGN,ATRIB(1)=BRIX;
;CHANGE 1 HECTARE OF STALKS TO THE NUMBER OF TONS OF STALKS
YIELDED BY
;THIS HECTARE AND PLACE IN QUEUE TO BE PROCESSED (STORED IN BUN-
DLES)
    UNBATCH,2;
PROCQ AWAIT(2),PROCESSOR/1;
    ACT/2,.009;PROCESSING
    FREE,PROCESSOR/1;
;CALCULATE THE YIELD OF SUGAR IN MG
;(MG OF JUICE TIMES BRIX AT TIME OF PROCESSING)
    ASSIGN,ATRIB(6)=ATRIB(5)*ATRIB(1)/100;
;COLLECT STATISTICS ON SUGAR AND BYPRODUCT YIELDS
    COLCT(4),ATRIB(3),HAY;
    COLCT(5),ATRIB(4),SILAGE;
    COLCT(6),ATRIB(5),JUICE;
    COLCT(7),ATRIB(6),SUGAR;
    COLCT(8),ATRIB(1),PRBRIX;
    TERM;
;
;DAILY UPDATE NETWORK
;
    CREATE,1;
;CALL SUBROUTINE NEWDAY
    EVENT,2,2;
    ACT,.99,,T2;
    ACT,,ATRIB(1).EQ.1,P1;
P1   PREEMPT(3),HARVESTER;
    ACT/3,STOPA(1);
    FREE,HARVESTER;
    TERM;
;TERMINATE THE SIMULATION AT END OF NOVEMBER
T2   TERM,91;
    ENDNETWORK;
```

```
FIN;
/*
//FT10F001 DD *
   1  32  12.78  0.00   1   1
   1  33  12.78  0.53   0   0
```

Appendix E. Listing of Economic Subprogram

```
C**********************************************************************
C
C ECON IS A MODEL WHICH USES INFORMATION FROM HARVEST SIMULATION
MODELS
C (SYSAJW.OUT, SYSBJW.OUT, OR SYSCJW.OUT) AND INFORMATION DESCRIB-
ING
C EACH OF THREE SYSTEMS (SYSA.DAT,SYSB.DAT,SYSC.DAT) TO PREDICT THE
C AVERAGE COST OF PRODUCING, HARVESTING, AND FIELD PROCESSING
ENOUGH
C SWEET SORGHUM TO PRODUCE ONE LITER OF ETHANOL.  THE COST ESTI-
MATION
C INCLUDES ALL INPUTS UP TO AND INCLUDING TRANSPORTING THE JUICE
TO AN
C EVAPORATION PLANT.
C OUTPUT IS THE ESTIMATED COST PER LITER OF ETHANOL FOR EACH OF X
YEARS
C WHERE X IS THE NUMBER OF YEARS OF DATA SUPPLIED TO THE PROGRAM.
C
C THE PROGRAM WAS WRITTEN BY JOHN W. WORLEY     FEBRUARY, 1990
C
C**********************************************************************
      REAL PURCH(15),LIFE(15),POWER(15),EMAINT(15),SALV(15),ADDHRS(15)
      REAL HAY,SILAGE,JUICE,SUGAR,FIXC,OPERC,LABC,FXC,OPC,LBC,ECPL(210)
      REAL LABSUM,LABM
      INTEGER NOPER(15),NUNIT(15)
      CHARACTER*20,SYSTEM,NAME(15)
      COMMON/UCOM1/PURCH,LIFE,POWER,EMAINT,SALV,NOPER,NUNIT,FCOST
C**********************************************************************
C PURCH=PURCHASE PRICE OF EQUIPMENT ($)
C LIFE=EXPECTED LIFE OF EQUIPMENT (H)
C ADDHRS=TIME EQUIPMENT IS USED IN OTHER OPERATIONS (H/YR)
C POWER=POWER RATING REQUIRED FOR EQUIPMENT (KW)
C EMAINT=EXPECTED MAINTENANCE COST OVER LIFE OF EQUIPMENT (% OF
PURCH)
C SALV=SALVAGE VALUE OF EQUIPMENT AT END OF LIFE (% OF PURCH)
C NOPER=NUMBER OF OPERATORS REQUIRED FOR EQUIPMENT
C NUNIT=NUMBER OF UNITS REQUIRED OF EACH ITEM
C N=NUMBER OF EQUIPMENT ITEMS INVOLVED IN HARVESTING
C M=NUMBER OF EQUIPMENT ITEMS INVOLVED IN PROCESSING
C NHA=NUMBER OF HECTARES PLANTED
C VHAY=VALUE OF RIND-LEAF HAY ($/MG)
```

```
C VSIL=VALUE OF PITH OR COMBINATION SILAGE ($/MG)
C VWSS=VALUE OF WHOLE-STALK SILAGE ($/MG)
C**********************************************************************
C
C READ SYSTEM DESCRIPTION DATA
      READ(10,100)SYSTEM,N,M,NHA,VHAY,VSIL,VWSS
      DO 50 I=1,N
        READ(10,110)NAME(I),PURCH(I),LIFE(I),ADDHRS(I),POWER(I),
     $  EMAINT(I),SALV(I),NOPER(I),NUNIT(I)
 50   CONTINUE
      DO 60 I=N+1,N+M
        READ(10,110)NAME(I),PURCH(I),LIFE(I),ADDHRS(I),POWER(I),
     $  EMAINT(I),SALV(I),NOPER(I),NUNIT(I)
 60   CONTINUE
 100  FORMAT(A20,3I5,3F6.2)
 110  FORMAT(A20,2F7.0,2F6.0,2F5.2,2I5)
C
C WRITE SYSTEM DESCRIPTION DATA TO OUTPUT FILE
      WRITE(20,100)SYSTEM
      WRITE(20,155)NHA
      WRITE(20,156)VHAY
      WRITE(20,157)VSIL
      WRITE(20,158)VWSS
      WRITE(20,160)
      DO 150 I=1,N
        WRITE(20,110)NAME(I),PURCH(I),LIFE(I),ADDHRS(I),POWER(I),
     $  EMAINT(I),SALV(I),NOPER(I),NUNIT(I)
 150  CONTINUE
 155  FORMAT(/,' NO. OF HECTARES PLANTED = ',I4)
 156  FORMAT(' VALUE OF RIND-LEAF HAY = $',F5.2,'/MG')
 157  FORMAT(' VALUE OF SILAGE = $',F5.2,'/MG')
 158  FORMAT(' VALUE OF WHOLE-STALK SILAGE = $',F5.2,'/MG')
 160  FORMAT(/,' HARVESTING ITEM',5X,'PURCH   LIFE   ADHR  PWR  MNT
     $SLV   OPER UNTS')
 161  FORMAT(/,'   YR HAYVAL  SILVAL TOTCOS  ETHPRO   ECPL')
      WRITE(20,180)
      DO 170 I=N+1,N+M
        WRITE(20,110)NAME(I),PURCH(I),LIFE(I),ADDHRS(I),POWER(I),
     $  EMAINT(I),SALV(I),NOPER(I),NUNIT(I)
 170  CONTINUE
 180  FORMAT(' PROCESSING ITEM')
      WRITE(20,161)
C**********************************************************************
C REMHA=HECTARES TO BE HARVESTED BY CONVENTIONAL HARVESTER
C REMMG=MASS OF WHOLE-STALK SILAGE HARVESTED FROM REMHA
C HAY=MASS OF RIND-LEAF HAY PRODUCED IN HARVEST SEASON (MG)
C SILAGE=MASS OF PRESS-CAKE OR COMBINATION SILAGE PRODUCED (MG)
C JUICE=MASS OF JUICE PRODUCED (MG)
C SUGAR=MASS OF SUGAR PRODUCED (MG)
C HARDY=NUMBER OF DAYS HARVESTER OR COMBINE OPERATED DURING
SEASON
C PRODY=NUMBER OF DAYS PROCESSOR OPERATED DURING SEASON
C NMOVE=NUMBER OF DAYS USED FOR MOVING THE OPERATION
C L=NUMBER OF YEARS IN SIMULATION
C HCSUM=SUMMING CONSTANT FOR CALCULATING MEAN HARVESTING
COST
```

```
 C PCSUM=SUMMING CONSTANT FOR CALCULATING MEAN PROCESSING COST
 C TCSUM=SUMMING CONSTANT FOR CALCULATING MEAN TRANSPORTATION
COST
 C BPVSUM=SUMMING CONSTANT FOR CALCULATING BYPRODUCT VALUE
 C WSSSUM=SUMMING CONST. FOR CALCULATING MEAN WHOLE-STALK
SILAGE VALUE
 C EPSUM=SUMMING CONST. FOR CALCULATING MEAN LITERS OF ETHANOL
PRODUCED
 C ECSUM=SUMMING CONST. FOR CALCULATING MEAN COST PER LITER OF
ETHANOL
 C FIXSUM=SUMMING CONSTANT FOR CALCULATING MEAN FIXED COST
 C OPRSUM=SUMMING CONSTANT FOR CALCULATING MEAN OPERATING
COST
 C LABSUM=SUMMING CONSTANT FOR CALCULATING MEAN LABOR COST
 C*********************************************************************
 C
      L=100
      HCSUM=0.
      PCSUM=0.
      TCSUM=0.
      BPVSUM=0.
      WSSSUM=0.
      EPSUM=0.
      ECSUM=0.
      HFXSUM=0.
      HOPSUM=0.
      HLBSUM=0.
      PFXSUM=0.
      POPSUM=0.
      PLBSUM=0.
 C  READ IN YEARLY SIMULATION DATA
      DO 1000 K=1,L
 200  READ(15,210)YMEAN,YLD,HEC,REJ,REMHA,REMMG,HAY,
     $SILAGE,JUICE,SUGAR,HARDY,PRODY,NMOVE
 210  FORMAT(F4.1,F5.1,3F5.0,4F6.0,F5.0,2F5.1,I3)
 C*********************************************************************
 C FCOST=COST OF DIESEL FUEL ($/L)
 C TCOST=TOTAL COST OF OPERATION ($/YR)
 C PFIXC=FIXED COST OF OWNING PROCESSING EQUIPMENT ($/YR)
 C POPERC=PROCESSING OPERATING COST FOR EQUIPMENT ($/YR)
 C PLABC=PROCESSING LABOR COST ($/YR)
 C HFIXC=FIXED COST OF OWNING HARVESTING EQUIPMENT ($/YR)
 C HOPERC=HARVESTING OPERATING COST FOR EQUIPMENT ($/YR)
 C HLABC=HARVESTING LABOR COST ($/YR)
 ********************************************************************
      FCOST=0.27
      TCOST=0.
      PFIXC=0.
      POPERC=0.
      PLABC=0.
      HFIXC=0.
      HOPERC=0.
      HLABC=0.
      HACST=0.
      PRCST=0.
 C CALCULATE FIXED, OPERATING EQUIPMENT, AND LABOR COSTS
```

```
      DO 250 I=1,N
        CALL COSCAL(I,HARDY,NMOVE,FXC,OPC,LBC)
        HFIXC=HFIXC+FXC
        HOPERC=HOPERC+OPC
        HLABC=HLABC+LBC
250   CONTINUE
      DO 280 I=N+1,N+M
        CALL COSCAL(I,PRODY,NMOVE,FXC,OPC,LBC)
        PFIXC=PFIXC+FXC
        POPERC=POPERC+OPC
        PLABC=PLABC+LBC
280   CONTINUE
C ADD COST OF MOVING PROCESSOR TO OPERATING COSTS
      POPERC=POPERC+REAL(NMOVE)*100.
C TOTAL COSTS
      HACST=HFIXC+HOPERC+HLABC
      PRCST=PFIXC+POPERC+PLABC
      TCOST=HACST+PRCST
      HCSUM=HCSUM+HACST
      PCSUM=PCSUM+PRCST
      HFXSUM=HFXSUM+HFIXC
      HOPSUM=HOPSUM+HOPERC
      HLBSUM=HLBSUM+HLABC
      PFXSUM=PFXSUM+PFIXC
      POPSUM=POPSUM+POPERC
      PLBSUM=PLBSUM+PLABC
C
C********************************************************************
C ADJUSTMENTS TO COSTS
C********************************************************************
C DEFINITIONS OF VARIABLES:
C
C DIST=AVERAGE DISTANCE TO EVAPORATION PLANT (KM)
C FRRTE=FREIGHT RATE ($/KM)(PARTIALLY TIED TO FUEL COST)
C LOAD=MASS OF TRUCKLOAD OF JUICE (MG)
C TRANS=COST OF TRANSPORTING JUICE ($/YR)
C CPROD=COST TO PRODUCE SORGHUM STALKS ($/HA)
C PRDCOST=COST OF PRODUCING STALKS READY FOR HARVEST ($/YR)
C HAYVAL=VALUE OF RIND-LEAF HAY ($/YR)
C SILVAL=VALUE OF PITH OR COMBINATION SILAGE ($/YR)
C WSSVAL=VALUE OF WHOLE-STALK SILAGE ($/YR)
C ETHPR=TOTAL VOLUME OF ETHANOL PRODUCED (L/YR)
C ECPL=TOTAL COST OF ETHANOL ($/L)
C********************************************************************
C ADD COST OF TRANSPORTING JUICE TO PLANT
      DIST=16
      FRRTE=1.21+FCOST*1.07
      LOAD=20.4
      TRANS=DIST*FRRTE*JUICE/LOAD
      TCOST=TCOST+TRANS
      TCSUM=TCSUM+TRANS
C ADJUST COST BY ADDING COST OF PRODUCING STALKS
      CPROD=365.
      PRDCST=NHA*CPROD
      TCOST=TCOST+PRDCST
C ADJUST COST BY SUBTRACTING VALUE OF BY-PRODUCTS
```

```
      HAYVAL=HAY*VHAY
      SILVAL=SILAGE*VSIL
      TCOST=TCOST-HAYVAL-SILVAL
      BPVSUM=BPVSUM+HAYVAL+SILVAL
 C ADJUST COST FOR AREA HARVESTED BY CONVENTIONAL SILAGE
HARVESTER
      WSSVAL=0.9*REMMG*VWSS-REMHA*246.
      TCOST=TCOST-WSSVAL
      WSSSUM=WSSSUM+WSSVAL
 C CALCULATE NUMBER OF LITERS OF ETHANOL TO BE PRODUCED AND
COST/LITER
      ETHPR=SUGAR*576.
      ECPL(K)=TCOST/ETHPR
      EPSUM=EPSUM+ETHPR
 C CALCULATE SUM FOR MEAN AND VARIANCE
      ECSUM=ECSUM+ECPL(K)
 C WRITE INFORMATION TO OUTPUT FILE
 900  WRITE(20,910)K,HAYVAL,SILVAL,TCOST,ETHPR,ECPL(K)
 910  FORMAT(1X,I3,4F8.0,F6.2)
 1000 CONTINUE
 C*********************************************************************
 C CALCULATE MEAN VALUES OF COST FACTORS
 C HCM=MEAN HARVESTING COST
 C PCM=MEAN PROCESSING COST
 C TCM=MEAN TRANSPORTATION COST
 C BPVM=MEAN VALUE OF YEARLY PRODUCTION OF BY-PRODUCTS
 C WSSVM=MEAN VALUE OF WHOLE-STALK SILAGE
 C EPM=MEAN YEARLY PRODUCTION OF ETHANOL (LITERS)
 C ECMEAN=MEAN COST PER LITER OF ETHANOL
 C EDVAR=VARIANCE OF COST PER LITER OF ETHANOL
 C ECMAX=UPPER LIMIT OF 90% CONFIDENCE INTERVAL FOR COST PER LITER
 C ECMIN=LOWER LIMIT OF 90% CONFIDENCE INTERVAL FOR COST PER LITER
 C FIXM=MEAN FIXED COST
 C OPRM=MEAN OPERATING COST
 C LABM=MEAN LABOR COST
 C*********************************************************************
      XYRS=REAL(L)
      HCM=HCSUM/XYRS
      PCM=PCSUM/XYRS
      TCM=TCSUM/XYRS
      BPVM=BPVSUM/XYRS
      WSSVM=WSSSUM/XYRS
      EPM=EPSUM/XYRS
      PFIXM=PFXSUM/XYRS
      POPRM=POPSUM/XYRS
      PLABM=PLBSUM/XYRS
      HFIXM=HFXSUM/XYRS
      HOPRM=HOPSUM/XYRS
      HLABM=HLBSUM/XYRS
 C CALCULATE MEAN AND VARIANCE OF COST PER LITER OF ETHANOL
      ECMEAN=ECSUM/XYRS
      SUM=0.
      DO 1100 K=1,L
        SUM=SUM+(ECPL(K)-ECMEAN)**2
 1100 CONTINUE
      ECVAR=SUM/REAL(L-1)
```

```
      ECMAX=ECMEAN+1.66*SQRT(ECVAR)
      ECMIN=ECMEAN-1.66*SQRT(ECVAR)
      WRITE(20,1150)L,ECMEAN,ECVAR
      WRITE(20,1155)ECMIN,ECMAX
 1150 FORMAT(/,' YRS= ',I4,'    MEAN COST PER LITER  = ',F5.2,
     $'    VARIANCE= ',F10.8)
 1155 FORMAT(' 90% CONF. INTERVAL FOR COST  = $',F4.2,'-$',F4.2)
      WRITE(20,1200)HCM,PCM
      WRITE(20,1210)TCM,BPVM
      WRITE(20,1215)WSSVM
      WRITE(20,1220)EPM
      WRITE(20,1225)PFIXM,POPRM
      WRITE(20,1230)PLABM
      WRITE(20,1235)HFIXM,HOPRM
      WRITE(20,1240)HLABM
 1200 FORMAT(/,' HARVEST COST= ',F10.0,' PROCESSING COST= ',F10.0)
 1210 FORMAT(' TRANSP. COST= ',F10.0,' BYPROD. VALUE= ',F10.0)
 1215 FORMAT(' WHOLE-STALK SILAGE VALUE= ',F10.0)
 1220 FORMAT(' LITERS OF ETHANOL PRODUCED= ',F10.0)
 1225 FORMAT(' PROCESSING FIXED COST= ',F10.0,' OPERATING COST= ',F10.0)
 1230 FORMAT(' LABOR COST= ',F10.0)
 1235 FORMAT(' HARVESTING FIXED COST= ',F10.0,' OPERATING COST= ',F10.0)
 1240 FORMAT(' LABOR COST= ',F10.0)
 2000 END
 C******************************************************************
 C  SUBROUTINES
 C******************************************************************
 C
 C******************************************************************
 C SUBROUTINE COSCAL CALCULATES FIXED AND OPERATING EQUIPMENT
COSTS AND
 C LABOR COSTS FOR EACH EQUIPMENT ITEM
 C THE FOLLOWING ARE DEFINITIONS OF VARIABLES USED IN THIS SUBROU-
TINE:
 C
 C RIRATE=REAL INTEREST RATE (FRACTION)
 C FCOST=COST OF DIESEL FUEL ($/L)
 C TIH=TAX, INSURANCE, AND HOUSING COST (FRACTION OF PURCHASE
PRICE/YR)
 C CLAB=COST OF LABOR ($/H)
 C SALVAL=SALVAGE VALUE (FRACTION OF PURCHASE PRICE)
 C CAPIT=CAPITAL INVESTMENT (PURCHASE PRICE - SALVAGE VALUE)
 C YRSLFE=EXPECTED LIFE OF EQUIPMENT BASED ON THIS YEAR'S USE (YRS)
 C CREC=YEARLY CAPITOL RECOVERY COST FOR THIS ITEM
 C CSTTIH=COST OF TAXES, INSURANCE AND HOUSING ($/YR)
 C USE=PORTION OF TOTAL HOURS USED FOR SORGHUM HARVEST (FRAC-
TION)
 C CRM=COST OF REPAIRS AND MAINTENANCE FOR THIS ITEM ($/YR)
 C FUEL=COST OF FUEL AND RELATED ITEMS (OIL AND GREASE) ($/YR)
 C DAYS=NUMBER OF DAYS HARVESTER OR PROCESSOR OPERATED
 C NMOVE=NUMBER OF DAYS SPENT MOVING THE OPERATION
 C FXC=FIXED COST OF OWNING THIS ITEM OF EQUIPMENT ($/YR)
 C OPC=OPERATING COST OF THIS ITEM OF EQUIPMENT ($/YR)
 C LBC=LABOR COST FOR OPERATING THIS ITEM OF EQUIPMENT ($/YR)
 C
 C******************************************************************
```

```
C
      SUBROUTINE COSCAL(I,DAYS,NMOVE,FXC,OPC,LBC)
      REAL PURCH(15),LIFE(15),POWER(15),EMAINT(15),SALV(15),ADDHRS(15)
      REAL FXC,OPC,LBC
      INTEGER NOPER(15),NUNIT(15)
      COMMON/UCOM1/PURCH,LIFE,POWER,EMAINT,SALV,NOPER,NUNIT,FCOST
      RIRATE=0.05
      TIH=.02
      CLAB=5.50
C CALCULATE FIXED COSTS
      SALVAL=SALV(I)*PURCH(I)
      CAPIT=PURCH(I)-SALVAL
      YRSLFE=LIFE(I)/(DAYS*16.+ADDHRS(I))
      CREC=(RIRATE*(1+RIRATE)**YRSLFE)/((1+RIRATE)**YRSLFE-1.)*CAPIT
     $+SALVAL*RIRATE
      CSTTIH=TIH*PURCH(I)
      FXC=(CREC+CSTTIH)*NUNIT(I)
C CALCULATE OPERATING COSTS FOR EQUIPMENT
      USE=DAYS*16./(DAYS*16.+ADDHRS(I))
      CRM=EMAINT(I)*PURCH(I)*USE/YRSLFE
      FUEL=1.15*0.75*POWER(I)*0.4615*DAYS*16*FCOST
      OPC=(CRM+FUEL)*NUNIT(I)
C CALCULATE LABOR COSTS
      LBC=NOPER(I)*(DAYS+NMOVE)*16.*CLAB
      RETURN
      END
```

Vita

John Wright Worley was born on December 27, 1950 in Fulton County, Georgia. He graduated from Milton High School in Alpharetta, Georgia in 1968 and entered the University of Georgia where he received the Bachelor of Science in Agricultural Engineering degree in 1973. He then worked for Gold Kist, Inc. until 1982, where he held positions as Farm Systems Product Manager, Mill Operations Manager, and Sales Engineer. He resumed his education and received the Master of Science degree in Agricultural Engineering from the University of Georgia in 1984. He then worked for nine months as Research Engineer and three years as Instructor in the Department of Agricultural Engineering at the University of Georgia. He expects to complete the requirements for the Doctor of Philosophy degree in Agricultural Engineering at Virginia Polytechnic Institute and State University in June, 1990. He plans to pursue a career in the academic field after completion of this final degree.