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ALTERNATIVE CROPS FOR ETHANOL FUEL PRODUCTION:
AGRONOMIC, PROCESSING, AND ECONOMIC CONSIDERATIONS

Research Report 84-1

by

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Preface

This report was made possible by support from the Agricultural Experiment Station at South Dakota State University (SDSU) and from a small research grant made available through SDSU's Title XII Strengthening Program. The Title XII program at SDSU receives funds from the U.S. Agency for International Development, to strengthen international programs at SDSU in dryland agriculture, rural development, human nutrition, and remote sensing.

Dr. Thomas Dobbs, Professor of Economics, was leader of the research project from which this report resulted. Leadership in Microbiology and in Plant Science was provided by Dr. Carl Westby and Dr. Eugene Arnold, respectively. Dr. Westby is in overall charge of the SDSU Alcohol Research Laboratory. Mr. Duane Auch, Plant Science Research Assistant, conducted literature reviews for and prepared initial drafts of Chapter II and the harvesting technologies section of Chapter III. Mr. William Gibbons, Microbiology Research Assistant and Ph.D. candidate, did the same for the storage and processing technologies sections of Chapter III. Literature reviews for and initial drafts of Chapters IV and V were the responsibility of Mr. Randy Hoffman, Economics Research Associate. The project was carried out as a <u>group</u> effort, however, with all members of the research team involved in planning, coordination, and manuscript revising. Duane Auch and Thomas Dobbs took responsibility for final organization and edit of the manuscript.

We appreciate the reviews of parts of this report by Dr. Ardelle Lundeen, Associate Professor of Economics, and Mr. Ralph Alcock, Assistant Professor of Agricultural Engineering. Special thanks are extended to Mrs. Nancy Hurtig, Mrs. Betty Prunty, and Mrs. Dawne Lamp for typing the manuscript.

Note on Units of Measurement

Metric units of measurement are used in Chapters II and III, which describe agro-climatic, harvesting, storage, and processing considerations for alternative crops. In Chapters III and IV, which deal with economic considerations and food-fuel conflicts, United States units of measurement are used. Annex A contains a table of conversion factors for metric and United States units. The following abbreviations have been used in this report for various units:

L = liter

kg = kilogram

t = metric ton

cwt = short hundredweights (100 pounds)

ODt = oven dried metric ton

cm = centimeter

m = meter

km = kilometer

C = centigrade temperature units

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I. Introduction

Sources and costs of energy for agricultural production, processing, and transportation became vital concerns during the 1970's, both in more developed countries and in less developed countries (LDCs) of the world. Agriculture itself has been identified in some circles as one possible fuel source, through the production and use of ethanol or other fuels from agricultural biomass. An extensive literature has been developed over the past 4 to 5 years on production of fuel alcohol from grains, and some research has been conducted on use of oil crops (such as sunflowers) for liquid fuel. Recent publications (e.g., World Book; National Research Council) have also explored biomass fuel possibilities in LDCs.

South Dakota State University (SDSU) has carried on a multi-discipline research program since 1979 on small-scale fuel alcohol (ethanol) production. Engineers, microbiologists, agricultural economists, and animal and plant scientists have been involved in this endeavor. Until 1983, most of the research at SDSU focused on production and utilization of alcohol (and byproducts) from corn, though some research in microbiology has been conducted on conversion of cellulosic materials to alcohol. As economic feasibility work on corn-based alcohol production neared completion in 1983, greater attention began to be focused on feedstocks other than corn. The prospects for fuel alcohol production in LDCs also began to receive some of the research team's attention.

This report is a result of the fuel alcohol research team's broadened focus during 1983. A comprehensive literature review was carried out to explore alternative starch and sugar crop alternatives for ethanol fuel production. Although the literature search was quite inclusive with respect to geographic regions, special emphasis was given to the agronomic and economic potential of various fuel alcohol crops in the Northern Plains region of the U.S., of which South Dakota is a part, and in LDCs of Asia, Africa, and Latin America. Our intent was to thereby determine possible energy crops deserving of more fuel alcohol research attention in the Northern Plains and also provide a document of use to ourselves and others considering various crops for fuel alcohol production in LDCs. Development assistance agencies, and universities such as SDSU which work with them, must be able to assess the energy producing potential of agricultural economies, along with food and fiber producing potentials. One kind of energy production that may be technically and economically feasible in some LDCs is fuel alcohol production from starch and sugar crops. (In this report, the terms alcohol and ethanol are used interchangeably.)

This report on alternative crops for fuel alcohol production is organized as follows. Chapter II covers agro-climatic considerations for various crops. Following that, harvesting, storage, and processing considerations are treated in Chapter III. Economic assessments of various crops are introduced next, in Chapter IV. The economic assessments must be considered quite preliminary for crops other than corn, as they draw on a rather sparse literature in some cases and on rough estimates of how certain crops might be processed in an alcohol plant like SDSU's in other cases. In the final chapter of this report (Chapter V), the potential conflict between "food and fuel" in use of agricultural resources is briefly examined. Emphasis is on the LDCs in that review of food-fuel conflict issues.

Throughout this report, the main focus is on "small-" or "community-scale" fuel alcohol production. Economies of size work against the economic feasibility of small-scale fuel alcohol production in many circumstances. However, our emphasis at SDSU has been on exploring the potential feasibility of small-scale production--in order to not only meet alternative energy production objectives, but to try to enhance employment and economic activity in small towns and rural areas, as well. The latter is an objective of most LDCs, as well as of rural states of the U.S. such as South Dakota. By "small-" or "community-scale" production in this report, we mean production by small-business or farmer cooperative units, not normally production by each individual farmer for his own fuel needs.

II. Agro-Climatic Considerations for Alternative Crops*

Climatic factors must be considered in the selection of a feedstock for ethanol production. Some crops are limited to cultivation within fairly specific climates, while others can be grown over a wide range of climates. The first portion of this section describes the temperature and moisture requirements of particular crops and identifies the general climates in which they can be grown. Soil factors are not extensively considered, although they have a major affect on crop adaptability. A second portion contains general estimates of yields from each crop under various growing conditions. For comparison among crops, potential ethanol yields per hectare are given based on crop yields and on ethanol conversion rates from available processing technology.

A vast number of crops could be considered as potential feedstocks for ethanol production. Preliminary evaluation of crops resulted in the selection of several crops which have potential to produce high amounts of starches or sugars. The starch crops discussed are cassava, yams, sweet potatoes, rice, corn, grain sorghum, and potatoes. Small grains such as wheat, barley, oats, rye, and millets are not extensively discussed, because, as will be noted in the discussion of ethanol production from corn, potential ethanol production per hectare from these crops is low compared to other starch crops. Sugar crops described include sugar cane, sweet sorghum, Jerusalem artichokes, sugar beets, and fodder beets.

A. Overview of crops suitable to different climatic conditions

The suitability of a geographic area for cultivation of a particular

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*Principal authors: Duane Auch and W. E. Arnold crop depends on many factors. Among the most important are the temperature and precipitation characteristics of the area. Many schemes have been developed to group climates of the world according to similarities in temperature and precipitation. These schemes are helpful for identifying general areas of the world that may be suitable for growing certain crops. Many useful classification systems are too detailed for use in this report. A simple classification system developed by Trewartha will be used, because its climatic groups tend to coincide with main production areas of some of the major world crops.

Trewartha has divided the world climates into major climatic groups with subdivisions called climate types and subtypes. Major areas of crop production have tropical humid, subtropical, or temperate climates (Table 2-1). Certain areas with dry or highland climates are also agronomically productive. However, crop production is minimal in areas with boreal climates and impossible in polar areas because of long cold periods. Areas too cold for crop production comprise an estimated 29% of the earth's land surface (Bennett). Boreal and Polar climates will not be discussed in this report because of their minor agronomic importance.

Crops which require high temperatures, high moisture, and a long growing season such as sugar cane, cassava, yams, and bananas are confined to tropical humid climates. Within the tropical humid group are the tropical wet type and the tropical wet and dry type (Table 2-1). In the tropical wet climate type, precipitation is uniformly distributed over at least 10 months of the year. The tropical wet and dry climate generally has less annual precipitation than the wet climate, and the precipitation is not uniformly distributed throughout the year.

Table 2-1. Descriptions of Selected Groups and Types of Climate from Trewartha's Classification of World Climates.[1/]

Climate Group	Climate Type	Temperature	Precipitation
1. Tropical humid	a. Wet	No killing frost; in marine areas, mean temperature of cold month over 18.3°C.	Not more than 2 dry months, often 180-250 cm annually.
	b. Wet and dry	"	High-sun = wet (zenithal rains), low-sun = dry; greater than 75 cm annually.
2. Subtropical	a. Dry summer	8-12 months above 10°C, mean temperature of cold month below 18.3°C.	Summer drought, winter rain; 40-75 cm annually.
	b. Humid	"	Rain in all seasons, 75-165 cm annually.
3. Temperate	a. Oceanic	4-7 months over 10°C, mean temperature of cold month over 2°C.	Precipitation in all seasons, droughts uncommon.
	b. Continental		
	1) warm summer	4-7 months over 10°C, mean temperature of cold month under 2°C. Mean temperature of warm month over 22.2°C.	Precipitation in all seasons, accent on summer; winter snow cover; half area receives less than 75 cm annually.
	2) cool summer	4-7 months over 10°C; mean temperature of cold month under 2°C; mean temperture of warm month below 22.2°C.	"

Table 2-1 (Continued)

4. Boreal		1-3 months over 10°C.	Meager throughout year.
5. Dry	a. Semiarid	In low latitudes, 8 or more months with mean temperatures over 10°C; In high latitudes, less than 8 months with mean temperature above 10°C.	Evapotranspiration exceeds precipitation, short moist season in low latitudes, meager rainfall in high latitudes.
	b. Arid	"	Evapotranspiration exceeds precipitation; constantly dry.
6. Highland		Temperature drops as elevation increases.	In tropics, annual precipitation increases with increased altitude up to 1,500 m then decreases at higher elevations; outside tropics, precipitation increases with increased elevation.

[1]Trewartha, Glenn T. An Introduction to Climates. New York, St. Louis, and San Francisco: McGraw-Hill Book Company, 1968.

Tropical humid climates are mainly found 20 to 40° north and south of the equator (Figure 2-1). Many developing countries have tropical humid climates.

Subtropical climates are differentiated from tropical climates by the fact that the coldest month has an average temperature of less than 18°C (Table 2-1; Trewartha). They are located in the middle latitudes farther from the equator than tropical climates (Figure 2-1). Some frosts may occur in subtropical areas, but marine areas may be without freezing temperatures throughout the year. Rice and cotton are grown in subtropical areas, but the growing season in the subtropics may be too short for optimal production of cassava, yams, sugar cane, and bananas.

Subtropical climates are divided into dry summer and humid types (Table 2-1; Trewartha). In the dry summer climate, rainfall occurs mainly in the cool season while the summers may be absolutely dry. Severe frosts are infrequent. Since rainfall occurs during the cool season, moisture loss by evapotranspiration is low. In the U.S., this type of climate is found in parts of California (Figure 2-1). The subtropical humid climate is found in the southeastern portion of the U.S. It generally has greater and more uniform annual precipitation than the dry summer climate. The growing season may be from 7 months to nearly the entire year in the subtropical humid climate type.

Temperate climates are usually found between the warm subtropical and cold boreal climates (Table 2-1; Trewartha). Within the temperate climatic group are oceanic and continental types (Table 2-1; Trewartha). Oceanic climates tend to have a cool summer, but the growing season may be as long as 180 to 210 days. Northern Europe and the northwestern

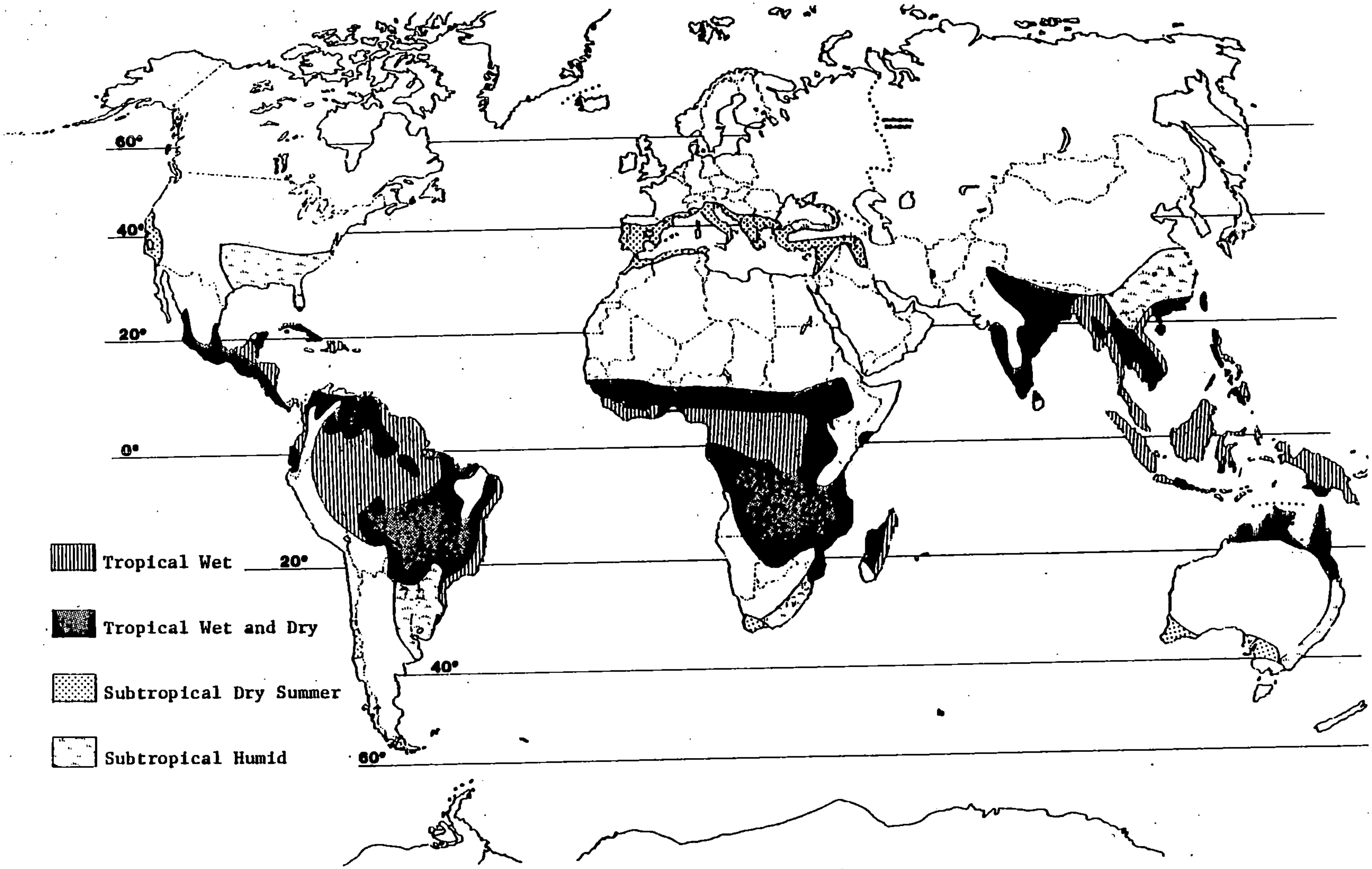

Figure 2-1. Tropical and Subtropical Types of Climate according to Trewartha's Classification (Trewartha).

coast of the U.S. have temperate oceanic climates (Figure 2-2). Rainfall is adequate in all seasons of the oceanic climate, and droughts are uncommon. Generally, cool season crops such as small grains, potatoes, and sugar beets are grown in temperate oceanic climates.

The eastern portion of the Northern Plains has a continental temperate climate (Figure 2-2). Cold winter temperatures generally prevail in temperate continental climates. Over half the area in temperate continental climates receive less than 75 cm of precipitation. More of the precipitation falls in the summer than the winter. The timing and amount of rainfall in the summer has greatest affect on agricultural productivity.

The continental temperate type has two important subtypes called the warm summer and cool summer subtypes, which have average July temperatures of above and below 22.2°C, respectively (Table 2-1). Summers are long, warm, and humid in the warm summer subtype. The period between killing frosts may be 150 to 200 days. Major corn production areas are in the warm summer subtype. In the cool summer subtype, summers are usually moderately warm, but short. Crops are similar to those grown in oceanic temperate climates (small grains, potatoes, and sugar beets). In the Northern Plains, a major portion of North Dakota and northern Minnesota have cool summer climates (Figure 2-2). The warm summer temperate climate extends southward to the southern border of Kansas.

In the dry climate group, evapotranspiration exceeds annual precipitation (Table 2-1). Approximate boundaries of dry areas are determined with a formula that utilizes mean annual temperature and

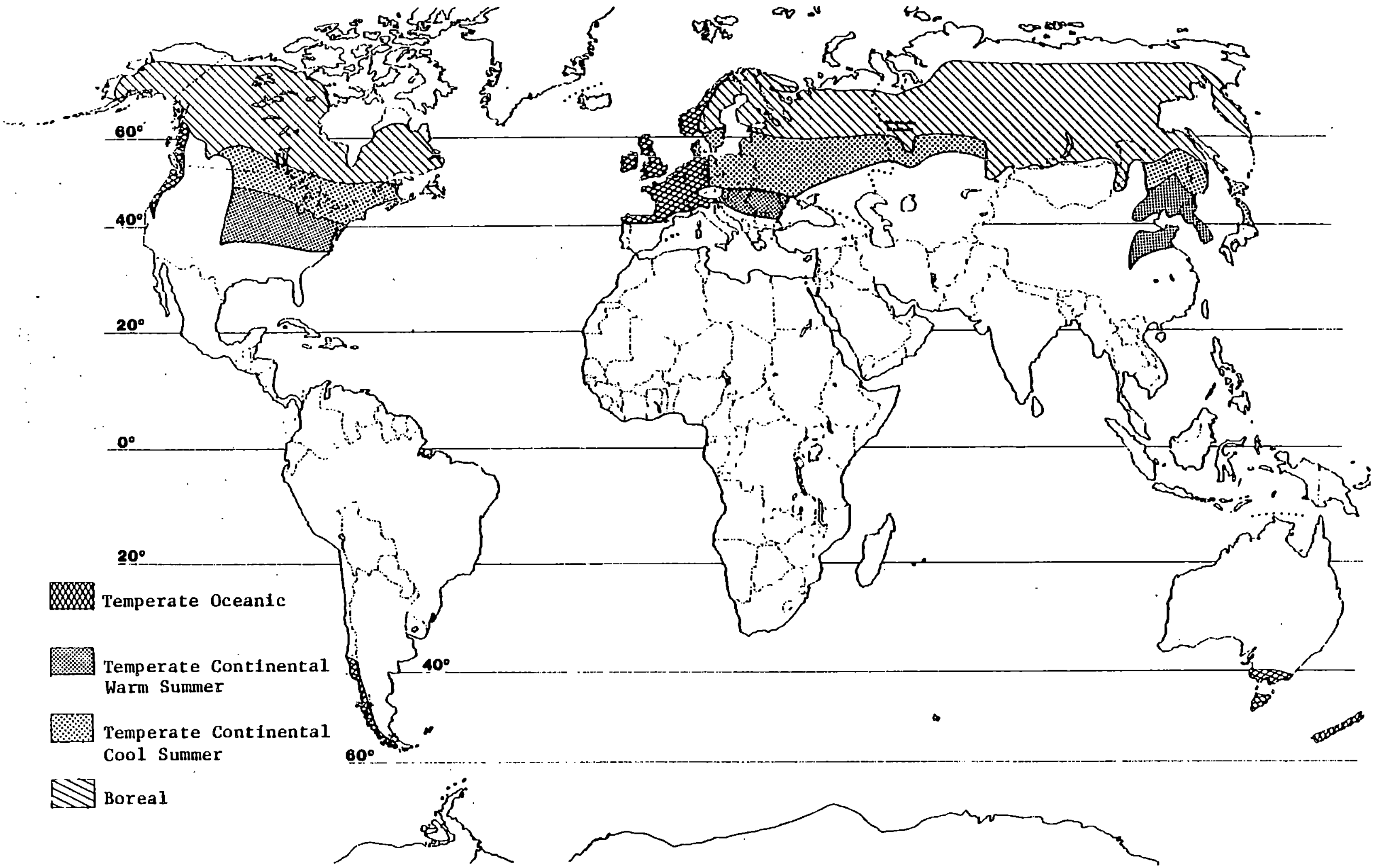

Figure 2-2. Temperate and Boreal Types of Climate according to Trewartha's Classification (Trewartha).

precipitation as well as the percentage of precipitation occurring in the winter. The dry climate group is divided into arid and semiarid types. Semiarid climates occur in much of the western U.S., including the western portion of the Northern Plains (Figure 2-3). They are also prevalent in many developing countries. Production of drought tolerant or very short season crops such as sorghum, millet, and small grains is possible in many semiarid areas. Without irrigation, crop production is not possible in arid regions, which occupy 12% of the earth's land surface (Bennett).

Climate in highland areas is dependent on altitude, latitude, and exposure. Zones of climate occur at different altitudes in tropical humid latitudes. Different crops are grown in the various zones up to 3,500 m, and perpetual snow is present above 4,250 to 4,500 m.

1. Tropical and subtropical crops

Tropical and subtropical crops are those which are limited to cultivation in tropical or subtropical areas, because they generally require a long growing season, high temperatures, and abundant soil moisture. Many short season crops grown in temperate areas can also be grown in tropical and subtropical areas. However, they are classified as temperate crops in this report. Starch producing tropical and subtropical crops discussed are cassava, yams, sweet potatoes, and rice. Sugar cane is the only tropical and subtropical sugar crop discussed. Although classed as tropical and subtropical crops, cassava and sweet potatoes may also be grown in some semiarid areas, but dry conditions limit production.

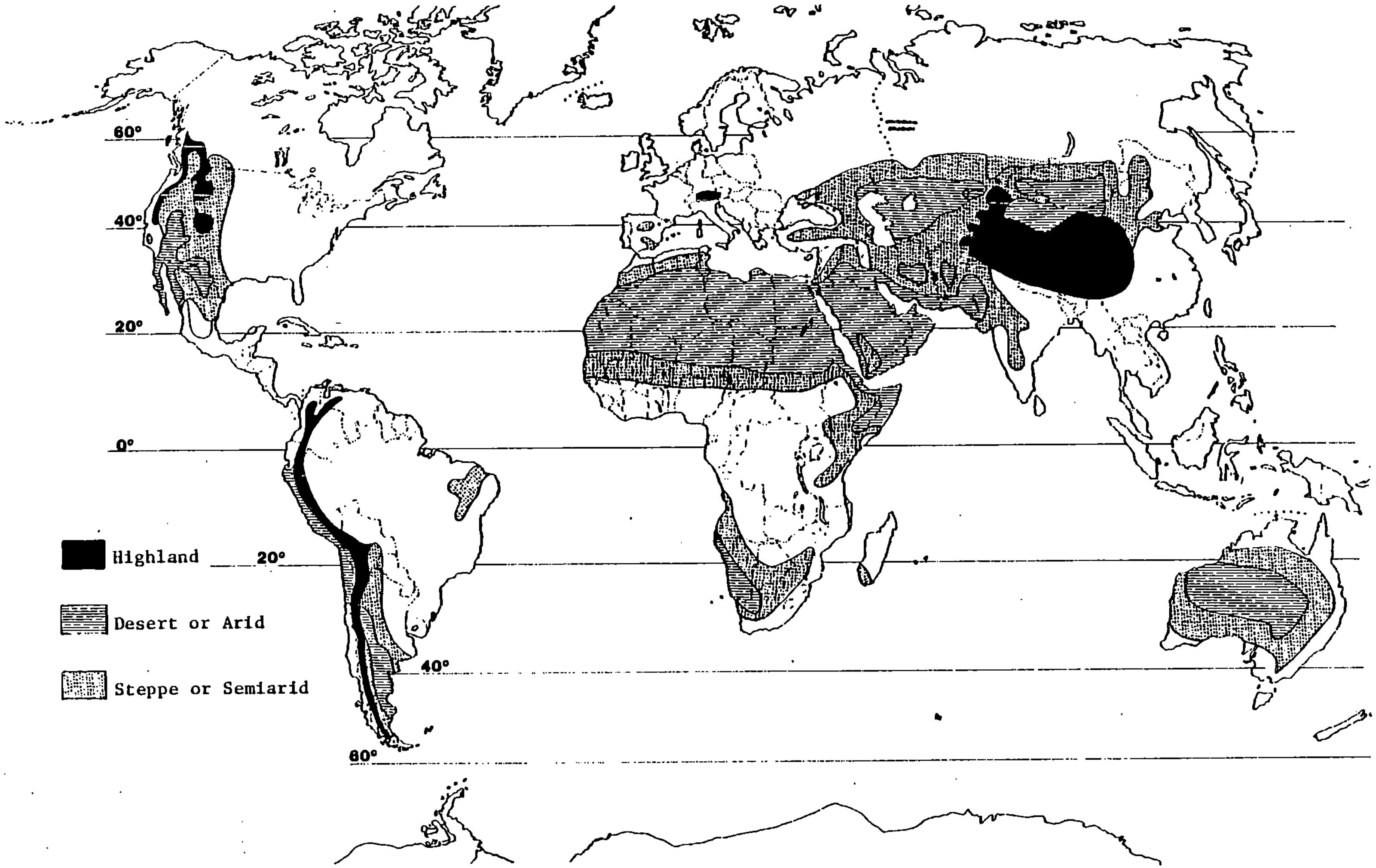

Figure 2-3. Highland and Dry Types of Climate according to Trewartha's Classification (Trewartha).

a. Starch crops

1) Cassava (Manihot esculenta)

Cassava is grown most extensively in tropical humid climates. It requires at least 10 months for maximum tuber production, and harvesting is usually done 1 to 2 years after planting (McClure and Lipinsky; Onwueme). Since it is sensitive to frost, cassava must mature before cold temperatures occur. Temperatures of 25 to 29°C and day lengths less than 10 to 12 hours are required for optimal growth (Kay; Onwueme). Consequently, cassava is not adapted to temperate or most subtropical areas (Table 2-2). Cassava is mainly grown between 15° north and 15° south latitude (Kay), but the extremes of the production area are 30° north to 30° south latitude. Cassava is generally not grown above an altitude of 1,000 m in humid tropical areas (Kay; Onwueme).

Highest yields are obtained when cassava receives 100 to 150 cm of well-distributed rainfall. Therefore, it is adapted to areas which are continually humid. However, tuber production and quality can be reduced by high amounts of rainfall, if adequate drainage is not provided (de Alvim and Kozlowski). Cassava is often a main crop in areas without a dry season, because it is propagated by cuttings rather than by seeds. Grain crops are difficult to cultivate in continually humid conditions due to problems with seed decay after planting. Also, with continual rain, it is difficult to harvest, dry, and store grains (Cobley).

Tropical humid areas with a dry season are also suitable for cassava, because it is drought tolerant at all stages of growth except planting time (de Alvim and Kozlowski; Onwueme). Consequently, planting is usually done at the beginning of the wet period. During dry periods,

Table 2-2. Adaptability of Potential Ethanol Fuel Crops to Various Climates without Irrigation (1 = good, 2 = fair, 3 = poor, 4 = not adapted).[1/]

Crops	Tropical Humid		Subtropical		Temperate			Boreal	Dry	
	Wet	Wet & Dry	Dry Summer	Humid	Oceanic	Continental			Semiarid	Arid
						Warm	Cool			
Starch Crops										
Cassava	1	1	4	3	4	4	4	4	3	4
Yams	1	2	4	4	4	4	4	4	4	4
Sweet potatoes	2	1	2	1	4	3	4	4	3	4
Rice	2	1	2	2	4	3	4	4	4	4
Corn	3	2	2	1	2	1	2	4	3	4
Grain sorghum	3	2	2	1	3	1	3	4	2	4
Millet	4	2	2	1	2	1	2	4	2	4
Potatoes	4	3	2	2	1	2	1	3	4	4
Wheat	4	3	1	3	1	1	1	4	2	4
Barley	4	3	1	3	1	1	1	3	2	4
Oats	4	4	1	2	1	1	2	4	3	4
Rye	4	4	3	3	1	2	1	3	2	4
Sugar Crops										
Sugar cane	3	1	4	2	4	4	4	4	4	4
Sweet sorghum	3	1	2	1	3	1	3	4	3	4
Sugar beets	4	4	2	3	1	2	1	3	4	4
Fodder beets	4	4	2	3	1	2	1	3	4	4
Jerusalem artichokes	4	3	2	3	1	1	1	4	3	4

[1/] Climatic classes are from Glenn T. Trewartha. An Introduction to Climates. New York, St. Louis, and San Francisco: McGraw-Hill Book Company, 1968. (See Table 2-1 and Figures 2-1 to 2-3).

plant growth stops, and older leaves drop. Plant growth and tuber formation begin again when adequate precipitation occurs. Cassava is grown in some semiarid areas where annual rainfall is as low as 50 cm, but yields are low.

2) Yams (Dioscorea spp.)

There are over 600 different species of yams (Kay). They belong to the genus Dioscorea and produce tubers, bulbils, or rhizomes which are high in starch. Yam species tend to have growth requirements which restrict their cultivation to the humid tropics at altitudes less than 1,000 m (Table 2-2; de Alvim and Kozlowski; Kay; Onwueme). They generally need 7 to 9 months to mature, and 25 to 30°C temperatures are required for optimal growth (Onwueme; USDA, 1974a; USDA, 1976; USDA, 1977b). Growth is restricted by temperatures below 20°C, and most yams are sensitive to frost. However, two species, Dioscorea opposita and D. japonica, are adapted to subtropical humid or even warm temperate climates.

Yams are not as widely distributed as cassava. In West Africa, most yams are grown between 4 and 10° north latitude (Kay; Onwueme). The limits of yam production are 20° north to 20° south latitude, because short-day conditions of 10 to 11 hours are required for tuber development (Kay). Yams are most often grown in areas with a long rainy season and a clearly demarcated dry season of 2 to 5 months (de Alvim and Kozlowski; Kay). However, yams can not tolerate dry periods longer than 3 or 4 months, and adequate rainfall is especially important during tuber formation. Highest yields occur with 120 to 150 cm of annual rainfall (de Alvim and Kozlowski; Kay; Onwueme). Waterlogging, however, restricts tuber initiation and causes tubers to decay.

Tubers usually mature immediately before the dry season, and they are planted in the dry season or early in the rainy season. They need little moisture to survive and have been shown to sprout in dry sawdust (Onwueme). Temperatures ranging from 20 to 30°C are required for sprouting. Sprouting is delayed by temperatures below 15°C and above 35°C.

3) Sweet potatoes (Ipomoea batatas Lam.)

Subtropical and tropical humid climates are suitable for cultivation of sweet potatoes (Table 2-2). The crop is not adapted to cool temperate areas, because it requires 4 to 6 months of warm temperatures and abundant sunlight (FAO, 1978). It is also sensitive to frost. Warm temperatures above 24 or 27°C are necessary for maximum growth, but temperatures above 32°C may injure tuberous roots (FAO, 1978; Martin, Leonard, and Stamp; Onwueme). Tuberous root development is promoted by relatively low temperature and light intensity (de Alvim and Kozlowski). Sustained temperatures below 10°C can cause damage, and sprouting does not occur below 16°C (Martin, Leonard, and Stamp).

Due to high temperature requirements for growth, sweet potatoes are grown between 40° north and 40° south latitude (de Alvim and Kozlowski). Altitudes of up to 2,100 m are suitable for sweet potatoes in humid tropical areas. They are more widely distributed than cassava and yams, because they have a shorter duration, and tuberization can occur at day lengths as long as 13.5 hours.

Sweet potatoes are suited better to tropical humid climates with a dry season than to continually wet climates. Optimum rainfall is 75 to

100 cm annually, with approximately 50 cm occurring during the growing season (Martin, Leonard, and Stamp; Onwueme). However, they are grown where annual rainfall is as low as 50 cm (Kay). Excessive rainfall can result in low yields because lush vine growth occurs at the expense of tuber production. Moderately dry conditions are desirable during tuberous root formation (de Alvim and Kozlowski). Waterlogged soil conditions retard root formation, hinder root enlargement, and cause root rotting (de Alvim and Kozlowski; Onwueme). Sweet potatoes are somewhat drought tolerant except 50 to 60 days after planting, which is the beginning of tuber bulking.

4) Rice (Oryza sativa L.)

Rice has a rather wide range of adaptation, especially if irrigation is available. It is grown between 49° north and 36° south latitude (de Alvim and Kozlowski; McClure and Lipinsky). In tropical humid areas, it is grown at altitudes as high as 2,000 m. The wide adaptability is due to the great genetic variability within the species. There are an estimated 30,000 rice varieties in the world (Gabel; Martin, Leonard, and Stamp). Some varieties can be grown on upland, others under moderately flooded conditions, and others where water becomes 1.5 to 5.0 m deep (de Alvim and Kozlowski). Varieties also differ greatly in duration of growth and response to day length and temperature. Therefore, generalizations about the growth requirements and adaptability of rice are difficult to make.

Rice requires temperatures of greater than 21°C during the growing season, which is 90 to 250 days in Asia and 110 to 180 days in the U.S. (Martin, Leonard, and Stamp; McClure and Lipinsky; Papadakis, 1966).

Consequently, most rice is grown in subtropical and tropical humid climates (Table 2-2). However, in some warm continental temperate areas, varieties can be grown which are tolerant to low temperatures at the seedling and reproductive stages (de Alvim and Kozlowski). Rice is cold sensitive, and temperatures of 5°C for 24 hours kill rice plants (Papadakis, 1970). The minimum temperature for germination is between 16 and 19°C (de Alvim and Kozlowski; De Datta). Optimum temperatures for leaf elongation, flowering, and ripening are 31°C, 30 to 33°C, and 20 to 29°C, respectively (de Alvim and Kozlowski). Cool night temperatures are important for ripening in subtropical and warm continental temperate areas (de Alvim and Kozlowski; Papadakis, 1970). They are not as important in tropical areas if solar radiation is adequate (de Alvim and Kozlowski). However, high temperatures and low solar radiation are two reasons for lower rice yields in continually wet tropical climates. Other problems with rice cultivation in continually wet tropical climates are low soil fertility levels and grain drying difficulties (Martin, Leonard, and Stamp; Papadakis, 1970). Highest yields per crop generally are found in temperate areas or in dry seasons of tropical areas when irrigation is given (Papadakis, 1970; De Datta). However, low temperatures prevent rice production in most temperate areas.

Insufficient rainfall also limits production in temperate and subtropical climates (De Datta). The water requirements of rice are dependent on topography, soil conditions, and length of growing season. Generally, at least 100 cm of annual rainfall are required for dryland rice cultivation (FAO, 1978; de Alvim and Kozlowski). Permeable sandy soils require three times more water than clay soils (de Alvim and

Kozlowski). Uniformity of rainfall distribution is important. Approximately 20 to 30 cm of evenly distributed rainfall per month is required for best yields (de Alvim and Kozlowski). Yields are highest when fields are flooded to a depth of 25 to 75 cm unless deep water or floating varieties are used (De Datta). At seeding time, however, many varieties (especially Indica types) require either exposure to air or shallow standing water for germination and rooting (de Alvim and Kozlowski). Water stress is most harmful during the period from 10 days before flowering to flowering.

b. Sugar Crops

Sugar cane (_Saccharum officinarum_ L.)

Production of sugar cane is limited to tropical humid and a few subtropical areas, because sugar cane requires a long warm growing season (Table 2-2). Sugar cane is grown between 35° north and 35° south latitude at altitudes up to 900 m. In frostless climates, sugar cane may remain in fields for over 2 years before harvest (de Alvim and Kozlowski). The average duration is 14 to 18 months, followed by a ratoon crop which is harvested after 12 months. Harvesting is done when maximum sugar content in the stalk is reached. In cool climates, sugar cane is harvested within 9 to 10 months, depending on the time of frost occurrence. Temperatures of -3°C kill leaf tissue and stop sugar accumulation (Martin, Leonard, and Stamp). Stalks are killed when temperatures reach -5°C; the stalks then deteriorate. Freezing temperatures to a soil depth of 7 to 8 cm will kill seed pieces, preventing emergence (de Alvim and Kozlowski). The optimum temperature for sprouting is 26°C, and optimal temperatures for growth are between 26.7 and 32.2°C.

Stem elongation is inhibited by night temperatures less than 21°C (McClure and Lipinsky).

Sugar cane is best suited for tropical humid climates with a short dry season prior to harvesting (Williams). Dry, cool, and sunny conditions stimulate sugar accumulation in the stalk. Under continually wet conditions, tillering is excessive and tonnage high, but the sucrose content is low. Uniform distribution of 120 to 150 cm of rainfall is necessary before the beginning of the maturation stage (McClure and Lipinsky; Paul; Wilsie). Generally, sugar cane requires 2.8 cm of water/t of production. Good drainage is important, although sugar cane tolerates occasional flooding. The water table should remain at least 1 m below the surface for optimal growth (Martin, Leonard, and Stamp; McClure and Lipinsky; Paul). Low levels of oxygen at the 70 cm level or above retard root growth (Martin, Leonard, and Stamp).

2. Temperate crops

Temperate crops are those which can be grown in areas with a relatively short growing season. Consequently, they are adapted to many temperate areas where the length of the growing season is restricted by cool temperatures. Corn, grain sorghum, and potatoes are starch producing temperate crops which will be discussed. Temperate sugar crops to be described are sweet sorghum, sugar beets, fodder beets, and Jerusalem artichokes.

These temperate crops are not, however, limited to cultivation in areas with temperate climates (Table 2-2). Corn, grain sorghum, and sweet sorghum do well in warm summer temperate climates, but are also well-suited to many tropical humid and subtropical climates. Grain sorghum is also grown widely in semiarid areas. Potatoes, sugar beets, and fodder beets require periods with cool temperatures and are grown primarily in cool temperate areas. However, they are also grown in some tropical humid, subtropical, or warm temperate climates. Most of the temperate crops can be grown in temperate zones of highlands of tropical and subtropical areas.

a. Starch crops

1) Corn (Zea mays L.)

Extremely diverse varieties of corn have developed so that corn is grown from 58° north to 40° south latitude (Martin, Leonard, and Stamp; Wilsie). In some tropical humid areas, corn is grown at altitudes as high as 4,000 m. Varieties in areas with a short growing seasons may mature within 50 days, while tropical varieties may require as many as 330 days. The wide adaptability of corn is partially due to differences in photoperiodic response among varieties. Corn is a short-day plant. Tropical varieties flower too late at temperate latitudes, and temperate varieties flower too early in tropical latitudes (Martin, Leonard, and Stamp). Varieties grown in the main corn producing areas mature in 90 to 150 days.

Most of the world's corn production is between the latitudes of 30 and 45° both north and south of the equator. Warm temperate and humid subtropical climates are most suitable for unirrigated corn production (Table 2-2). Cool and oceanic temperate climates are generally too cool for corn, although corn is an important crop in some cool temperate areas. The optimal temperatures for growth are between 24 and 30°C, and corn is generally not grown where middle summer temperatures average less than 19°C (Aldrick, Scott, and Leng; Hafliger). No germination or plant growth occurs at temperatures below 10°C. Prolonged temperatures between 7°C and freezing will kill many corn varieties (Martin, Leonard, and Stamp). Plants smaller than 15 cm tolerate a light frost without injury (Wilsie). At later stages, temperatures of 2°C on clear, still nights can cause injury (Aldrick, Scott, and Leng).

With adequate moisture, corn tends to yield better in temperate than in tropical climates, because midseason temperatures above 27°C reduce yield (Martin, Leonard, and Stamp). Temperatures above 35°C inhibit seedling growth (de Alvim and Kozlowski). Low solar radiation during cloudy conditions may be another limiting factor in humid tropical conditions (Haflinger). Corn can be damaged severely by excessive water and, therefore, requires good drainage. Excessive moisture during the maturation period makes harvesting difficult, and losses due to spoilage may be severe. Consequently, corn is often grown in tropical humid climates with a dry season rather than in continually wet climates.

Corn usually can not be grown for grain production in semiarid regions without irrigation. Subtropical areas with a dry summer require irrigation for summer cultivation of corn, and they may be too cool for winter cultivation. More than 38 cm of precipitation annually and 20 cm seasonally are usually required for corn production (Martin, Leonard, and Stamp; McClure and Lipinsky). One mm of water is required for every 20 kg of grain produced per hectare. Maximum production generally occurs in areas with 60 to 100 cm of annual precipitation (Martin, Leonard, and Stamp). Precipitation requirements are higher in tropical and subtropical areas than in temperate areas. They are also higher at low altitudes than at high altitudes. Corn is grown in some high altitude areas receiving less than 15 cm of precipitation annually.

Corn is most sensitive to drought during flowering and fertilization (Wilsie). Moisture levels during the period 3 weeks before to 3 weeks after silking are more important than annual rainfall in determining yield. Temperatures above 38°C during silking can cause high evapotranspiration rates, and internal water supply may not be adequate for pollen tube germination.

2) Grain sorghum (*Sorghum bicolor* L. Moench)

Grain sorghum is a widely adapted crop which grows between 45° north and 45° south latitude. It can be grown in warm temperate, subtropical and tropical climates (Table 2-2). Cool temperate climates generally do not provide a sufficiently long warm period for sorghum cultivation. The growing season for sorghum ranges from 90 to 140 days, with an average of 100 to 120 days (House). Germination does not occur unless soil temperatures are above 12°C, so sorghum can not utilize as much of the growing season in cool summer temperate climates as cool season crops do. Maximum percentage and rate of emergence occurs at temperatures above 25°C (Martin, Leonard, and Stamp). Optimal temperatures for early season growth are between 27 and 32°C (Doggett; McClure and Lipinsky). Lower temperatures are generally required during flowering (Martin, Leonard, and Stamp). However, House stated that floral development and seed set is normal at temperatures of 40 to 43°C, if moisture is adequate. In Peru, sorghum will not set seed at temperatures less than 15°C (FAO, 1961). Freezing temperatures before harvest can destroy seed germination if the seed contains more than 25% moisture (Martin, Leonard, and Stamp). In the first 3 weeks of growth, plants may survive slight frost, but temperatures slightly below freezing will kill older plants.

Sorghum is better adapted to semiarid regions than many other cereals, because sorghum plants become nearly dormant during hot and dry conditions. After being wilted for 14 days, sorghum plants have been shown to fully recover within 5 days after provision of adequate moisture (Doggett). Sorghum also has a thicker leaf cuticle, lower leaf area per plant, and a more extensive root system than corn (Lipinsky and Kresovich; Martin, Leonard, and Stamp). Maximum production occurs where annual precipitation averages 65 cm, but sorghum is grown in areas with 40 cm of annual precipitation. Approximately 332 kg of water are required to produce 1 kg of dry matter (House). Corn and wheat use 368 and 514 kg of water, respectively, to produce 1 kg of dry matter. Maximum uptake of water in sorghum is during the late boot and flowering stages (Martin, Leonard, and Stamp; House). Adequate soil moisture as well as warm temperatures are important for good stand establishment in semiarid areas.

In tropical areas, planting should be timed so that the sorghum blooms when temperatures are not extremely high. Sorghum can be cultivated during rainy periods in some tropical humid areas, because it can withstand soil waterlogging better than other cereals, especially corn. Rachie (Wall and Ross) observed that sorghum survived in standing water for several weeks. House indicated that sorghum grows, though not well, in flooded conditions where corn will die. However, light, well drained soils are generally best for sorghum production. Continually wet conditions can cause problems with sorghum harvesting and storage, so sorghum is generally grown in drier areas of the tropics (FAO, 1961).

3) Potatoes (<u>Solanum tuberosum</u> L.)

Potatoes are grown throughout the world but are most suited for cool temperate climates (Table 2-2). Cool climates at altitudes of 2,000 to 3,500 m are major production areas in some low latitude areas (Hanis). Varieties which are somewhat resistant to frost can be grown at altitudes as high as 4,000 m. In humid tropical and subtropical areas, high temperatures limit potato production (Klages). However, in some areas, they are grown during cool periods, even though conditions may not be optimal. Leaf growth is favored by temperatures of 20°C, while 25°C is optimal for stem growth (Hanis). Temperatures above 21°C can reduce yield, and cool night temperatures are especially important (Kay; Martin, Leonard, and Stamp). Temperatures of 16 to 18°C retard vegetative growth and stimulate tuber initiation and growth (FAO, 1978; Hanis; Martin, Leonard, and Stamp). Tuber growth is retarded by soil temperatures above 20°C (Martin, Leonard, and Stamp). A second growth may occur at 27°C, but tuber growth stops at temperatures above 29°C. High light intensity during the growing season may cause tuberization to occur at higher temperatures (Kay).

Potatoes are photoperiod sensitive. Long days with warm temperatures favor vegetative growth while short days and cool temperatures favor early tuberization (Martin, Leonard, and Stamp; McClure and Lipinsky). Maximum tuber production occurs with intermediate day lengths and cool temperatures. However, varieties differ in photo-periodic response. In South America, varieties only produce acceptable yields with 12 to 13 hour day lengths (Kay). In temperate areas, early varieties require 15 to 16 hour days, while late varieties produce reasonable yields at either short or long day lengths.

Potatoes generally require 90 to 130 days to mature, but some varieties may need up to 210 days (Kay; McClure and Lipinsky). Tubers are planted at least two weeks prior to the last killing frost (Martin, Leonard, and Stamp). The minimum temperature for sprouting is 4°C, and the optimal temperature is 24°C. Tubers freeze at approximately -2°C, and completely frozen tubers disintegrate upon thawing. Potatoes are generally sensitive to frost, and short periods of -2°C temperatures can completely destroy a crop (Kay). However, some varieties can withstand exposure to temperatures of -5 to -10°C, while other varieties can not withstand temperatures of 0 to -1°C (Hanis). Potatoes are particularly sensitive to frost in the early growth stages (Kay).

Adequate soil moisture throughout the season is necessary for production of well-formed tubers (Martin, Leonard, and Stamp). From 30 to 60 cm are required during the growing season in the Great Plains of the U.S., but up to 76 cm may be required in subtropical areas (Kay). In experiments in Britain, yields increased by 1.4 t/ha for each centimeter of rainfall (Hanis). Potatoes are most sensitive to drought conditions during the period from tuber initiation to maturity. Poor drainage reduces soil aeration, restricting root and tuber formation. Cold, waterlogged soil conditions after planting may prevent tubers from sprouting. Incidence of late blight and other diseases are related to humid growth conditions and are especially difficult to control in tropical areas.

b. Sugar Crops

1) Sweet sorghum (Sorghum bicolor L. Moench)

Sweet sorghum is a member of the same genus and species as grain sorghum. It is distinguished from grain sorghum by higher sugar content in the stalks and lower seed production. The stalks are used for production of syrup. Sweet-stemmed grain sorghum varieties are being developed which have both high sugar content in the stalks and high grain yields (Jackson and Lawhon; Lipinsky and Kresovich). The varieties are either sweet sorghum hybrids or crosses of sweet sorghum and grain sorghum varieties.

Sweet sorghum has growth requirements similar to grain sorghum. It has a wide area of adaptation which includes tropical, subtropical, and warm summer temperate climates (Table 2-2). In the U.S., sweet sorghum is grown in an area from Minnesota to Alabama (Lipinsky, et al.). However, 90% of the production is in the southeastern states. Lipinsky, et al. indicated that sweet sorghum can potentially be produced wherever cotton, corn, grain sorghum, sugar beets, or sugar cane are grown.

Between 90 to 150 days are required for the crop to mature, depending on the photoperiodic response of the variety (McClure and Lipinsky; Paul). In Australian variety trials, crop duration ranged from 82 to 124 days. Warm temperatures between 20 and 35°C are required for growth (Ferraris and Stewart). With adequate moisture, sweet sorghum will thrive at temperatures as high as 40°C (McClure and Lipinsky). Growth stops with cool temperatures of 12 to 15°C, and plants should mature before the first frost for maximum biomass and sugar production (Ferraris and Stewart; Jackson and Lawhon; McClure and Lipinsky). Sweet sorghum is generally planted when soil temperatures are 21°C or higher. Consequently, in cool summer temperate climates, sweet sorghum may not be planted early enough to mature before the first frost. Yields of stalk sugars and biomass per hectare are correlated with the number of growing degree days, when other factors such as soil moisture and fertility are optimal (Jackson and Lawhon). Sugar concentration of stalks is higher in cool areas than warm areas; however, biomass production is less, resulting in less sugar per hectare.

In the U.S., only southern areas have growing seasons which extend beyond sweet sorghum maturity, and double crops of sweet sorghum can be produced in some humid subtropical and humid tropical areas (Jackson and Lawhon). In temperate areas, biomass and stalk sugars are produced until the first killing frost. Therefore, if varieties with more cold tolerance were developed, higher could probably be obtained in the Northern Plains.

Sweet sorghum varieties are not as well-adapted to semiarid regions as are grain sorghum varieties, but sweet sorghum is more drought tolerant than corn (McClure and Lipinsky). Approximately 3 cm of water are required to produce 1 t of stalks, and optimal precipitation is greater than 45 cm during the growing season. In wet climates, good drainage is important, especially during the early growth stages (Ferraris and Stewart; McClure and Lipinsky).

Low levels of solar radiation may be a limiting factor in continually wet tropical climates. Adequate solar radiation is especially important during the fruiting stage (Ferraris and Stewart). In trials in Texas, approximately 75% of the variation in yield was accounted for by differences in solar radiation during the fruiting stage.

2) Sugar beets and fodder beets (*Beta vulgaris* L.)

Sugar beets have been bred for high sugar concentration and for processing into sugar. On the other hand, fodder beets have a larger root with a lower sugar concentration than sugar beets. Fodder beets are used extensively for livestock feed in Europe. Since the two crops are closely related, they are assumed to be adapted to similar geographic areas. Sugar beets are grown in cool temperate climates such as those found in Europe, the U.S.S.R., and Canada (Table 2-2). In the U.S., they are grown in the north central states and the Northern Plains without irrigation (Lipinsky, et al.). With irrigation, they are grown at altitudes of 2,100 m in mountain states and in the California Imperial Valley. Sugar beets are not cultivated in tropical areas, but possibly could be grown at higher altitudes.

Present sugar beet distribution is not only affected by climatological factors, but also by the location of processing facilities. The USDA estimated in the early 1900's that 270 million acres of land in the U.S. have suitable climate and soil for sugar beet production (Doney). Considering that sugar beets are normally grown in a 4-year rotation, 60 to 70 million acres could be grown annually. However, only 1.2 million acres of sugar beets were harvested in 1980 (USDA, 1981b).

The growing season is approximately 5 months for both sugar beets and fodder beets (Hayes; Paul). Their growth requirements are similar to those of potatoes. Optimal temperature for seed germination is 15 or 16°C (FAO, 1978; Martin, Leonard, and Stamp), however, fodder beets will germinate at temperatures as low as 5°C (Hayes). Plant growth is favored by temperatures of about 24°C (Martin, Leonard, and Stamp). Cool temperatures before harvest stimulate sugar accumulation, and maximum sugar production occurs with night temperatures of 15°C (Johnson, et al.). Temperatures during the last month of growth should average 18°C or less, but a soil temperature of 10°C causes roots to be small with low sugar content (International Land Development Consultants; Johnson, et al.). In subtropical climates where irrigation is given, sugar accumulation can be stimulated by withholding irrigation. Optimal weather for seed production is 6 weeks of temperatures less than 21°C, cloudy days with less than 10.6 hours of sunshine, and wet conditions followed by 2 weeks of dry weather (Martin, Leonard, and Stamp). Seed production is also dependent on long photoperiods. Top growth of mature sugar beets is killed by temperatures less than -2 or -3°C, while seedlings may be killed by -4°C temperatures (FAO, 1978; Martin, Leonard, and Stamp). Fodder beets tend to be more resistant to late season frosts than sugar beets (Hayes). In temperate climates, roots must be harvested before the soil freezes.

Sugar beets require irrigation if annual rainfall is less than 45 cm (Martin, Leonard, and Stamp). In cool areas, 53 cm of water is needed to produce a 45 to 67 t/ha yield, and in warm areas up to 100 cm may be required. A dry period before harvest is necessary in the tropics or subtropics (International Land Development Consultants). The month of harvesting should have 5 cm or less of rainfall. Sugar beets yield as well when soil moisture is maintained at a high level as when it is allowed at fall to 60 to 70% of available water between irrigations (Johnson, et al.). Sugar beets are most sensitive to moisture stress 3 to 4 weeks after emergence (International Land Development Consultants).

Sugar beet production has been hindered in humid subtropical and tropical areas by climatic conditions that not only result in low sugar production but also in excessive disease infestation. Rhizoctonia crown rot and Sclerotium root rot attacked sugar beets grown in Louisiana (Johnson, et al.). "Caida" (caused by Aphanomyces cochlioides) has caused sugar beet production in Chili and Argentina to be limited to temperate areas. Even in warm temperate areas of the north central U.S., Cercospora leaf spot and Aphanomyces have limited sugar beet production. In South Dakota, sugar beet cultivation was discontinued in the early 1960's due to leaf spot diseases and low sugar yields ("What's With the Specialty Crops?"). All fodder beet varieties are highly susceptible to curly top disease and moderately susceptible to Cercospora leaf spot (Theurer, Doney, and Gallian). The disease susceptibility of fodder beets may limit its distribution unless resistant varieties are developed, through crosses with resistant sugar beet varieties.

3) Jerusalem artichokes (Helianthus tuberosus L.)

Until recently only limited research had been conducted on Jerusalem artichokes, so its growth requirements have not been detailed. The crop is adapted for cultivation in temperate climates, and France is a major producing country ("JA - the Myth and Reality Explained"; Martin, Leonard, and Stamp; Stauffer, Chubey, and Dorrell; USDA, 1936). There are conflicting opinions concerning its adaptability to subtropical and tropical climates, but cultivation of Jerusalem artichokes may be possible in subtropical areas with cool and relatively dry seasons (Table 2-2). According to Tindall, low yields are obtained in tropical areas at sea level, but Jerusalem artichokes are grown at altitudes above 450 m. Kay indicated that in tropical areas, Jerusalem artichokes yield best at altitudes of 300 to 750 m, but in India they are grown at altitudes as high as 3,600 m. Malaysia, West and East Africa, and the Caribbean are other tropical areas where Jerusalem artichokes are grown (Tindall). In Hawaii, it serves as an ornamental plant (Yoshida). Boswell (USDA, 1936) reported that Jerusalem artichokes appear to be better adapted to the northern two-thirds of the U.S. than the southern one-third. Problems with planting stock and poor yields were noted by researchers in southern Louisiana and southwestern Texas.

Jerusalem artichokes require a growing season of at least 125 days (Kay; Martin, Leonard, and Stamp; USDA, 1936). Flowering is stimulated by long nights, and tuberization occurs shortly before flowering (Wyse and Wilfahrt). Temperatures ranging from 18 to 27°C are optimal for growth, and plants appear to have moderate tolerance to frost (Tindall; Stauffer, Chubey, and Dorrell; Wyse and Wilfahrt). Tubers survive freezing temperatures of temperate climates and will sprout in the spring if left in the ground over winter (Lukens). Dormancy of tubers must be broken by exposure to 4°C temperatures for 16 weeks, and seed dormancy is broken by 7 days of 2°C temperatures (Wyse and Wilfahrt).

Water requirements for Jerusalem artichokes have not been determined, but the crop does not appear to be adapted to unirrigated semiarid regions. It is generally grown in areas with at least 55 cm of annual rainfall (Lukens; USDA, 1977a). Boswell (USDA, 1936) recommended that Jerusalem artichokes not be grown where moisture is insufficient for corn, but Lukens indicated that it will produce a yield where corn fails. Metcalf (USDA, 1977a) reported that Jerusalem artichoke can be grown where conditions are too dry for potatoes or beets. Irrigation may be needed to promote sprouting of tubers in dry soil (Kay). Jerusalem artichokes can tolerate up to 125 cm of rainfall when good drainage is available (Kay; Lukens). Like many other root crops, Jerusalem artichokes produce poor yields in heavy soils, especially when waterlogging occurs (Kay).

B. Potential ethanol yields from alternative crops

Yield data for alternative crops can be converted to potential ethanol yields to allow agronomic comparisons among crops. The yield of ethanol per hectare is dependent on the amount of feedstock produced per hectare and the amount of ethanol which can be produced from a unit of feedstock. Therefore, the estimate of potential ethanol yield is expressed as the number of liters produced per hectare of land cultivated.

Ethanol production from a unit of feedstock varies according to the amount of fermentable carbohydrates produced by the crop, the processing method used, and the quality of ethanol produced. Consequently, a range of values will be used in this section to convert crop yields to potential ethanol production per hectare.

Comparisons of potential ethanol yields from crops grown under different climatic and management conditions are made. Whenever possible, average yield levels in developing countries are compared to those in developed countries, as well as to those under near optimal farmer management and climatic conditions. The definition of developing countries used in this report is from the FAO 1980 Production Yearbook, Volume 34 (FAO, 1981a). Statistics collected by the FAO and USDA are used for estimates of crop yield whenever possible. If statistics were not available to us, experts' estimates of farmers' yields are used. Experimental yields of sweet sorghum, fodder beets, and Jerusalem artichokes are cited because the crops are not extensively cultivated. For these crops, farmers' yields were projected as 75% of experiment yields under the assumptions that the farmers are supported by an adequate extension system and that experiments were reliably conducted under "practical field conditions" (International Land Development Consultants). Comparisons of the ethanol yields from the various crops must be made cautiously considering the wide variety of growing conditions and cultivation methods.

1. Tropical and subtropical crops

a. Starch crops

1) Cassava

Cassava tuber yields can be extremely variable from one location to another, depending on management level, soil conditions, and climate. Frequently, local varieties are grown under marginal conditions with low fertilizer or labor investments. Under such conditions, yields are generally as low as 3 to 5 t/ha (Kay; McClure and Lipinsky). However, with good environmental conditions and low input levels, yields may be 10 to 12 t/ha. Normal yields are 25 to 30 t/ha on plantations with good soil fertility, sufficient moisture, and selected varieties (McClure and

Lipinsky). Yields above 50 t/ha are reported, but are uncommon.

The world average yield of cassava in 1980 was 8.8 t/ha (FAO, 1981a). Almost all the cassava is grown in developing countries. In Brazil, which is the world's largest producer of cassava, the average yield was 11.9 t/ha. Other major producing countries are Thailand, Indonesia, and Zaire, which had national yield averages of 13.3, 9.4, and 6.6 t/ha, respectively. India had the highest average yield in 1980 with 17.6 t/ha. In general, yields in Africa are lower than in South America or Asia, partially due to semiarid conditions in some of the producing countries.

The amount of ethanol produced from cassava tubers may range from 150 to 200 L/t ("Production Per Acre Equation"). Kosaric, et al. cited a range of 165 to 180 L/t. The actual production is dependent on the starch content of the tubers as well as the process used. Different cultivars processed similarly may not produce the same amounts of ethanol (Ueda, et al.). Using Kosaric's conversion rates and the average yield in 1980, the potential ethanol yield in Brazil is 1,964 to 2,142 L/ha.

Table 2-3 illustrates the potential for ethanol production under various crop yield levels. In developing countries, cassava ethanol yields per hectare are higher than most other crops except sugar cane and sugar beets. However, in making comparisons among crops, the time from planting to harvest needs to be considered. Cassava may not be harvested for 1 or 2 years after planting. In some areas, several short season crops could be grown in a 2-year period, resulting in higher total ethanol yield per hectare than obtained with cassava. Cassava may

Table 2-3. Comparison of Crop and Potential Ethanol Yields in Less Developed Countries (LDC), Developed Countries (DC) and High Yielding Areas.

Crop	Ethanol Yield	LDC Crop[1]	LDC Ethanol[2]	DC Crop[1]	DC Ethanol[2]	High Crop	High Ethanol[2]
	L/t	t/ha	L/ha	t/ha	L/ha	t/ha	L/ha
				Starch Crops			
Cassava	165–180	11.0	1,815–1,980	—	—	30.0[3]	4,950–5,400
Sweet potatoes	142–194	8.0	1,136–1,552	19.6	2,783–3,802	21.5[4]	3,053–4,171
Yams	113–152	9.4[5]	1,062–1,429	—	—	30.0[6]	3,390–4,560
Rice	332–409	2.67	886–1,092	4.94	1,640–2,020	7.21[7]	2,394–2,949
Corn	350–416	1.83	640–761	4.77	1,670–1,984	8.47[7]	2,964–3,523
Grain sorghum	331–425	1.03	341–438	3.20	1,059–1,360	4.55[8]	1,506–1,934
Potatoes	83–117	9.86	818–1,154	13.4	1,112–1,568	56.6[9]	4,698–6,622
Wheat	354	1.95	690	2.62	927	6.18[10]	2,189
				Sugar Crops			
Sugar cane	62– 84	55.1	3,416–4,628	80.2	4,972–6,737	117.0[11]	7,254–9,828
Sugar beets	85–112	33.4	2,839–3,741	39.2	3,332–4,390	62.7[12]	5,329–7,022

[1] 1980 average yields (FAO, 1981a).

[2] Values calculated by multiplying L/t x t/ha.

[3] Normal yield with good management and conditions (McClure and Lipinsky).

[4] Average yield in Japan in 1980 (FAO, 1981a)

[5] World average yield, 1965-74 (Onwueme).

[6] High yield with good management and conditions (Onwueme).

[7] Average yield in California in 1980 (USDA, 1981b).

[8] Average yield in Spain in 1980 (USDA, 1981b).

[9] Average yield in Washington in 1980 (USDA, 1981b).

[10] Average yield in the Netherlands in 1980 (FAO, 1981a).

[11] Average yield in Columbia in 1980 (FAO, 1981a).

[12] Average yield in Oregon in 1980 (USDA, 1981b).

have the most potential in areas where sugar cane cannot be grown and in areas where only one crop is grown per year.

Major improvement in cassava production technology can be expected in the future, because little agronomic research has been done on cassava compared to other major crops. Hybrids with improved disease resistance and yield potential are being developed (Onwueme). Increased emphasis on selection of better yielding local varieties should also improve yields.

2) Yams

Nearly all the yams are produced in developing countries. From 1965 to 1974, Africa produced 98% of the world production of yams with Nigeria alone having 76% of the world yam production (Onwueme). Recent official statistics of yam production were not available to us.

Reported estimates of yam yields under various conditions are quite variable. Onwueme indicated that with commercial yam production, yields range from 8 to 30 t/ha, depending on location, variety, and cultural practices. The average world yield from 1965 to 1974 was 9.4 t/ha. According to Kay, normal yields in West Africa, Southeast Asia, and the West Indies are 7.5 to 17.5, 12.5 to 25.0 and 20.0 to 30.0 t/ha, respectively. Martin (USDA, 1976) feels that these yield estimates are too high, but he states that under very good conditions yields average 15 to 20 t/ha. Onwueme estimated mean yields at 9 t/ha in West Africa and 11 t/ha in the West Indies.

Experimental yields from D. alata have ranged from 40 to 50 t/ha (USDA, 1976). The highest yield of D. rotundata is 67.3 t/ha. These yields indicate the potential of yams in good soil with proper agronomic practices such as elimination of diseased plants and use of high quality tubers. Approximately 2.24 t of tubers/ha are required for planting, so yields available for use are less those given above (Kay).

There is potential to improve yam yields, because research has only recently begun on the crop. Development of improved varieties offers considerable promise. However, hybridization is difficult, because flowering and seed production are irregular (Onwueme; de Alvim and Kozlowski). This problem is partially offset by the wide genetic variability in local varieties and species of yams. According to Onwueme, without development and implementation of improved production practices, yams will continue to be replaced in West Africa by cassava and sweet potatoes. Cassava and sweet potatoes are replacing yams, because they do not require staking, are propagated by nonedible plant parts, and are better adapted for mechanization. Cassava has an added advantage of adaptability to soils with low fertility, while sweet potatoes have a shorter duration than either cassava or yams.

We are unaware of any studies done to determine ethanol yield from yams. However, estimates based on fermentable carbohydrate content range from 113 to 152 L/t (USDA, 1938). Using these conversion rates, a 15 t/ha yield could potentially result in the production of 1,710 to 2,280 L of ethanol/ha. Under similar conditions, cassava would probably outyield yams in ethanol production, because yams have a lower carbohydrate content (Table 2-3).

3) Sweet potatoes

According to Kay, yields from sweet potatoes range from 2.5 to 50 t/ha, with 17.5 to 20.0 t/ha being "satisfactory" yields. Most sweet potatoes are grown in developing countries with China, Indonesia, and Vietnam being major producers. The average yield in developing countries in 1980 was 8.0 t/ha. In contrast, yields averaging 21.5 t/ha were produced in Japan, which was the largest producer of sweet potatoes among developed countries (FAO, 1981a). On a limited area, average sweet potato yields in Israel were 40 t/ha. Average yields of 18.0 t/ha were obtained in the Republic of Korea, which is a developing country with favorable growing conditions. High yields there may also be the result of fertilization, since average fertilizer use per hectare of arable land is high in Korea (FAO, 1981b). Even with high input levels, average yields in the U.S. are 11.9 t/ha, due to less than optimal growing conditions in some production areas. Potential for developing improved varieties is great, because a large number of cultivars exist and mutations occur frequently.

Ethanol production from sweet potato roots is variable, because starch content ranges from 8 to 29% (Onwueme). Jacobs and Newton (USDA, 1938) estimated that between 142 and 194 L of 99.5% ethanol can be produced from 1 t of sweet potato roots. In developing countries, the potential ethanol yield per hectare from sweet potatoes is lower than for cassava (Table 2-3). It is similar to yams, even though sweet potatoes usually mature in 4 to 6 months compared to 7 to 9 months for yams. The potential ethanol yield for sweet potatoes is higher than other starch crops with similar durations.

4) Rice

Much of the world's rice is produced in tropical areas. However, yields tend to be highest in warm temperate or subtropical climates.

Lowland rice yields of 3.0 and 5.0 t/ha are normal with high yielding varieties, high input use, and controlled water levels (International Land Development Consultants). However, in California, with irrigation and a subtropical climate, the average yield was 7.21 t/ha in 1980 (FAO, 1981a). Highest recorded yield for one crop of rice is 13.2 t/ha in Japan (de Alvim and Kozlowski). In developing countries, local lowland rice varieties yield 1.5 to 2.5 t/ha when input use is low and irrigation is unavailable. Yields of floating rice or upland rice are often lower than lowland rice.

Although productivity per crop may tend to be higher in warm temperate climates than in the tropics, annual productivity is often higher in tropical areas, because up to four crops may be grown in a single year. In Japan, yields of 10.9 and 15.3 t/ha/year have been reported in farmers' fields with two and three crops, respectively (de Alvim and Kozlowski). In the Phillipines, four crops in 1 year produced a total yield of 23.7 t/ha. Systems with two rice crops per year are common in developing countries. The production of three or four crops is generally not practiced for several reasons. Water levels must be controlled through irrigation and good drainage. Mechanized tillage may be required to reduce land preparation time, unless transplanting can be done without tillage. Finally, continuous rice cultivation may lead to the buildup of plant diseases and insects. Disease resistant, high yielding varieties, as well as improved agronomic practices, have been developed through international research efforts. However, there is still great potential for yield improvement through research to meet localized needs.

An estimated 332 to 409 L of 99.5% ethanol can be produced per ton of unhusked rice (Hall; USDA, 1980b; USDA, 1938). Potential alcohol production per hectare from a single crop of rice is low compared to cassava, but two rice crops can probably be produced within the time required to produce a single crop of cassava or yams (Table 2-3). Two low or medium yielding rice crops would produce roughly the same amount of ethanol as one low or medium yielding crop of a tropical tuber. Three or four rice crops could result in the production of ethanol in quantities equivalent to that obtained from the highest yielding tubers.

As a result, whether rice or tuber crops are grown for ethanol depends on the environmental and economic conditions of the area. In most areas, rice will probably not replace the tropical tuber crops, because the tubers are often grown under conditions too dry or otherwise unsuitable for rice. However, in some situations, cassava or sweet potatoes could possibly be more productive than upland rice. Sweet potatoes could also be incorporated into some rice based cropping systems having a significant fallow period.

b. Sugar crops

Sugar cane

Approximately 91% of the sugar cane produced in the world is grown in developing countries (FAO, 1981a). Brazil, India, and Cuba are the world's largest producers. Comparisons of yields of different countries are difficult to make, because annual yields are often reported. In some growing areas, such as Hawaii and Peru, sugar cane is harvested after a growing period of two years. World average yield from 1977 to 1978 was 56.5 t/ha/year (McClure and Lipinsky). The country with the highest average yield was Columbia, with 117 t/ha/year. Brazil, India, and Cuba produced 43, 56, and 54 t/ha/year, respectively.

In developing countries, yields of 100 to 120 t/ha/year are possible under good management and favorable climatic conditions often found on large estates (International Land Development Consultants). Small holdings generally produce 50 to 70% less than large estates. The theoretical maximum yield of sugar cane, based on photosynthetic capacity, is 280 t/ha/year (McClure and Lipinsky). However, the highest recorded yield is 190 t/ha/year. In subtropical areas, cool temperatures limit the length of growing season, resulting in low yields. For example, in Louisiana, the growing season is only 5 months because soil temperatures are too cool for emergence (Lipinsky, et al.). Consequently, average yields are 53 t/ha/year (McClure and Lipinsky). Even in Hawaii, where a 24-month growing season is possible, temperatures are not optimal for maximum production. In some areas, moisture conditions may also limit the length of the growing season. Irrigated sugar cane usually yields more than unirrigated, except in high rainfall areas.

Experimental results have indicated that yields can be increased in short season areas by using close row spacings (McClure and Lipinsky). There is also potential for the development of hybrids with greater cold tolerance and yielding ability than those presently grown (Lipinsky, et al.). The development of high yielding hybrids for ethanol production is especially promising, because many high yielding hybrids have not been used in the past due to poor characteristics for sugar processing (James). Some of these varieties may be acceptable for ethanol production, because sugar quality is not important.

The potential ethanol yield from a 100 t/ha sugar cane crop could be from 6,250-8,330 L/ha, based on conversion rates given in the literature. Kellough and Knapp (SERI, 1981) cited several references indicating that 63.3 L of ethanol can be produced from a ton of sugar cane. Conversion rates of 62.5, 72.1, 76.3, and 83.8 L/t are noted by other authors (Bagbey; Doney; Kampen; USDA, 1980b). Variability of feedstock sugar content may partially account for the differences in alcohol yield from sugarcane.

In developing countries, ethanol production per hectare of crop is twice as high from sugar cane as from cassava and yams, which are similar to sugar cane in duration (Table 2-3). However, cassava is usually grown with lower management levels and under conditions unsuitable for sugarcane.

In Louisiana, where the growing season is only 5 months, ethanol yields could average from 3,286 to 4,400 L/ha. Consequently, under short season conditions, ethanol production potential from sugar cane is greater than short season starch crops. The ethanol yields are similar to sugar beets and fodder beets (Tables 2-3 and 2-5).

2. Temperate crops

a. Starch crops

1) Corn

Sixty percent of the corn hectarage in the world is in developing countries, but 63% of the world production is produced in developed countries (FAO, 1981a). Forty-three percent is produced in the U.S. alone. Average yield in North America is 5.71 t/ha, compared to 1.22, 1.85, and 2.24 t/ha in Africa, South America, and Asia, respectively. Yields of approximately 4.0 t/ha are possible in tropical areas with adequate moisture and good management (International Land Development Consultants). Since most corn varieties have a short duration, more than one crop can be produced per year in some tropical areas. Experimental yields of 20.0 t/ha/year have been reported with more than one crop per year (de Alvim and Kozlowski).

Highest yields in the U.S. in 1980 occurred in California under irrigation. The average yield was 8.47 t/ha (USDA, 1981b). In Ohio, where precipitation is generally adequate without irrigation, average yield in 1980 was 7.09 t/ha. Average yields may be 2.5 to 3.0 t/ha in areas of the U.S. where soil or climatic factors are less than optimal.

Corn yields in the U.S. increased from an average yield of 1.63 t/ha between 1910 and 1914 to 5.77 t/ha between 1970 and 1972 (Martin, Leonard, and Stamp). Development of high yielding hybrids has made a major contribution to increased yields. Annual yield improvement due to genetics continues at a rate similar to the time when hybrids were first introduced (McClure and Lipinsky). In developing countries, low yields are partially due to suboptimal environmental conditions and to infrequent use of hybrids. Production of hybrids requires resources often unavailable in developing countries. Hybrids grown in developed countries often are inappropriate for developing countries because seed must be purchased each season, and seed distribution systems in many developing countries are not adequate to provide farmers a dependable seed supply.

Because of its relatively high ethanol yield per ton, corn is the major feedstock for ethanol production in the U.S. Approximately 387 L of ethanol can be produced from a ton of corn (Gallion; Hanway and Harlan; McClure and Lipinsky; SERI, 1982). Conversion rates ranging from 350 to 416 L/t have been reported (Doney; SERI, 1981). Ethanol production per ton of corn is higher than from barley, rye, and oats, and it is approximately equivalent to wheat (Hall; SERI, 1981).

Among the small grains, wheat has the highest potential ethanol production per hectare based on average crop yields. Corn has a much higher potential for ethanol production per hectare than wheat in developed countries, but in developing countries it is about the same as wheat (Table 2-3). Corn does not yield as much ethanol per hectare as the tropical root crops or most sugar crops, except possibly Jerusalem artichokes (Tables 2-3, 2-4, 2-5, and 2-6). However, corn is more easily stored than these crops. With the low corn yields now found in developing countries, corn does not appear to have high immediate potential for ethanol production. In developed countries, it has better potential than other starch crops except rice and sweet potatoes, which are restricted to tropical and subtropical areas.

2) Grain sorghum

World grain sorghum hectarage in 1980 was approximately one-third that of corn. Grain sorghum is grown predominantly in developing countries. Eighty-six percent of the grain sorghum hectarage and 71% of the production in 1980 was in developing countries (FAO, 1981a). Major areas of grain sorghum cultivation occur in Asia and Africa. More hectares of grain sorghum were harvested in India in 1980 than in any other country of the world, but the U.S. led the world in total production.

Since sorghum is often grown under low moisture conditions, average yields are usually low. In developing countries, yields are also affected by low input investment. For example, yields in India in 1980 averaged 0.75 t/ha (FAO, 1981a). Average yields in Africa in 1980 were 0.70 t/ha, while in Latin America they were 2.35 t/ha. Yields are higher in Latin America than in Africa and Asia largely because hybrids are grown in Latin America. In the U.S., where a major portion of the grain sorghum is grown in semiarid areas of Kansas, Texas, and Nebraska, average yield from 1978 to 1980 was 3.40 t/ha. Yields in southwestern Europe averaged 4.28 t/ha in 1980. Farmers using irrigation have produced yields greater than 11.0 t/ha (House; McClure and Lipinsky). Under optimal conditions, yields can average 7.0 to 9.0 t/ha.

The potential ethanol yield per hectare from grain sorghum is low compared to other crops listed in Table 2-3, due to low average crop yields. Ethanol yield per ton of grain sorghum is similar to corn. Kellough and Knapp (SERI, 1981) cited sources indicating ethanol yields of 331 to 425 L/t of grain sorghum. Commonly noted rates for conversion of grain sorghum to ethanol are 387 and 401 L/t (Hall; Hanway and Harlon; SERI, 1982; USDA, 1980b). Grain sorghum may have potential as an ethanol fuel producing crop in semiarid areas, but where conditions are more favorable, other crops appear to have more promise.

3) Potatoes

Since they are a cool season crop, approximately three times as many hectares of potatoes are cultivated in developed countries as in developing countries (FAO, 1981a). World potato production is centered in Europe and the U.S.S.R. Approximately 30% of the world's production of potatoes is produced in the U.S.S.R. Among developing countries, China and India are major producers, and potatoes are also grown extensively in highland areas of South America.

Average 1980 yield in the U.S.S.R. and Eastern Europe was 10.6 t/ha, compared to 22.1 and 28.1 t/ha in Western Europe and North America, respectively. China produced 8.6 t/ha of potatoes and India produced 12.0 t/ha. In the U.S. highest yields generally occur in Washington and Oregon, where the growing season is long and cool (Table 2-3). There is potential for improving yields in countries with low yields. Average yields in the U.S. increased from 5.4 t/ha in 1890 to 25.6 t/ha in 1971, through use of higher yielding varieties, better planting stocks, and improved cultural methods (Martin, Leonard, and Stamp).

Between 83 and 117 L of ethanol can be produced from a ton of potato tubers. Hanway and Harlon and a U.S. Department of Energy Report (SERI, 1982) indicated that ethanol yields of 117 L/t are possible. Doney and Gallian cited ethanol yields of 83 and 85.8 L/t, respectively.

Based on the above ethanol yields and present crop yields in developing countries, potatoes have less potential for ethanol production per hectare than other tropical root crops and the sugar crops (Table 2-3). Ethanol yield (L/ha) potential is equivalent to rice and more than corn, wheat, and grain sorghum. However, the amount of area suitable for potato production in developing countries is small compared to that suitable for rice, corn, wheat, and grain sorghum.

With average yields in developed countries, potential ethanol production per hectare of potatoes is less than all other crops except grain sorghum and wheat (Table 2-3). However, crop yields in Eastern Europe and the U.S.S.R., which are classed as developed, are lower than average yields in developing countries. Therefore, the average yield for developed countries is not representative of those in Western Europe and North America. In Western Europe, potential ethanol yield from potatoes is 1,834 to 2,585 L/ha, which is greater than the potential for cereals and possibly Jerusalem artichokes (Tables 2-3 and 2-6).

b. Sugar crops

1) Sweet sorghum

Presently, sweet sorghum is a minor crop in the U.S. It is used for forage and silage in the Great Plains region and for syrup in the more humid Gulf and Appalachian states (McClure and Lipinsky). Official statistics of production are unavailable, but an estimated 800 to 1,200 ha were cultivated annually for syrup production between 1976 and 1978. Sweet sorghum syrup production has declined from 190 million L in 1920 to presently less than 4 million L. Recent developments in sugar processing have made it possible to refine sugar from sweet sorghum (Lipinsky, et al.).

There are two groups of sweet sorghum varieties grown. Syrup varieties are grown in the southeastern U.S., while sugar variety cultivation is planned for the Rio Grande Valley of Texas (Lipinsky, et al.). Syrup varieties produce about 30% more biomass per hectare than sugar varieties, but sugar varieties have a greater total soluble solid content (McClure and Lipinsky, Paul). Rio, Roma and Ramada are examples of sugar varieties, and Sart, Dale, and Brandes are syrup varieties

(McClure and Lipinsky). Sweet sorghum yields are often cited without reference to variety or type. Consequently, comparisons of yields among different growing areas are difficult to make.

Current sweet sorghum yields in the U.S. have been estimated at 44 t/ha by Martin, Leonard, and Stamp (1976). Lipinsky, et al. (1976) cited yields of 22.4 to 44.8 t of millable stalks/ha, which is approximately equivalent to total wet biomass yields of 31.4 to 62.7 t/ha. They also reported yields of 44.8 to 112 t/ha in Texas and 90 t/ha with irrigation in Arizona. Ferraris and Stewart (1979) indicated that in Queensland, Australia yields of 40 to 50 t/ha occur frequently in the Callide Valley, which is somewhat dry. Under drier conditions and with poor soils, yields range from 25 to 35 t/ha.

Yields of sweet sorghum are correlated with growing degree days, when sufficient water and nutrients are available (Jackson and Lawhon). Consequently, yields are greater in the tropics and subtropics than in temperate areas. More than one crop is possible in tropical areas, since maturity occurs within 90 to 150 days, depending on variety (Lipinsky, et al.).

Table 2-4 contains yield data from experiments at several locations. According to Jackson and Arthur, there is a tendency for lower yields in temperate areas than subtropical areas. However, short duration varieties in subtropical areas produced yields similar to those in temperate areas. Sweet sorghum yielded poorly in India and Puerto Rico, but results are from single experiments and may not be illustrative of yield potential in those areas.

Table 2-4. Potential Ethanol Yield of Sweet Sorghum Based on Yields from Research Trials.

Trial Location	Crop Yield[1/] Experimental[2/]	Farmers'(projected)[3/]	Potential Ethanol	Reference
	----- t/ha -----		L/ha	
Texas	61.9 (Rio, 104 days)	46.4	2,043-2,368[4/]	McClure and Lipinsky
	119.5 (MN 1500, 175 days)	89.6	3,944-4,571[4/]	
Louisiana	83.6 (Rio, 82 days)	62.7	2,759-3,198[4/]	" " "
	91.9 (69-13, 113 days)	68.9	3,033-3,515[4/]	
Ohio	87.9 (Sart, 133 days)	65.9	2,901-3,362[4/]	" " "
	51.7 (Rio, 133 days)	38.8	1,706-1.978[4/]	
Nebraska	82.2 (Hybrid)	61.7	3,099[5/6/]	Clegg
	91.0 (Wray)	68.2	3,566[5/6/]	
Israel	84.0-121.8 (MN 9)[7/]	63.0-91.4	2,772-4,661[4/]	Ferraris and Stewart
	75.6-89.6 (Rio)[7/]	56.7-67.2	2,495-3,427[4/]	" " "
India	14.0 (Rio ON)[7/8/]	10.5	462-536c1[4/]	" " "
	28.0 (100 N)[7/8/]	21.0	924-1,071[4/]	" " "
Puerto Rico	37.8 (67-15)[7/8/]	28.4	1,247-1446[4/]	Alsina, Valle-Lamboy, and Mendez-Cruz
	21.8 (Rio)[7/8/]	16.4	720-835[4/]	" "
Florida			3,926	Jackson and Arthur
Texas			4,023	" " "
Louisiana			3,729	" " "
Missouri			3,434	" " "
Ohio			2,846	" " "
California	96.3 (Keller)	72.2	4,436[5/]	Hills, et al., 1981
California	129.2 (Wray)	96.9	4,044[5/]	Hills, et al., 1983

1/ Whole plant wet biomass yield, variety and duration in parenthesis. Rio and Sart are sugar and syrup type varieties, respectively.

2/ Variety names and days to maturity, when available, are in parenthesis.

3/ 75% of experimental yields (International Land Development Consultants).

4/ Conversion rate of 44 to 51 L ethanol/t of sweet sorghum x projected farmers' yield.

5/ 75% of L/ha cited in literature to get projected farmers' ethanol yield.

6/ Includes ethanol yield from grain.

7/ Originally given in fresh stalk weight, increased by 40% to represent whole plant weight (Lipinsky, et al.).

8/ Single experiment.

An estimated 44 to 51 L of ethanol can be produced from a ton of fresh whole plants of sweet sorghum (SERI, 1981). Actual ethanol yields from sweet sorghum vary with fermentable content, which is influenced by genetics and growing conditions. Using 44 t/ha as a conservation estimate of present yield in the United States, ethanol potential may be between 1,936 and 2,244 L/ha. This is slightly higher than potential yields from corn in developed countries (Table 2-3). According to yield estimates given in Tables 2-3 to 2-6, sweet sorghum appears to have greater potential per hectare for ethanol production than corn, but less potential production per hectare than sugar cane, sugar beets, and fodder beets. In irrigated field trials in California, ethanol production potential from sweet sorghum was 224 L more than corn in one year and 981 L more in another year (Hills, et al., 1983; Hills, et al., 1981). In the same studies, sugar beets and fodder beets had greater ethanol potential per hectare than sweet sorghum.

Although potential ethanol production from sweet sorghum may be less than from the other sugar crops, the crop has wider adaptability and can be grown under somewhat poorer conditions. Sweet sorghum also produces large amounts of biomass, which could be utilized as technology is developed for conversion of cellulose to ethanol. Yields can probably be increased markedly through plant breeding and agronomic research, since little attention has been given to this crop compared to sugar cane and sugar beets.

Efforts are being made to develop sweet-stemmed grain sorghum hybrids (Lipinsky and Kresovich). A hybrid tested in Nebraska produced 2,177 L and 2,529 L of ethanol/ha from the stalks and seed, respectively

(Clegg). Total ethanol yield was only 618 L/ha more than the commonly grown Wray sweet sorghum variety, because the utilization of carbohydrates for seed production resulted in lower sugar levels in the stalk. However, the production of seed rather than stalk sugars may reduce storage problems associated with processing sweet sorghum, because the seed can be stored for processing at a time when stalks are no longer available. Also, less room is needed for storing seed than stalks.

2) Sugar beets

Over half of the world's sugar beets are produced in Europe (FAO, 1981a). Sugar beet hectarage is low in developing countries, since it is a temperate climate crop. China, Iran, and the United Arab Emirates had 700,000 of the 800,000 ha planted in developing countries in 1980. Approximately 7.9 million ha of sugar beets were planted in developed countries.

Yields tend to be correlated with the length of growing season, and irrigated sugar beets generally yield more than unirrigated. Irrigation is usually unavailable in Europe, and average yields in 1980 were 39.0 t/ha (FAO, 1981a). In the U.S., 40 to 45% of the sugar beets are irrigated (McClure and Lipinsky). West of the 100th median in North America, all the sugar beets are irrigated (Martin, Leonard, and Stamp). The average yield from 1978 to 1980 was 37.2 t/ha in North Dakota, where irrigation is not given, and the growing season is short (USDA, 1981b). In contrast, during the same period, under irrigated conditions in Oregon and California, average yields were 57.8 and 57.2 t/ha, respectively. Yields of 78 t/ha are reported in the coastal region of

California (Lipinsky, et al.).

Since 1967, significant yield increases have occured due to breeding of improved hybrids (Martin, Leonard, and Stamp). Hybrids have been developed for areas which were at one time considered unsuitable for sugar beets, and the area of cultivation may be expanded further through plant breeding (Doney). Disease resistant varieties have been developed; however, crop rotation is still required to avoid severe losses from nematodes, diseases, or insects (Lipinsky, et al.). Sugar beets are generally grown in a field once every 4 years.

Recent reports indicate that at least 84.6 L of ethanol can be produced from a ton of sugar beet roots (SERI, 1982). Hanway and Harlon reported an ethanol yield of 112.5 L/t. A conversion rate of 92.1 L ethanol/t of sugar beet roots is given by several sources (Bagbey; Gallion; SERI, 1981). Based on crop yield, sugar beets have a high potential for ethanol production (Table 2-3). Among temperate crops, only fodder beets may produce higher ethanol yields than sugar beets (Tables 2-3 and 2-5). Ethanol yield of four crops were compared in irrigated field studies conducted in California (Hills, et al., 1981; Hills, et al., 1983). Sugar beets yielded 7,700 L/ha in 1980 compared to 5,692, 5,916, and 8,065 L/ha for corn, sweet sorghum, and fodder beets, respectively. In 1981, sugar beets yielded 6,645 L/ha, while corn, sweet sorghum, and fodder beets produced 4,411, 5,393, and 7,579 L/ha, respectively.

3) Fodder beets

Production of fodder beets is centered in Europe, and very few are grown in the U.S. Information on yields obtained by European farmers is not available to us. According to Doney, fodder beet root yields are generally 50 to 100% higher than sugar beets. Under this assumption, estimated fodder beet yields in Europe would be between 58.5 and 78.0 t/ha, based on average sugar beet yields in 1980 (FAO, 1981a). Similarly, fodder beet yields in developing countries which produce sugar beets would be between 50.1 and 66.8 t/ha. Yields as high as 139 t/ha have been reported in European trials (Theurer, Doney, and Gallian).

Fodder beet yields cited in the U.S. are usually from field experiments. Several fodder beet varieties produced yields ranging from 50.1 to 136.2 t/ha in irrigated trials conducted on farmers' fields in Idaho ("Technical Section - Fodder Beet Research"). Results of selected research station trials are listed in Table 2-5. An approximate projection of average yields which farmers may obtain has been calculated as 75% of experimental data (International Land Development Consultants). Highest yields occur with irrigated conditions and long growing seasons, such as found in California. Under dryland conditions, yields tend to be higher in Michigan than in North and South Dakota, due to greater annual precipitation.

Estimated ethanol yields per ton of fodder beet roots range from 64.6 to 125.0 L/t (Hall; Sachs, 1980). The estimate of 125.0 L/t is probably somewhat unrealistic, considering normal sucrose levels in fodder beets. The potential ethanol production from a feedstock can be estimated using the assumption that 1 kg of fermentables will produce 0.6 L of ethanol (Hills, et al., 1981). Fodder beet sucrose content ranged from 9.8 to 13.1% in a study conducted by USDA researchers at six

Table 2-5. Potential Ethanol Yield per Hectare of Fodder Beets Based on Yields from Research Trials.

Trial Location	Crop Yield Experimental	Crop Yield Farmers' (projected)[1]	Potential Ethanol[2]	Reference
	----- t/ha -----		L/ha	
California	141.4	106.0	6,360-8,268	"U.S. Beets Top Europe's"
Idaho	138.6	104.0	6,240-8,112	" " " "
Utah	102.3	76.7	4,602-5,983	" " " "
Colorado	100.4	75.3	4,518-5,873	" " " "
Michigan	95.0	71.0	4,260-5,538	" " " "
North Dakota	80.4	60.3	3,618-4,703	" " " "
California (irrigated)	142.5	106.9	6,414-8,338	Hills, et al., 1981
California (irrigated)	113.6	85.2	5,112-6,646	Hills, et al., 1983
Idaho	79.1-152.3	59.3-114.0	3,558-8,892	Theurer, Doney, and Gallian
Utah	65.0-101.9	48.8-76.4	2,928-5,959	" " "
South Dakota (dryland)	58.9	44.2	2,652-3,448	Kingsley and Evjen Kingsley and Volek

[1] 75% of experimental yields (International Land Development Consultants).

[2] Conversion rate of 60 to 78 L ethanol/t of roots x farmers' projected yields.

locations ("U.S. Beets Top Europe's For Alcohol Production"). Based on a sucrose content of 10 to 13%, 1 t of fodder beet roots will produce 60 to 78 L of ethanol.

Fodder beets can produce more ethanol per hectare than most other temperate crops, even under less than optimal conditions such as found in unirrigated portions of the Northern Plains. Potential ethanol production per hectare from fodder beets may range from 3,510 to 6,084 L/ha in Europe and from 3,006 to 5,210 L/ha in developing countries.

Sources differ on the question of the ethanol production potential of fodder beets compared to sugar beets. In the USDA study, fodder beets and sugar beets produced the same amount of sucrose per hectare at all locations ("U.S. Beets Top Europe's For Alcohol Production"). The higher yields of fodder beets were offset by lower sucrose content compared to sugar beets. Consequently, potential ethanol production per hectare was the same. Potential ethanol production from fodder beets was 364 L/ha greater than sugar beets in one year and 935 L/ha more in another year of a study conducted in California (Hills, et al., 1981; Hills, et al., 1983). However, growing costs were higher for fodder beets than sugar beets, so costs per liter of ethanol were similar. Doney indicated that fodder beets produce 20% more fermentable sugars than sugar beets, while Theurer, Doney, and Gallian found that fodder beets produce 3 to 15% more.

Hybrids from crosses between sugar beets and fodder beets tend to produce higher yields of fermentables per hectare than either sugar beet or fodder beet hybrids (Doney; Theurer, Doney, and Gallian). Fodder beets have low disease resistance, but it should be possible to develop disease resistant hybrids through crosses with sugar beet varieties adapted to the U.S. Theurer, Doney, and Gallian stated that fodder beet or sugar beet x fodder beet hybrids must produce at least 10% more fermentables per hectare than sugar beets in order to be more feasible than sugar beets for ethanol production. The higher fermentables yield is needed to offset higher transportation costs resulting from the lower sugar content per ton of fodder beets or sugar beet x fodder beet hybrids compared to sugar beets.

4) Jerusalem artichokes

More Jerusalem artichokes are grown in Europe than in North America. According to Martin, Leonard, and Stamp, Jerusalem artichokes have been grown in France on 197,600 to 321,100 ha annually. Official statistics of yields in Europe were not available to us, but Kay indicated that yields average 30 t/ha on sandy soils.

Most of the Jerusalem artichokes in the United States are grown in cool, humid sections of the Pacific Northwest. Martin, Leonard, and Stamp estimated yields to be 22.4 t/ha with favorable conditions. Yields in the Midwest and East were estimated at 11.2 to 13.4 t/ha.

Kay stated that yields in India range from 12 to 25 t/ha and can be as high as 37.5 t/ha. Again, estimates of yields in other developing countries were not available to us.

Only limited research has been conducted in North America on Jerusalem artichokes. Reported experimental yields have been quite variable in the Northern Plains area, ranging from 17.9 to 76.2 t/ha (Table 2-6). Yield variability is probably due to a lack of information on proper cultural practices, as well as to differences in yield

Table 2-6. Potential Ethanol Yield per Hectare of Jerusalem Artichokes Based on Yields from Research Trials.

Trial Location	Crop Yield: Experimental	Crop Yield: Farmers' (projected)[1]	Potential Ethanol[2]	Reference
	——— t/ha ———		L/ha	
Manitoba	46.8 (branching)	35.1	2,457-3,861	Stauffer, Chubey, and Dorrell
	31.6 (non-branching)	23.7	1,659-2,607	" "
Minnesota	37.3[3/4]	28.0	1,960-3,080	Waters, Davis, and Richle
	25.1[3/4]	18.8	1,316-2,068	" " "
Several	17.9-22.4[5]	13.4-16.8	938-1,848	USDA, 1936
Not given	24.6[5]	18.4	1,288-2,024	Routley
Manitoba	76.2[3]	57.2	4,004-6,292	Chubey and Dorrell
	6.7-9.0[6]	5.0-6.8	350- 748	" " "
Nebraska	24.6 (dryland)[4]	18.4	1,288-2,024	Univ. Neb.-Lincoln Coop. Ext. Serv.
	29.1 (irrigated)[4]	21.8	1,526-2,398	" " "
California	59.4 (irrigated)[3]	44.5	3,116-4,897	" " "

1/75% of experimental yields (International Land Development Consultants).

2/Conversion rate of 70 to 110 L/t of tubers x farmers' projected yields.

3/Highest yield among seven varieties.

4/Single experiment.

5/Means of several varieties.

6/Range of yields from varieties excluding highest yielding variety.

potential among varieties. In a study conducted in Canada by Chubey and Dorrell, a Russian strain of Jerusalem artichoke yielded 76.2 t/ha, but yields of North American varieties averaged from 6.7 to 9.0 t/ha. Since little research effort has been invested in Jerusalem artichokes, there should be potential to improve yields through varietal selection, better fertilization, and refined cultural practices.

Projected farmer yields are given in Table 2-6. However, farmers' yields may be less than indicated in the table, because with present mechanical harvesting methods, only 60 to 70% of the tubers produced are harvested (Dorband). Unfortunately, harvesting methods used to obtain the experimental data were not stated.

Ethanol production per ton of Jerusalem artichoke tubers may range from 70 to 110 L, depending on the fermentables content. Chubey and Dorrell found that sugar content of different varieties ranged from 13.2 to 27.7%. Average sugar content is 15 to 18% (Wyse and Wilfahrt). Consequently, a range of 70 to 91 L of ethanol/t of tubers was given by Underkofler, McPherson, and Fulmer. Kelloug and Knapp (SERI, 1981) cited several sources indicating an ethanol potential of 83 L/t of tubers. The highest ethanol yield noted was 110 L/t of tubers (Sachs).

Based on cited conversion rates, ethanol yields from Jerusalem artichokes may range from 2,100 to 3,300 L/ha in Europe if root yields average 30 t/ha. Both fodder beets and sugar beets probably have greater potential than Jerusalem artichokes for ethanol production per hectare in Europe. Ethanol yields from Jerusalem artichokes in India could range from 840 to 2,750 L/ha based on tuber yields of 12 to 25 t/ha. Jerusalem artichokes may have potential for ethanol production in developing countries when compared with yields of other crops (Table 2-3). However, definitive conclusions can not be drawn because yield data are insufficient. There are also questions regarding Jerusalem artichoke adaptability to tropical climates. In North America, Jerusalem artichokes may have greater potential for ethanol production per hectare than starch crops; however, experimental results have been quite variable.

As a forage crop, Jerusalem artichokes can produce 16.8 to 21.3 t of top growth/ha ("JA - the Myth and the Reality Explained"). Suggestions have been made to use both the top growth and tubers for ethanol production (Froid). However, practices to obtain maximum top growth result in low tuber yields. When tuber yields are optimal, top growth quality is low. Also, technology for producing ethanol from Jerusalem artichoke top growth is not adequately developed at the present time.

C. Summary

Selection of the most agronomically appropriate feedstock for ethanol production can not be based only on general descriptions of growth requirements and on potential ethanol yield per hectare. A necessary part of the selection process is to test the crops under the range of climatic and soil conditions found in the region. An understanding of the growth requirements of the crops is necessary, however, to choose crops for field evaluation. After field evaluation, none of the crops may appear to be appropriate, or more than one crop may seem to have potential. In any case, economic and processing considerations, which are discussed in the following chapters, are also critical.

All the temperate crops discussed in this chapter have agronomic potential for use as feedstocks in the Northern Plains region. However, probably none of the crops are suitable for the entire region, because climatic conditions in the region are so diverse. Tropical and subtropical crops are not suitable for large-scale commercial production in the region, although small amounts of sweet potatoes are produced in southeastern parts of the region.

In the Northern Plains, the adaptability of commonly grown temperate crops such as corn, grain sorghum, and potatoes is probably generally indicated by the present distribution of these crops in the region. Without irrigation, corn tends to perform best in southern and eastern portions of the region, which are most humid and warm. Sorghum is also grown in the warmest portions of the region but often where it is too dry for corn. Unirrigated potato production occurs mostly in the cooler, northern parts of the region. Sugar beets are also grown without irrigation in the cooler areas as well as in southern Minnesota. However, the distribution of sugar beet production may not be a good indicator of extent of adaptability, because production usually occurs only in the proximity of processing facilities. Consequently, economic factors, which influence the number and location of plants, as well as agronomic factors, affect sugar beet geographic distribution.

Fodder beets, sweet sorghum, and Jerusalem artichokes are adapted to at least part of the Northern Plains region. The specific areas in which they can be grown are difficult to predict, because they are not extensively cultivated, and only a limited number of field studies have been done. Fodder beets can probably be grown where sugar beets are cultivated. However, research is needed to determine how far west they can be grown without irrigation. The same question arises with sweet sorghum and Jerusalem artichokes. Another question concerning sweet sorghum is how warm the growing season must be to produce economically feasible yields.

A final point is that the area of adaptation may be enlarged for sweet sorghum, Jerusalem artichokes, and fodder beets through plant breeding, since only a limited amount of research has been conducted on these crops. Varieties with shorter duration, greater cold tolerance, or more drought tolerance than present varieties could possibly be developed. Varieties with greater disease resistance than present varieties may be needed, especially in the case of fodder beets. Fodder beets are susceptible to some diseases which have been problems in sugar beets, but for which resistant sugar beet varieties have been developed.

III. Harvesting, Storage, and Processing Considerations for Alternative Crops*

A. Alternative technologies for harvesting

The introduction of a new crop involves the introduction of technology needed to produce the crop. The technology to be introduced includes appropriate agronomic practices and possibly machines. Local conditions determine the technology needed. This section will describe alternatives in harvesting technology, because a specific crop can often be harvested by several different methods -- ranging from very labor intensive to highly mechanized. Starch crops are grouped as cereals (corn, grain sorghum, and rice) and roots and tubers (potatoes, cassava, sweet potatoes, and yams), because of similarities in harvesting methods among crops in each group. Similarly, the sugar crops are grouped as forages (sweet sorghum and sugar cane) and roots and tubers (Jerusalem artichokes, sugar beets, and fodder beets).

1. Starch crops

a. Cereals (corn, grain sorghum, rice)

In developed countries, sophisticated combines cut, thresh, and clean cereal grains in a single operation. The same basic machine can be adjusted to harvest different crops. Rice harvesting often requires that the combine be equipped with half tracks or large tires having mud lugs. A special head attachment, which snaps the ears from the stalks, is necessary for harvesting corn. A head attachment with a reel and cutting bar can be used for sorghum and for direct harvesting of small

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*Principal authors: William Gibbons, Duane Auch, and Carl Westby grains, although improved attachments are available for sorghum. Farmers sometimes cut small grain with a swather a few days before combining. This practice allows grain and green weeds to dry in a windrow before combining. The combine here, however, must be equipped with an attachment to pick the dried plants off the ground.

The threshed and cleaned grain is collected in a tank on the combine. When the tank becomes full it is emptied into trucks or wagons which haul the grain to be stored in bulk at the farmstead or local elevator. In situations where facilities and equipment are not available for handling bulk grain, combines are used which have a provision for bagging the grain immediately after it is threshed and cleaned. This system is not widely used, because the labor requirement is high compared to bulk handling.

Corn or rice may have up to 28% moisture, so they must be dried for storage. Combining of sorghum or small grains is usually not done until the grain has 13% or less moisture content. Sorghum sometimes requires drying, while small grains are generally not dried.

Ear corn can be picked for storage in cribs when it has 20% grain moisture or less. In the southern U.S., some ear corn is picked but not husked to reduce insect damage. After drying naturally in the cribs, ear corn is shelled with a machine or fed to livestock. Picker-shellers shell the corn as it is picked, and the grain is usually dried artificially. With the advent of high capacity grain dryers, combines have nearly replaced picker-shellers and corn pickers in the U.S., because combine harvesting requires less labor and results in less field loss.

Binders and stationary threshing machines were the most advanced machines for harvesting small grains before combines were developed. Binders are horse or tractor drawn machines which cut the grain and tie it into bundles. The bundles are set up by hand into shocks to dry. After drying, the bundles are loaded into wagons and taken to a stationary threshing machine. Threshing machines separate the grain from the straw and chaff.

In developing countries, the gathering of cereals for threshing or shelling seldom involves mechanization, unless farmers have large, unfragmented holdings, and labor is scarce. Ears of corn are often individually picked by hand. Heads of other cereals may be picked individually, or the whole plant is cut with a hand sickle. Hand harvesting may be practiced not only because labor is abundant, but also because field conditions may be unsuitable for mechanization. For example, rice is sometimes harvested when fields are flooded due to heavy rains and poor surface drainage. In some areas, crops are grown on rough terrain which may prevent the use of machines for field harvesting.

Threshing or shelling of grain is usually done near the homestead or at the edge of the field. Farmers and laborers often carry the grain containing plants or corn ears to the homestead unless roads are available for use of two-wheeled carts or four-wheeled wagons. Cattle, mules, or horses are used for draft power.

Small threshing machines, powered by gasoline or diesel engines (or by electricity, when available), are used in many developing countries. One developed in India has a capacity of 100 kg of grain/hour (Congdon). Most of these machines thresh and separate the grain from the straw.

Engine and hand driven corn shellers are also used. Efforts are being made to develop threshing machines which would be economically feasible for farmers with small holdings. A machine with a treadle and rotating, spiked cylinder is used to thresh rice. One person is able to power the machine with his foot and hold the grain heads against the cylinder to knock the kernels loose. The output of the machine is approximately 150 kg of grain/hour (AID). However, wheat, sorghum, and barley can not be threshed with the threadle thresher, because the kernels are usually too tightly attached to the head.

Traditional methods of threshing may utilize cattle to trample the grain from the heads. The cattle sometimes pull a sled or similar device to hasten threshing. An implement with disks has been developed to improve threshing with cattle. Many farmers thresh grain manually by slapping the plants against a hard object or by beating the heads with a stick.

After threshing the grain by peddle thresher, cattle, or hand, the grain must be separated from the straw and chaff. Hand powered winnowing machines have been developed. However, most winnowing is done by hand-pouring the grain and chaff from a platform so that the wind blows the chaff away from the grain. Winnowing baskets are also used, especially when winds are not prevalent. The grain is shaken in the flat baskets in a forward or circular motion so that light material moves out of the basket. Water is sometimes used with the basket to float out light material, and then the grain is dried. With the baskets, about 45 kg of grain can be cleaned per hour (AID).

Before storage, cleaned grain is usually dried by spreading it in the sun and stirring it occasionally. Ear corn may be hung to dry near household fires or in trees.

b. Roots and tubers (potatoes, cassava, sweet potatoes, yams)

Harvesting of root and tuber crops tends to be more labor intensive than harvesting of cereals. Better mechanized harvesting systems have been developed for potatoes than for sweet potatoes, cassava, and yams. A wide variety of potato harvesting methods exist, and the type used depends on several factors --including soil characteristics, stoniness, topography, labor supply, crop use, and desired storage life (Smith). The method with the lowest labor requirement utilizes machines that lift the tubers from the soil, shake and screen out the soil, and then convey the tubers into trucks or trailors (Martin, Leonard, and Stamp). In the Netherlands, one person can harvest large areas quickly with these machines (Shelef, Azoc, and Moraine). However, potato harvesting machines are often ineffective in separating stones and clods from the tubers, so in areas with stones or heavy soils, two to seven people may be needed to ride the machines and sort out unwanted material. Consequently, labor costs may be high in areas with stony or cloddy soil. Also, more than 10% of the tubers can be bruised, if the speed of separating components of the machine is increased to break the clods (Smith). Losses can be less than 5%, or equivalent to hand harvesting, with proper machine adjustment.

Machines are used which put the tubers in a windrow on the ground rather than conveying them into trucks or wagons. The tubers are then picked up by hand and put into baskets, crates, or bags. Sorting of the tubers is done either by hand in the field or by machine at the warehouse. With wet, heavy soil or weedy conditions, this method results in cleaner tubers than the completely mechanized system. Presently developed mechanical harvesters can not be used on some very heavy, strong soils or steeply sloping fields.

As in potato harvesting, sweet potatoes are harvested with machines which lift the roots, sort them, and convey them onto trucks or trailers. Other types of machines lift the roots, separate them from the soil, and drop them on the ground. The roots are allowed to dry for a few hours and are then picked up by hand. Sweet potato vines generally do not die before harvest as potato vines do, so the vines are cut before lifting the roots. Shielded 8-inch colters may be mounted on the harvesting machine, or the cutting may be done in a separate operation with rotary or flail mowers.

Sweet potato roots are more susceptible than potato tubers to mechanical injuries such as bruises, scratches and cuts, which can dramatically reduce storage life of roots. However, even hand harvesting can result in significant bruising if roots are carelessly tossed on piles.

Extensive efforts are being made to develop mechanical harvesters for cassava and yams, and it may be possible to develop machines suitable for use on light soils (Williams). Designing machines to harvest cassava and yams is difficult because of the growth characteristics of the plants. Cassava tubers are long and break easily. They also spread over 1 m from the plant and penetrate down to 50 or 60 cm. Many yam varieties produce one or two large tubers per stand. The tubers also penetrate deeply into the soil. With improved management, the tubers are larger and deeper than under poor management, making mechanical harvesting even more difficult. In Trinidad, one *D. alata* tuber was grown which weighed 81 kg, but typical size is much smaller (USDA, 1976). Some varieties produce branched tubers, which are damaged easily. There is a need to develop cassava and yam varieties which are resistent to damage and are shallow bearing, so that they can be harvested mechanically (Onwueme). *Dioscorea esculenta* and similar types of yams can be harvested with machines used for potatoes, because the tubers are small and numerous (USDA, 1974a).

Various types of plows are sometimes used to lift potatoes and sweet potatoes out of lighter textured soils. Tractors or animals provide the draft power. Even in developed countries, moldboard plows with wide bottoms are used to lift sweet potatoes, because mechanical injury is less and storage life longer than with harvesting machines. The plows bring the tubers to the surface but do not separate them from the soil. Tubers are then gathered manually. Plows are also used in some cases for lifting cassava roots, but losses are generally high. Studies have shown that 75 to 83% of the cassava tubers can be recovered using moldboard plows, but mechanical injury may be high (Onwueme). Problems involved with using moldboard plows include clogging from plant residues and covering of tubers by upturned soil. In Mexico and Brazil, tractors mounted with heavy screens and rotary mowers are used to push down and cut cassava plants before lifting the tubers.

Hand harvesting of root and tuber crops is widely practiced in developing countries. Potato vines are usually removed about a week before harvesting in tropical areas, and hoes or forks are used to dig up the tubers (Kay). The potato tubers are often left on the soil surface to allow the skin to dry and toughen. They must be picked up within a few hours in hot, dry weather to avoid sun scald (Martin, Leonard, and Stamp). Sweet potatoes are harvested in a similar manner, but the harvesting is traditionally done as the tubers are needed. However, delayed harvesting results in increased sweet potato weevil damage (Doney).

Cassava tubers can be harvested by pulling the stems in light soils, but they may need to be dug with a hoe in heavy soils (International Land Development Consultants). One man can harvest up to 1,000 kg/day if the soil is loose, but only about 500 kg/day when the soil is compacted (Onwueme). Harvesting is also harder when the soil is dry than when it is wet. Before lifting, the stem is cut a few inches above the ground with a machette, which is also used to loosen the soil around the tubers. If the tubers are not lifted soon after the stem is cut, they will sprout. Cassava tubers keep in the soil for a long time if the plants are not cut. Harvesting is usually done in the dry season where rainfall is seasonal and throughout the year in continually wet climates.

Yams can be harvested once or twice in a growing season. The total yield in a season is not affected by harvesting frequency. However, farmers may get higher prices for early harvested yams, and better quality planting material is produced at the second harvest. Eating quality is best with the single harvest system. When double harvesting is practiced, the first harvest must be done carefully so that the plant survives. Soil is removed from around the tuber without disrupting the root system. The tuber is cut below the base of the stem and the soil is replaced over the roots. Tubers are harvested again within a few weeks after the leaves drop. Under the single harvest system, lifting is done only after senescence. The vine is discarded, and the tubers are dug with a spoon-shaped stick, a fork, or a shovel. Large tubers must be dug carefully. Some varieties produce particularly succulent and fragile tubers.

2. Sugar Crops

a. Forages (sweet sorghum, sugar cane)

Both sweet sorghum and sugar cane are harvested for the sugars produced in their stalks. A wide variety of harvesting systems have been developed for sugar cane. However, efforts to develop suitable harvesting machines for sweet sorghum have been minimal, because sweet sorghum is a minor crop in most countries. Annual production in the U.S. averaged less than 4,000 ha between 1973 and 1975 (Lipinsky, et al.).

Corn binders are presently used in harvesting sweet sorghum. The bundles are sometimes shocked to dry in the field or near the processing facility. Bundles are loaded into trucks or trailers by hand or with mechanical loaders. Lipinsky, et al. suggested that some of the methods used for handling dry alfalfa may also be feasible for sweet sorghum, but no reports of their use were found.

Machines for harvesting silage can be used to harvest fresh sweet sorghum. However, the resulting short storage life may be a major problem for ethanol processors. If sweet sorghum is chopped to the size of silage, conversion of sugars by respiration occurs within 24 hours

(Broadhead). Breakdown of sucrose can occur within 2 or 3 hours on a hot day (Wall and Ross). However, forage harvesters can be modified to chop stalks into billets 13 to 15 cm long by removing some of the knives, increasing the feeding rate, and slowing the cylinder speed (Wright, et al.). The cylinder speed, however, can not be slowed on "cut and throw" type machines. On all machines, knives must be kept in good condition, and a slow ground speed of 0.67 m/second must be used for best performance. Billets of 10 to 40 cm length can be kept without sugar loss for at least 48 hours with outdoor storage (Broadhead). Wright, et al. pneumatically separated seedheads and leaves from billets at a small (1.8 t/hour) processing plant. Approximately 13% of the seedheads were not separated but could easily be picked out by hand while the billets were conveyed to the mill. Also, 16% of the billets were lost to trash, but most of these were from the tops, which are low in sugar. Before processing for sugar and syrup, sweet sorghum leaves and tops are removed; however, this process may not be necessary for ethanol production (McClure and Lipinsky).

A limited number of harvesters have been developed which cut the stalks, remove the juice, and leave the remaining fiber in the field (Wall and Ross). Sugar cane harvesters may also be used to harvest sweet sorghum, but modifications may be necessary to collect seedheads separately (Ferraris and Stewart).

A wide variety of sugar cane harvesting machines have been developed according to the needs of specific growing areas. Probably the most common mechanical harvesting systems use combines to perform all the harvesting steps. The sugar cane tops are cut first, then the stalks are cut or broken at the base and conveyed into the machines. The stalks are cut into billets, and then forced air separates the billets from the leaves. The billets are dropped into tractor-drawn trailers traveling alongside the harvestors.

Generally, the fields are burned before harvest to reduce the amount of leaf material and to improve sugar refinability. However, the sugar content of burned cane is lower than that of unburned cane (Baxter; Martin, Leonard, and Stamp). Some machines are able to harvest unburned cane and are advantageous in areas where moist conditions can hinder burning (Baxter). They are also used for harvesting unburned cane for planting stock. Machine output is lower when harvesting unburned cane compared to burned cane. The difference in output between the two systems depends on the variety and extent of lodging.

Combine harvesters are used extensively in Australia and in areas producing moderate yields (McClure and Lipinsky). High yielding recumbent (lodged) sugar cane, such as found in Florida and Hawaii, is difficult to harvest with most combines, although some recent models are designed for use on recumbent sugar cane ("Harvester for Recumbent Cane . . ."). Other problems associated with combine harvesting include soil compaction from the heavy machines, as well as sugar loss and deterioration resulting from chopping (Barnes; McClure and Lipinsky). In some areas water must be used to clean the chopped cane before milling, and large amounts of sugar are dissolved and not recovered from the water (Leffingwell).

"Soldier" machines are used in areas such as Louisiana where sugar cane yield is low, and stalks are erect. These machines gather the stalks, cut them at the top and base, and lay them on the ground in a heap. One machine can cut two to six rows at a time and place them in one heap. After cutting, the heaps are burned. Mechanical grab loaders are used to load the whole canes into trucks or wagons.

An early method of mechanized harvesting, which is still practiced, involves the use of a bulldozer-like push rake to break burned cane stalks and force them into windrows. In wet areas, the push rakes may pull up stools, so v-cutters are used to cut the stalks and form the windrow. Mechanical grab loaders put the cane into trucks or trailers. This system is widely used in Hawaii where sugar cane growth often forms a tangled mat which is difficult to harvest by other mechanical methods. Estimates are that up to 10% of the sugar cane is not recovered when it is harvested by push rakes and grab loaders (Humbert). Also, milling problems occur, because the stalks are not topped, and a great amount of extraneous material is mixed with the stalks. Up to one-fourth of a load transported to a mill may consist of trash, rocks and mud. Rocks may inadvertently pass through the cleaning process and cause severe damage to milling equipment.

Only about 20% of the world's sugar cane harvesting is fully mechanized ("Field Mechanization"). The remainder is cut by hand with specially designed knives. The process involves cutting the stalk at the base as well as the top; then a special instrument is used to remove the leaves. Semimechanized harvesting systems are used in Mexico and parts of Florida. The stalks are cut by hand and placed at right angles to the sugar cane rows. Then the windrows are loaded by machines that continuously pick up the stalks and convey them onto a truck or wagon moving alongside the machine. The windrows may also be loaded by use of grab loaders. Manual loading is done in many countries where labor is cheap and abundant. With totally manual systems, one person can handle approximately 2 t/day (International Land Development Consultants). When only the cutting is done manually, 3 to 4 t can be done by one person per day. Echevarria reported that in Mexico, 3.5 t can be harvested per day per man if cutting and loading are done manually, and as much as 5.5 t can be harvested per man per day with semimechanized systems.

Sugar cane needs to be transported to the processing plant within a few hours of cutting to avoid inversion and deterioration of sugars. The most rapid cane transport system is containerized delivery by semitrailers. In Mexico, tractor drawn trailers with capacities up to 20 t and trucks with 10 t capacities are used (Echevarria). In the Philippines, trucks with up to 16 t capacity are used (Atienza and Demeterio). The truck and trailer boxes may be equipped with chains or lateral discharge for rapid unloading. Buffalo or bullock drawn carts are used where cutting and loading is done by hand. They are especially useful under wet field conditions, because they are lightweight and very maneuverable. Haulage rate is about 0.6 t/km/hour. Steel framed dumping bullcarts have recently been introduced in the Philippines. When small transport vehicles are used and fields are a long distance from the plant, the loads are often transferred to more efficient transportation vehicles such as railroad cars. In the Philippines, portable rails are sometimes used to move the railroad cars into the fields for direct transport to the mill.

b. Roots and tubers (Jerusalem artichokes, sugar beets, fodder beets).

As in the case of sweet sorghum and sugar cane, much more effort has been put into the development of sugar beet and fodder beet harvestors than Jerusalem artichoke harvestors, because Jerusalem artichokes are a minor crop. Steele estimated that at least fifty different sugar beet and fodder beet harvesters are produced in the world by approximately twenty different companies. Harvesting of Jerusalem artichokes is mainly done with modified potato harvesters, although harvesters designed specifically for Jerusalem artichoke are being developed.

Potato harvesters need modification because the Jerusalem artichoke tubers have smaller size, thinner skin, and wider distribution in the soil than potato tubers. The tubers are also strongly attached to the plant, so agitation of the potato digger must be increased to break the tubers loose (Lukens). Injury to the tubers may result from excessive agitation. Conventional potato diggers collect only 60 to 70% of the tubers produced (Dorband). Using hand labor to pick up tubers missed by the machine, 70 to 80% of the tubers produced can be recovered. Plows can be used to lift tubers, but they are generally less effective than potato harvesters or hand harvesting (McClure and Lipinsky). Hand lifting with a fork is the most effective method, but is not feasible for large scale production where wages are high. Even when harvesting is done manually, sufficient numbers of tubers remain in the soil to cause significant volunteer growth the following season. Harvesting is done when the leaves begin to wither and die. The large woody top growth must be removed before mechanical harvesting. In temperate climates, harvesting can be delayed until spring, but it must be completed before sprouting begins.

Sugar beets should be harvested when sucrose content reaches a maximum. At this stage, the lower leaves turn brown and the upper leaves turn yellow (Clements; Martin, Leonard, and Stamp). In temperate areas, harvesting must be done before the first frost. The harvesting operation involves lifting the root, cutting the top from the root, and separating soil and trash from roots and tops (Lipinsky, et al.). The top is cut either while the root is still in the ground or after it has been lifted. Usually, a separate top recovery machine is used if the tops are cut before lifting. The machine cuts the tops from up to six rows at a time and gathers them into a windrow. Since the tops are valuable livestock feed, they are collected by forage harvesters. Then up to six rows of roots are lifted at one time by a harvester which shakes loose the dirt and conveys the roots into a hopper or separate vehicle. If the tops are not removed before lifting, another type of harvesting machine lifts the plants and passes them through rotating disks which cut the tops from the roots. The tops are cut from the roots at the base of the lowest leaf scar.

Harvesting machines may have hoppers to collect the roots, or they may elevate the roots into tractor drawn trailers or trucks driven alongside the machine. Machines with hoppers may not be efficient in high yielding fields unless they are emptied on the move (Steele). The topped roots are hauled directly to the processing plant or to a central location for transfer to railroad cars or large semitrailers. With mechanized harvesting and favorable conditions, 8 to 10 ha of sugar beets can be harvested in a 24-hour day (Lipinsky, et al.).

In the U.S., the transition from hand to machine harvesting of sugar beets occurred between 1943 and 1958 (Lipinsky, et al.; Martin, Leonard, and Stamp). However, according to Steele, a significant portion of the sugar beets grown in Eastern Europe is presently harvested by hand. Special two-pronged forks are used to lift the sugar beets manually (Dowling). The dirt is knocked off, the tops are cut, and the beets are piled in the field. The topped beets are loaded into trucks or trailers by hand or mechanical loaders. With a totally manual system of harvesting, 125 to 150 hours may be required to harvest 1 ha (Lipinsky, et al.). Horse drawn implements for lifting sugar beets from the soil were developed in the 1920's (Dowling). They resemble two-wheeled steel plows with one or two flat blades.

3. Summary

Complicated, high capacity harvesting systems are available for most crops which are grown extensively in developed countries. However, such systems have not been well developed for cassava, yams, sweet sorghum, or Jerusalem artichoke, because they are not important crops in most developed countries. Mechanical cassava harvestors are being tested by researchers in several developing countries, so increased mechanization of cassava will probably occur in the future. Also, the harvesting methods for sweet sorghum and Jerusalem artichoke can be expected to improve, if the crops prove feasible as feedstocks for ethanol or other products. Hand harvesting is widely practiced for most crops grown in developing countries. Efforts are being made to introduce intermediate forms of technology for harvesting. Whether increased mechanization occurs in a particular developing country is dependent on the economic situation and governmental policies of the country.

B. Alternative technologies for storage

The storage method used for a particular crop depends on the type of crop, its ultimate use, the length of storage, and the availability of technology. The capacity of the storage facility depends on the above factors and on crop availability within a given radius of the storage site.

Ethanol plants must be run year-round for fuel ethanol production to be technically and economically efficient. Therefore, if a crop is to be used for fuel ethanol production, it, or a substitute crop, must be available throughout the year. Consequently, some form of crop storage is usually necessary during part of the year. However, storage may not be needed if a crop can be harvested throughout the year. Likewise, if two or more different crops can be harvested at different times of the year, the need for storage may be greatly reduced. This assumes, however, that the different crops can be processed to ethanol using the same facility and process.

The primary storage concern regarding fuel ethanol production is to minimize carbohydrate loss using the most cost and energy effective storage method available. Many advanced storage technologies for crops destined to become human food are much too energy intensive and costly to be used for fuel ethanol production. On the other hand, simpler storage methods often used in less developed countries frequently do not provide long-term storage. They may result in excessive storage loss and/or deterioration, thus making the methods unsuitable for ethanol production. Some storage methods currently used for traditional crops may be adequate for fuel ethanol production. However, it is clear that new storage technologies will be required to store the high-biomass crops currently being evaluated for ethanol production.

In summary, storage technologies for fuel ethanol production should be simple, economical, energy effective, and capable of minimizing sugar loss. Easily adaptable technologies are needed for less developed countries (high labor, low capital investment) as well as developed countries (low labor, high capital investment).

1. Starch crops

a. Cereals (corn, grain sorghum, rice)

Corn and rice generally contain 20 to 30% moisture at harvest and therefore must be dried prior to or during storage. Grain sorghum may require drying, depending on atmospheric and/or agronomic factors. Cereal grains must have 13 to 15% moisture or less before they can be safely stored.

In developed countries, batch and continuous flow drying systems are commonly used (Luh; De Datta). These systems are semi-automated and generally use natural gas or other fossil fuels as an energy source. In recent years, however, solar energy has also been harnessed to power these dryers.

In less developed countries, grain is generally dried by spreading it on a flat surface and allowing it to sun dry for 4 to 5 days (Luh; De Datta). This process, however, is difficult to control, because atmospheric conditions may be quite variable. Due to this fact, batch dryers are gaining popularity in less developed countries.

Once harvested and dried (if necessary), the grain may be stored using a variety of methods. A storage method should meet several requirements: (1) it must provide proper aeration to prevent spontaneous heating; (2) it must maintain the grain at a low moisture content (13 to 15%) so as to prevent degradation by microorganisms and insects; and (3) it must provide proper containment to protect against rodents, birds, insects, and spillage (Sinha and Muir).

In developed countries, grain is generally stored either in large, centrally located warehouses and elevators or in smaller bins located near the production site. High crop yields per hectare, large hectarage holdings per farmer, and the availability of transportation during harvest lead to this flexibility. Storage for 1 to 2 years is generally possible.

In less developed countries, grain is generally stored in smaller quantities, often in sacks or baskets within the farmer's home (De Datta). When larger volumes of grain are involved, grain may be stored in bins or bunkers. Grain is often stored near the production site, because crop yields may be low, land holdings may be small, or transportation may be limited. Storage time is limited from a few months to a year, and losses may be high.

b. Roots and tubers (potatoes, cassava, sweet potatoes, yams)

The primary factors which affect the storage life of root and tuber crops are temperature, relative humidity, and the condition of the crop following harvest. Temperature and relative humidity must be controlled within specific limits to prevent rotting, sprouting, respiration, and degradation by pests. Damaged tubers and roots must also be eliminated from storage piles to prevent rotting (Onwueme).

Many tubers (potatoes, sweet potatoes and yams) are cured following harvest to increase storage life. Curing is accomplished by subjecting the tubers to high temperature (27 to 32°C) and high humidity (85 to 95%) for 4 to 7 days immediately after harvesting (Onwueme). Curing promotes rapid healing of wounds inflicted during harvesting, and it increases the toughness of the skin (periderm) of the tuber. This in turn reduces the likelihood of microbial infections and makes the tuber more resistant to wounding during subsequent handling (Onwueme).

Potatoes are often stored above or below ground level in insulated, moisture/vapor-proof bins or warehouses. These structures allow for ventilation and the precise control of temperature and relative humidity, which are maintained at 3 to 15°C and 85 to 100%, respectively (Smith). Storage for 6 to 9 months is generally possible.

In some less developed countries, potatoes are stored above ground in bins or barns, or below ground in pits. These storage methods do not allow for temperature or relative humidity control, and storage conditions are therefore dependent on atmospheric factors. As a result, storage time may be limited, and tuber losses may be high.

Long-term storage of cassava may not be necessary, because it can be harvested throughout the year when roots reach maturity. This is important, since preliminary research indicates that the roots may be kept refrigerated for only up to 1 week (FAO, 1977).

Sweet potatoes are often stored in temperature and relative humidity regulated warehouses in developed countries. The optimum temperature range for storage is 13 to 18°C, and the relative humidity optimum is 85 to 95%. Storage for 6 to 9 months is generally possible (Edmond and Ammerman).

Sweet potato storage in less developed countries may be in underground pits or in above ground barns. Tubers may also be left in the ground, and harvested only as needed. Atmospheric conditions affect storage time and tuber quality (Onwueme).

Yams may be stored for 6 to 9 months in climate controlled rooms at 15°C and low relative humidity (Adesuyi). In less developed countries, yams are generally stored in barns or on raised platforms in the field. Both are outdoor structures dependent on good ventilation for successful storage. The ventilation serves two purposes: (1) it prevents the buildup of high humidity which favors rotting; (2) it prevents the tubers from overheating due to respiration. These structures are effective for yam storage through the dry season, but once the rainy season starts, the tuber rapidly deteriorates. Therefore, storage time is generally limited to less than 6 months, unless the yams are moved inside.

The size of the storage facility for root and tuber crops is dependent on storage method and on crop availability. When climate controlled warehouses are utilized, economics of scale dictate that the storage facility be large and centrally located. The closely regulated storage conditions reduce the risk of a rapidly spreading biological or physical action which could destroy the entire crop. In less developed countries, small storage facilities with no environmental control are often used when transportation is limited or crop yields are low. As a result, storage loss may be high.

2. Sugar crops

a. Forages (sweet sorghum, sugar cane)

Sweet sorghum and sugar cane, when grown for the production of crystal sugar, are generally harvested and then immediately processed, since sugar deterioration begins within 48 hours after harvest (Barnes). Therefore, in tropical or subtropical areas where the crop can be grown and harvested year round, the need for storage is eliminated. However, in temperate regions where sweet sorghum is being considered for fuel ethanol production, storage for 6 to 9 months is required. Three forms of storage are currently being considered for forage type sugar crops.

The most promising process, which is adaptable to both developed and less developed countries, involves chopping the forage crop into billets (stalk pieces) 10 to 20 cm in length (Wright, et al.). The billets are dried to 15% moisture using either waste heat from the alcohol plant or heated air from solar collectors. The dried billets can then be stored for 6 to 9 months under well ventilated, dry conditions.

In developed countries, modified forage harvestors would be suitable for chopping the crop into billets, and mechanized drying equipment could be modified to dry the billets. In less developed countries, manual labor often could be used to replace machines in both the harvesting and drying processes. In addition, if a dry season occurred during harvest, the billets could be spread out on the ground and dried under atmospheric conditions.

A second possible storage technique makes use of technology developed for storage of hay crops. The forage crop is first mowed and field dried to reduce the moisture content. The stalks are then baled or shocked using commercially available equipment. The bales or shocks are then stacked in such a way as to provide adequate ventilation and covered with tarps. The crop is generally stored near the production site. The major factor limiting storage time is the degree to which the whole stalks can be dried under atmospheric conditions.

In the third process, which is probably most feasible in developed countries, the forage crop is mowed and then immediately processed through a roller-type mill to extract a dilute sugar solution (Lamb, Von Bargen, and Bashford). The fibrous residue is left in the field to help maintain soil fertility and tilth. The dilute sugar solution is then transported to a centrally located facility where the sugar is concentrated to 40 to 50%. This solution is then stored in large tanks until use. The two main disadvantages of this process are that energy usage for concentrating the sugar solution is high, and a large amount of tank capacity is required for storing the sugar concentrate. However, if waste heat or solar-generated heat could be used to concentrate the juice, this technique might be feasible.

b. Roots and tubers (Jerusalem artichokes, sugar beets, fodder beets)

Storage of sugar containing root and tuber crops is primarily dependent on temperature, relative humidity, and crop condition. Therefore, maximum storage life is achieved when undamaged roots or tubers are stored in a climate controlled environment. This method of storage, however, may be too costly for the purpose of ethanol production, and other processes may be needed.

Jerusalem artichokes have a thin skin which makes them especially susceptible to dehydration and microbial attack. Storage in cool or below zero (^{o}C) conditions under high humidity can inhibit microbial attack for prolonged periods of time (Fleming and Groot Wassink). The most satisfactory storage conditions are 0.5 to 1.7^{o}C and 82 to 92% relative humidity (McGlumphy, et al.). This method requires a climate controlled storage facility.

Artichoke tubers may also be left in the ground throughout the winter in a frozen condition. Tubers can then be harvested in the spring. In some climates, the tubers may be harvested as needed during the yearlong growing season.

Sugar beet and fodder beet storage methods have been developed for beet sugar processing plants (Fox; Swift). The most cost and energy efficient process involves below ground storage in earthen pits lined and covered with plastic and straw (Hayes). The earth and straw serve as insulation, thereby maintaining a low temperature (5 to 15^{o}C) and eliminating costly refrigeration. Ventilation is provided by holes cut through the plastic lining at regular intervals. Storage for 6 to 9 months is possible, and this method may be adaptable for both developed and less developed countries.

Another option for storage of tuberous sugar crops is to slice the tubers into pieces and dry them to 10 to 15% moisture (Dykins, et al.; McGlumpty, et al.). This requires a large energy input, however, solar energy or waste heat might be used for drying. The advantage of drying is that the crop could be stored year-round in well ventilated bins or warehouses.

C. Alternative technologies for processing

The following factors affect the design and/or operation of a fuel ethanol plant: (1) crop(s) to be processed, (2) source of energy for fuel ethanol plant, (3) concentration of ethanol produced, (4) ultimate use of feed byproduct(s), (5) size and location of ethanol plant, and (6) availability of skilled labor. However, regardless of these factors, an operational fuel ethanol plant will require equipment and technically trained oeprators. Necessary equipment includes: (1) cook and/or fermentation tanks, (2) a distillation tower, (3) a feed-byproduct recovery system, and (4) a steam boiler. Technically trained operators, in the fields of microbiology and engineering, are also required. Other requirements for the fuel ethanol plant are site specific, and trade-offs here are possible between the needs of less developed countries and developed countries.

In less developed countries, manual labor is relatively cheap and abundant. However, technical equipment and people with technical experience are generally in short supply. The opposite of this situation occurs in developed countries. Therefore, in less developed countries manual labor may be substituted for equipment, whereever possible, in a fuel ethanol plant. On the other hand, in developed countries equipment is likely to replace manual labor.

The size and location of the fuel ethanol production plant depends, in part, on feedstock availability and associated transportation costs. Plant size is limited by the amount of feedstock produced within a given radius from the plant. Costs may be prohibitive, if the feedstock must be transported from too great a distance. By the same reasoning, the plant should be centrally located in the production area to minimize transportation costs. If the feedstock is stored in one large, central facility, the ethanol plant should be located in close proximity. If the feedstock is stored in smaller facilities located at the agronomic production site, the ethanol plant should be located centrally with respect to these sites.

1. Starch crops

a. Cereals (corn, grain sorghum, rice)

Two processes are used to convert cereal grains to fuel ethanol and distillers' feed. The wet milling process (Casey) separates the cereal grain into three major fractions--starch, protein, and oil. The protein and oil fractions can be incorporated in human or animal foods, while the starch fraction is saccharified to glucose, which is then fermented to ethanol. This method requires a large investment in capital equipment and is energy intensive. Therefore, due to economies of scale, this process is only practical for plants producing at least 20 to 30 million gallons of ethanol annually.

The dry milling process, on the other hand, requires a much lower capital investment and is less energy intensive (USDA, 1980b; SERI, 1980). Therefore, it is practical for plants producing as little as 0.25 million gallons of ethanol annually.

Four steps are involved in the batch conversion of grain to ethanol and distillers' feeds using the dry milling process (Westby and Gibbons; Gibbons and Westby, 1983b). During cooking, the first step, grain is transported from storage and cleaned, using air cyclones and magnets. The grain is then milled, weighed, and augered into a cook-fermentation tank filled with water and a small quantity of amylast enzyme. The corn-water-enzyme slurry, called mash, is then heated to 90 to 95^{o}C and held for 0.5 to 2 hours. During this time, the amylast enzyme converts the grain starch to dextrins. The mash is then cooled to 55 to 60^{o}C, the pH is adjusted from 3.8 to 4.5 with sulfuric acid, and a small quantity of amyloglucosidase enzyme is added. After holding for 6 to 12 hours, during which time the dextrins are converted to glucose, the mash is cooled to 28 to 30^{o}C and is inoculated with a culture of yeast.

During batch fermentation, the second step, yeast converts glucose to ethanol and carbon dioxide. Heat is also generated by yeast during the fermentation process, and it must be dissipated by cooling to prevent inhibition of yeast fermentation. After 48 to 60 hours, fermentation is complete, and the mash, now called beer, contains 8 to 12% (v/v) ethanol.

In the third step of the process, distillation, beer is continuously pumped into a sieve plate distillation tower that produces 95% fuel ethanol and stillage (ethanol free beer) (Stampe, et al.). Alternatively, the beer can be centrifuged before distillation, if the distillation tower is of the type that is clogged by beer solids. However, here about 15% of the ethanol is lost in the solid fraction. The 95% ethanol from distillation can then be upgraded to 100% ethanol in a separate anhydrous distillation column.

In the fourth step, the stillage is continuously pressed or centrifuged to separate the solid fraction (distillers' feed) from the liquid fraction (thin stillage). The distillers' feed is used primarily as a high protein supplement in livestock feeds and part of the thin stillage is used to replace a portion of the water added to corn in the cooking process.

This general dry milling process is suitable for both developed and less developed countries. The process is reasonably simple and requires a minimum of operator expertise. The process also lends itself well to microprocessor control, thereby reducing the labor requirements for process monitoring. In larger scale plants continuous cooking and continuous fermentation processes may be substituted for traditional batch processing to take advantage of available technology.

b. Roots and tubers (potatoes, cassava, sweet potato, yams)

Conversion of starch containing root and tuber crops to fuel ethanol and distillers' feed can be accomplished by any of three processes. The wet milling process (Casey) separates the crop into a protein fraction, which can be used in foods or feeds, and a starch fraction, which can be saccharified to glucose and then fermented to ethanol. Due to the large capital investment and economies of scale, this process must be operated on an annual production scale of at least 20 million gallons of ethanol.

The dry milling process (USDA, 1980b; SERI, 1980) can also be used to convert starchy root and tuber crops to ethanol. The same four step procedure as described for cereal grains can be used (i.e., cooking, fermentation, distillation and centrifugation). The major difference between the two processes is that only 4 to 6% (v/v) ethanol beers are produced from tuber crops, as compared to 8 to 12% (v/v) beers with cereal crops.

The difference is due to the low starch, high moisture content of tuberous crops. When pulped and mixed with water in the cooking process, the resultant high viscosity of tuber mashes limits the amount of tuber pulp that can be added (without making mixing and pumping difficult). This, in turn, limits the ethanol concentration of the beer following fermentation, and increases energy consumption for distillation. Consequently, production costs are higher than costs for processing cereal crops.

The dry milling process, however, may be feasible for both developed and less developed countries if low cost energy sources for distillation are available. Starch containing root and ruber crops can be converted to fuel ethanol and wet distillers' feed with a minimum of operator expertise. As with the conversion of cereal crops, microprocessors may be used to replace some plant technicians, and continuous processing may be desirable in large-scale plants.

A third option for converting starch containing root and tuber crops to ethanol is solid phase fermentation (Aidoo, Henry, and Wood; Kirby and Mardon). In the solid phase fermentation process, the crop is first pulped, and the pulp is then inoculated with microorganisms (Kirby and Mardon). The may be a co-culture, containing both starch degrading organisms (i.e., <u>Bacillus</u> or <u>Aspergillus</u> spp.) and glucose fermenting organisms (i.e., <u>Saccharomyces</u> or <u>Zymomonas</u> spp.), or it may be a monoculture, consisting of an organism able to both hydrolyze starch and ferment the resultant glucose to ethanol (i.e., <u>Schwanniomyces</u> spp.) (Dhawale and Ingledew). In either case, the pulp is then allowed to ferment for 36 to 72 hours. Following fermentation, the pulp is pressed and/or dried to recover the 8 to 10% (v/v) ethanol beer. The beer is then distilled to produce fuel ethanol and the distillers' feed is used in livestock rations.

This process shows potential for producing ethanol and distillers' feed from root and tuber crops at lower costs and energy consumption than either the wet or dry milling processes (Gibbons and Westby, 1983b). In addition, since the process is simpler, there is less need for skilled technicians. However, the solid phase fermentation process if relatively new, and much more research is needed before commercialization can begin. That research should determine optimum fermentation parameters and optimum fermentor design.

2. Sugar crops

a. Forages (sweet sorghum, sugar cane)

The most widely used process for converting forage crops to ethanol is fermentation of diffused juice. In the manufacture of ethanol from sugar cane, for example, the cane is conveyed through rotating knives and/or shredders. The resulting coarse, fibrous blanket of cane then passes through a magnetic chute (to remove tramp metal) and into the first mill crusher. Following this, the cane is alternately sprayed with water and pressed with up to six or more mill crushers. The exhausted fiber (bagasse) exits the last roll and is generally used as boiler fuel. The mill juice is clarified, concentrated, and fermented to ethanol and the beer is subsequently distilled (Barnes; USDA, 1980b).

This process may also be suitable for ethanol production from sweet sorghum. However, the large capital investment required for equipment and the need for fresh feedstock limits the application of this technology to large-scale plants located in tropical areas.

Another method for obtaining sugar juice from forage type sugar crops is in-field mechanical expression (Lamb, Von Bargen, and Bashford; Bryan, et al.). In this process the crop is passed through a series of roller mills. The pressed stalks are left in the field, and the juice is transparted to the alcohol plant where it is concentrated, fermented, and distilled to produce alcohol.

This process is suitable for both developed and less developed countries, however the juice storage problems mentioned previously may limit its application to tropical areas where the fresh feedstock can be harvested year-round. Alternatively, in subtropical or temperate regions, the ethanol plant could be run using another, more easily stored feedstock when the fresh forage crop is not available.

When dried forage billets are used the ethanol plant can be operated year-round on a single feedstock. Three processing methods are currently being evaluated for ethanol production from forage crop billets. Each of the processes appears to be feasible for both developed and less developed countries.

One process uses a Tilby separator to remove the sugar containing pith of forage billets from the fiber containing rind (McClure and Lipinsky; Lipinsky). The rind fiber is a valuable byproduct used in construction materials. The pith can be rehydrated and pressed to recover sugar juice which can then be fermented to ethanol.

In the EX-FERM process, developed by Rolz, de Cabrera, and Garcia, forage crop billets are extracted and fermented simultaneously in an aqueous solution. Following fermentation the extracted billets are removed from the fermentation liquid, and fresh billets are added. Two to three such cycles are necessary to obtain 10% (v/v) ethanol beers. To reduce material handling problems horizontal packed-bed fermentors are recommended (Rolz).

A modification of the EX-FERM process, termed diffusion fermentation (Gibbons and Westby, 1983b), shows even more promise in reducing material handling problems. Here the billets are augered through a diffusion fermentor against a flow of water and suspended yeast cells. As the billets move through the fermentor, the sugar is diffused into the surrounding water, where yeast cells ferment this sugar to ethanol. Exiting from one end of the fermenter are exhausted billets which are used in livestock rations, and from the other end exits 8 to 10% (v/v) ethanol beer which is then distilled.

A third process is solid phase fermentation (Gibbons and Westby, 1983b; Bryan and Parrish). This process is also used for starch containing roots and tubers and is described in the starch crop processing section of this report. The only difference between processing starch and sugar crops is that there is no need for inoculating the pulp of sugar crops with starch degrading microorganisms. Only sugar fermenting mibrobes, such as Saccharomyces cereviside, are required. If dried billets are used in the process, they are first ground, and the resultant pulp is rehydrated prior to inoculation.

Each of these processes are likely to produce ethanol and feed byproduct from forage crops at lower cost and energy expenditures than the sugar cane refining process currently used. However, since these processes are new, research is needed to optimize fermentation parameters and fermentor design before commercial application can occur.

b. Roots and tubers (Jerusalem artichokes, sugar beets, fodder beets)

As was the case with forage crops, the most common method for producing ethanol from sugar containing root and tuber crops involves fermentation of diffusion juice. Sugar beets or fodder beets, for example, are sliced into cossettes and augered through a diffusion tube against a flow of hot (70 to 80°C) water. The extracted sugar solution exiting one end of the diffusor can be concentrated and then fermented to ethanol, while the spent cossettes are used as livestock feed (USDA, 1980b). This process, however, is energy, cost, and technology intensive and therefore is not practical for less developed and most developed countries.

More promising conversion methods for developed and less developed countries include the EX-FERM (Rolz, de Cabrera, and Garcia) and solid phase fermentation (Gibbons and Westby, 1983b; Kirby and Mardon) processes described previously for forage crops. These processes should be more cost and energy efficient than the diffusion process. However, since they are still in the development phase, commercialization has yet to occur.

IV. Economics of Producing Ethanol from Alternative Crops *

The preceding sections of this report have been concerned with the physical and technical feasibility of producing fuel alcohol from alternative crops. Central to these analyses has been the examination of the physical characteristics of each of the selected crops--their yields under different climatic and soil conditions; the methods of planting, harvesting, and storing each crop; and the nutrient and chemical content of each crop which indicate those processing operations that are likely to be successful in producing an acceptable yield of fuel alcohol.

Although determining the amount of alcohol that can be produced is a necessary step in selecting a feedstock for fuel alcohol production, it is not a sufficient step. To the technical feasibility analysis of growing a crop for fuel alcohol production must be added the economic feasibility of such an undertaking. This section of the report seeks to combine the physical parameters of crop production, storage, and processing into fuel alcohol with the cost parameters associated with each of those production steps. The outcome should provide a basis for determining what crop or crops are suited for fuel alcohol production at least cost in various less developed countries (LDCs) throughout the world and in the Northern Plains of the U.S.

The organizational format of this section is similar to that of the preceding sections. The crops selected for analysis are divided into two groups--starch crops and sugar crops. From that point on, each crop is individually examined to determine crop prices or production and harvesting costs, storage and processing costs, and byproduct credits.

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Where data permit, a range of cost estimates is provided for each crop to reflect (1) whether or not a crop is irrigated, (2) production in different climatic zones of the earth, and (3) different processing technologies that may be used in developed countries versus technologies that may be used in less developed countries.

There are certain procedures that are used in this study to determine the costs of producing fuel alcohol regardless of the feedstock being examined. The assumptions used with these procedures are stated here to avoid repetitiveness throughout the remainder of the report.

One of these assumptions concerns the cost of growing and harvesting the basic feedstocks for alcohol production. Wherever adequate price data are available, the cost is assumed to equal the average market price of each commodity, calculated over the years 1979 to 1981. The base year for this study's analyses is 1981. All cost data are adjusted through the use of price indices to indicate their value in that year.

Market price data for most of the crops being examined in this report are available for the U.S. and in many cases, for South Dakota. Those crops for which U.S. price data are available include corn, grain sorghum, rice, potatoes, sugar cane, sugar beets, and sweet potatoes. There are not published, well-established market prices for cassava, yams, sweet sorghum, fodder beets, or Jerusalem artichokes.

Theoretically, the market prices of commodities should reflect the long-run total cost of producing, storing, and transporting those commodities. Firms producing fuel alcohol are competing with other users of commodities and, therefore, can expect to pay market prices for the feedstocks.

However, there are some problems with using market prices of commodities for the assumed feedstock cost in alcohol production--especially for those commodities in which there is a limited market, such as potatoes, sugar beets, and sweet potatoes. Generally, the prices paid per unit to farmers for these types of commodities are quite high relative to other agricultural crops. It is possible that an expansion in the supply of a particular commodity could lead to lower average per unit production costs, and therefore lower prices (lower alcohol feedstock cost) paid to producers (assuming a competitive market for that commodity). It is also possible that higher prices will be required to bring forth larger quantities of some feedstocks.

A second problem with using prices paid to farmers for commodities to represent alcohol feedstock costs is that the markets from which these prices are taken may be distorted by government policies. These distortions may result from government subsidized price supports, government held commodity reserves, or restrictions on imports and exports of commodities. The latter distortion is especially applicable to sugar crops, both in the U.S. and in many less developed countries.

The result of these distortions is often an artificially high price paid for the affected commodities. This, in turn, has an adverse effect on the economic feasibility of alcohol production from those commodities. At present, these market distortions are realities, but the elimination of such distortions is an area that policy makers may want to consider when examining fuel alcohol production possibilities.

Published information on local commodity prices for most developing countries was not available to us as we carried out our economic analyses.

Also not readily available were cost data for construction and operation of fuel alcohol plants in LDCs. This study takes two approaches as a result of these limitations.

First, in using commodity feedstock prices, we assume no difference in feedstock prices between LDCs and developed countries, except where specific data indicate otherwise. Although there is likely to be a quite different mix of inputs for producing feedstocks in developed countries compared to LDCs, there is no a priori reason to necessarily believe that the average cost per unit of feedstock will differ between the two groups of countries.[1/]

The second approach pertains to the cost of processing feedstocks into fuel alcohol. These costs are likely to differ between developed and less developed countries. Normally, it is assumed that LDCs will substitute labor for capital items where it is possible, since LDCs have a relative abundance of labor compared to capital. However, this may not be possible in fuel alcohol production. To perform basic processes of the industry requires a certain amount of capital construction. Also, many of the people employed in the alcohol plants need to be trained in microbiology and engineering at some minimum level.

For most feedstocks, there are no published estimates of the cost of processing the commodity into fuel alcohol for LDCs. The World Bank (World Bank, 1980) notes that actual processing costs are going to be country specific. However, for purposes of comparison, the Bank has

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[1/] However, because agriculture is generally less efficient and lower yielding in many LDCs, costs per unit of a commodity may be higher.

divided countries into three categories: (1) low cost countries, (2) medium cost countries, and (3) high cost countries. These divisions are based on countries' domestic plant construction capabilities. Brazil was given as an example of a low cost country, where alcohol plant technology is well-developed. Medium cost countries, such as Thailand, were assumed to have capital costs 25% higher than low cost countries, and high cost countries, such as the Sudan, were assumed to have capital costs 50% higher than medium cost countries.

In cases where there are no processing cost estimates for LDCs, we used the World Bank's criteria to make estimates. Considering that Brazil's fuel alcohol production facilities are probably at least as efficient as those of the developed nations, the cost figures calculated for the developed countries for each feedstock have been assumed to apply to LDC "low cost countries". From this low cost basepoint, the estimates for medium and high cost LDCs have been derived.

Another factor that affects the total net cost of alcohol production, and for which there is little information relating to LDC conditions, is the value assigned to the feed byproduct. In the U.S., the byproduct from corn is used as a protein supplement in livestock rations. In this use, it has a relatively high value in comparison to the total costs of producing the alcohol. In many LDCs, there is an absence of large feedlots or livestock herds to which the byproduct can be fed. Therefore, it may not have the value in LDCs that it has in the U.S. However, it is possible that the byproduct could be used in LDCs as human food. No studies were found in which this possibility was explored and, therefore, no value for the byproduct in that use is given in this report. Instead, it is assumed that the byproduct credit given for studies done in developed nations will be applicable to LDCs, as well.

One other assumption is made in this report in relation to the feed byproduct credit. For some of the crops examined, there were no studies found that made any estimate of the value of the feed byproduct in any use. For those crops, it was assumed that their byproduct credit would be directly related to their raw feedstock protein content per gallon of alcohol. This content was compared to the protein per gallon of alcohol produced from corn. The ratio computed in this comparison was then multiplied by the value of the corn byproduct credit to establish a per gallon byproduct credit for the other crops. This method provides only a very rough estimate of the byproduct value for certain crops. A closer look at these crops as alcohol feedstocks would examine exact protein content of each byproduct itself, as well as the exact amount of byproduct produced in relation to the amount of alcohol produced.

We have not systematically treated transportation and storage costs for alternative feedstocks, although such costs may be implicitly included in some of the production costs and prices relied on. More detailed analyses of individual feedstocks would need to include careful examinations of those costs, however.

In contrast to previous sections of this report, in which metric units were used, the economics section is presented in United States units. Costs are stated in U.S. dollars per gallon, for example. Appendix A of this report consists of a metric conversion table, for use by international audiences. Also, Appendix B contains the cost tables in U.S. dollar per liter terms.

A. Starch crops

The starch crops for which economic analyses were conducted are the same as those discussed in previous sections. They include: (1) grain sorghum, (2) corn, (3) rice, (4) potatoes, (5) cassava, (6) sweet potatoes, and (7) yams.

1. Grain sorghum

Two factors are significant determinants of the economic feasibility of using grain sorghum for fuel alcohol production. One is the alcohol yield obtainable per unit of grain sorghum. The other is the per unit cost of grain sorghum as a commodity.

In this study, a 3-year average of grain sorghum prices received by farmers in South Dakota is assumed to represent the cost of sorghum for alcohol production in 1981 (the base year). According to Agricultural Prices Annual Summary (USDA, 1980 to 1982) this 3-year (1979 to 1981) average price is $2.12/bushel.

There are a variety of estimates of alcohol yield from grain sorghum. These range from 2.2 gallons of 200 proof alcohol/bushel (SEIS) to 2.7 gallons of 200 proof alcohol/bushel (Hall). Using the price of grain sorghum given above, feedstock costs for ethanol production can be calculated to range from $.79 to $.96/gallon.

The storage of grain sorghum and the procedures for processing it into fuel alcohol are generally the same as for corn. After being stored at 10 to 15% moisture, the grain sorghum is milled, gelantinized, liquified, saccharified, fermented, distilled, and the whole stillage is centrifuged.

Two cost estimates for this processing have been obtained. The first estimate (Meo and Sachs) breaks production costs down only by fixed and variable costs. This estimate is for a plant producing 50,000 gallons of 190 proof alcohol/year, assuming an interest rate of 15% for amortization and for the cost of operating capital. Variable costs (including feedstocks, net of the feed byproduct credit) were estimated to be \$1.47/gallon, and fixed costs were estimated to be \$.62/gallon, for a total annual cost of \$2.09/gallon of ethanol.

The second estimate (SEIS) placed total fixed and operating costs, exclusive of the feedstock, at \$.68/gallon in a plant producing 50 million gallons of 200 proof ethanol annually. Adding this to the cost of producing the grain sorghum in South Dakota (\$.79 to \$.96/gallon) results in total ethanol production costs of \$1.47 to \$1.64/gallon. The author of this report estimates a byproduct credit of \$.52/gallon. Therefore, production costs of ethanol from grain sorghum net of the feed byproduct range from \$.95 to \$1.12/gallon.

Thus, the ethanol production costs from grain sorghum in the Northern Plains region is estimated to be as low as \$.95/gallon (with byproduct credit), for a 50 million gallon of 200 proof ethanol/year plant, and as high as \$2.09/gallon (with byproduct credit), for a 50,000 gallon of 190 proof ethanol/year plant. It should be noted, however, that neither study was involved with the actual production of alcohol in a working plant. Both studies used cost data from other analyses, as well as <u>potential</u> alcohol yields, for their costs of production calculations.

One other estimate of the cost of processing grain sorghum into fuel alcohol is provided from experiments at South Dakota State University (Hoffman and Dobbs). This estimate has actually been made using corn as a feedstock, but the characteristics of grain sorghum are so similar to corn that the same general processing procedures can be assumed to apply.

The South Dakota State University (SDSU) study examines annual fixed and operating costs for a plant capable of producing 175,000 gallons of 185 proof alcohol/year. These costs totaled $.87/gallon, not including feedstock cost, but including a $.30/gallon feed byproduct credit. Adding on the feedstock cost of grain sorghum results in a total cost of between $1.66/gallon and $1.83/gallon.

All of the cost estimates listed so far have referred to alcohol production in the U.S. There were no data found that referred to the costs of producing fuel alcohol from grain sorghum in less developed countries. Therefore, the World Bank procedures were used to estimate these costs.

Table 4-1 shows the range of costs estimated for three different fuel alcohol plants in low, medium, and high cost LDCs. Note that "low cost countries" cost estimates are the same as for developed countries which were estimated earlier. Inherent in this approach is the assumption that grain sorghum as a feedstock will cost the same in LDCs as in the Northern Plains region of the U.S.--$2.12/bushel.

Cost estimates for small-scale plants in "low cost countries" range from $1.66/gallon of 185 proof alcohol produced in a 175,000 gallon/year plant to $2.09/gallon of 190 proof alcohol produced in a 50,000 gallon/year

Table 4-1. Estimate of Costs of Producing Fuel Alcohol in LDCs and the U.S. from Grain Sorghum.

Country Type	Plant A1/	Plant B2/	Plant C3/
	----------$/gallon----------		
Low Cost Countries and the U.S.	$2.09	$1.66 - $1.83	$ .95 - $1.12
Medium Cost Countries	$2.25	$1.74 - $1.91	$1.04 - $1.21
High Cost Countries	$2.64	$1.95 - $2.12	$1.26 - $1.43

1/Plant A is assumed to produce 50,000 gallons of 190 proof alcohol annually (Meo and Sachs).

2/Plant B is assumed to produce 175,000 gallons of 185 proof alcohol annually (Hoffman and Dobbs). The range of costs represent a range in per bushel alcohol yields, from 2.2 to 2.7 gallons/bushel (SEIS; Hall).

3/Plant C is assumed to produce 50 million gallons of 200 proof alcohol annually (SEIS). The range in costs represent a range in per bushel alcohol yields, from 2.2 to 2.7 gallons/bushel (SEIS; Hall).

plant. Alcohol produced in a 50 million gallon/year plant is estimated to cost much less. However, this report is primarily concerned with small-scale production levels.

"Medium cost countries" could expect costs of \$1.74 to \$1.91/gallon and \$2.25/gallon of 185 to 190 proof alcohol for the 175,000 gallon/year and 50,000 gallon/year plants, respectively. For those same levels of production, the "high cost countries" production cost estimates are \$1.95 to \$2.64/gallon.

These cost figures may be somewhat low because they include a credit for an animal feed byproduct. This credit may be harder to justify in LDCs than in developed countries, given the absence of large feedlots in LDCs that can handle a wet feed byproduct without extensive transportation or storage costs. However, the credit might be applicable if the byproduct is utilized as a human food.

2. Corn

In the U.S., corn is the feedstock that has been most thoroughly examined as a feedstock for producing fuel alcohol. With the rise in the price of petroleum fuels, a number of experimental and commercial plants have sprung up across the U.S. using corn as their basic input. A number of estimates of alcohol yield, variable costs, and capital costs are therefore available for alcohol production from corn.

As with grain sorghum, a market for corn is well-established and, hence, a market price is easily determined. This price is what fuel alcohol producers can expect to pay for corn feedstocks. In South Dakota, the 3-year (1979 to 1981) average price farmers received for corn was \$2.42/bushel (USDA, 1980 to 1982).

Alcohol yield from corn will vary with the type of operation and the proof being produced. Realistic yields are in the range of 2.4 to 2.6 gallons of 185 to 200 proof ethanol/bushel of corn (Hoffman and Dobbs; SERI, 1980; USDA, 1980b). This translates into an average raw feedstock cost of $.93 to $1.01/gallon of alcohol produced, using 1979 to 1981 South Dakota corn price data.

The processing of corn into fuel alcohol is a well-established procedure. The corn is stored at about 15% moisture. Then it goes through the steps of grinding, cooking, fermenting, distilling, and centrifuging.

There are numerous estimates of the cost of processing corn into fuel alcohol, but we cite only two studies here. The first study (Hoffman and Dobbs) was done at SDSU using data from the actual operation of an experimental small-scale dry milling plant. Processing costs were estimated for this plant at an assumed annual production level of 175,000 gallons of 185 proof alcohol. Processing costs for this plant were $1.17/gallon, not including feedstock cost. A byproduct credit of $.30/gallon was estimated, leaving a net cost of $.87/gallon. The interest rate used for amortizing capital costs over their economic lifetimes was set at 15%.

When the cost of the corn feedstock is added to the other capital and operating costs estimate for the SDSU plant, the total cost of producing ethanol from corn in South Dakota ranges from $1.80 to $1.88/gallon.[2/]

[2/] These estimates differ slightly from those found in Hoffman and Dobbs, due to different assumptions on cost of the feedstock and to different methods of accounting for the denaturant cost.

The other study (SEIS) estimates the cost of producing fuel alcohol to be $.58/gallon, not including feedstock costs. This is for a plant producing 50 million gallons of 200 proof ethanol annually, using a 15% interest rate to amortize capital costs. The SEIS study also estimates a feed byproduct credit of $.38/gallon of alcohol, thus leaving net processing capital and operating costs, other than feedstock costs, at $.20/gallon, or $.24/gallon indexed to 1981.

Again, the total cost of alcohol production, after deducting for the feed byproduct credit, is arrived at by adding feedstock costs (previously calculated to be $.93 to $1.01/gallon) to $.24/gallon. This results in total costs for this very large plant in the range of $1.17 to $1.25/gallon of ethanol produced.

How do these alcohol production costs from corn feedstock look in less developed countries? As with grain sorghum, the actual cost of the feedstock and the operating costs of alcohol plants are going to be country specific. Not considering corn costs in specific LDCs (although it is likely that corn is more expensive in many LDCs), the operating inputs for alcohol plants and the plant technologies used are assumed to be similar in developed countries and LDCs. Fixed costs of capital construction are factored upward, using the World Bank criteria referenced earlier, to reflect likely levels of capital costs in low, medium, and high cost LDCs. Total alcohol production costs in LDCs and in the U.S. with corn as a feedstock are shown in Table 4-2.

If a 50 million gallon/year plant is built, alcohol production costs in a "low cost country" using corn as the feedstock could be as

Table 4-2. Estimate of Costs of Producing Fuel Alcohol in LDCs and in the U.S. from Corn.

Country Type	Plant A1/	Plant B2/
	-----$/gallon-----	
Low Cost Countries and the U.S.	$1.80 - $1.88	$1.17 - $1.25
Medium Cost Countries	$1.88 - $1.96	$1.26 - $1.34
High Cost Countries	$2.09 - $2.17	$1.48 - $1.56

1/ Plant A is assumed to produce 175,000 gallons of 185 proof alcohol annually (Hoffman and Dobbs). The range in costs represent a range in per bushel alcohol yield, from 2.4 to 2.6 gallons/bushel (Hoffman and Dobbs; SERI, 1980; USDA, 1980b).

2/ Plant B is assumed to produce 50 million gallons of 200 proof alcohol annually (SEIS). The range in costs represent a range in per bushel alcohol yield, from 2.4 to 2.6 gallons/bushel (Hoffman and Dobbs; SERI, 1980; USDA, 1980b).

low as $1.17/gallon. With a smaller plant, producing only 175,000 gallons, the costs could be as high as $1.88/gallon in "low cost countries".

Alcohol production costs in "medium cost countries" range from $1.26/gallon in the largest plant to $1.96/gallon in the smallest plant. For "high cost countries", this range is from $1.48 to $2.17/gallon.

As with grain sorghum, these cost estimates include a credit for the feed byproduct, which may not be as applicable to LDCs as it is to developed countries, unless the byproduct can be utilized as human food.

3. Rice

Rice is a commodity that is only grown in selected areas of the U.S., and is not grown at all in South Dakota or the rest of the Northern Plains region. However, rice is the main crop in many LDCs located in tropical or subtropical areas. For that reason, rice as an alcohol feedstock is given some consideration in this report.

The average price of rice received by U.S. farmers for the years 1979 to 1981 was $10.78/cwt (USDA, 1980 to 1982). Average alcohol yield from rice is about 4 gallons of 200 proof alcohol/cwt (USDA, 1980b).[3/] Therefore, the feedstock cost to an alcohol producer using rice would be quite high--about $2.70/gallon.

No studies were found in which the costs of converting rice into alcohol were reported. However, the processing of rice into alcohol involves the same basic steps as when corn is used as the feedstock.

[3/] The alcohol yield assumed here is at the lower end of the range indicated in an earlier section of this report.

The capital and operating costs reported in the SDSU fuel alcohol study should, therefore, be applicable. Since rice has a protein content per gallon of alcohol nearly equal to that of corn, the feed byproduct credit is assumed here to be the same for rice as for corn.

Using the SDSU data, costs of producing fuel alcohol from rice in a 175,000 gallon/year plant would equal $1.17/gallon in processing costs plus $2.70/gallon for feedstock costs. Assuming a feed byproduct credit of $.30/gallon (as with corn) results in a net total cost of $3.57/gallon. This cost is quite high in comparison to the cost of gasoline in the U.S. and many other parts of the world.

Alcohol production costs from rice feedstocks in LDCs categorized as low, medium, and high cost countries are shown in Table 4-3. A plant of the size assumed here would have costs ranging from $3.57/gallon in the U.S. and low cost LDCs to $3.86/gallon in high cost LDCs. In general, alcohol production from rice is likely to be much more expensive than from corn or grain sorghum.

4. Potatoes

Potatoes differ from the starch crops discussed so far in that the starch is in the form of a tuber instead of a grain. As such, the procedure for processing potatoes into fuel alcohol differs somewhat from that of the grains.

However, when calculating per gallon feedstock costs, potatoes resemble the grains in that there is a well-established market in the U.S. for potatoes from which a market price/alcohol feedstock cost can be determined. The average price received by farmers for potatoes in the years of this study (1979 to 1981) was $3.62/cwt (USDA, 1980 to 1982). This price was for producers in South Dakota.

Table 4-3. Estimate of Costs of Producing Fuel Alcohol in LDCs and the U.S. from Rice.

Country Type	Alcohol Plant[1/]
	$/gallon
Low Cost Countries and the U.S.	$3.57
Medium Cost Countries	$3.65
High Cost Countries	$3.86

1/ The plant is assumed to produce 175,000 gallons of 185 proof alcohol annually (Hoffman and Dobbs).

Alcohol yield from potatoes has been estimated to range from 20 (Doney) to 28 (Hanway and Harlon) gallons/ton. This breaks down to between 1.0 and 1.4 gallons/cwt. At an average price of $3.62/cwt, feedstock cost for alcohol made from potatoes would be between $2.59 and $3.62/gallon.

There were no studies found in which potatoes were used as a feedstock for fuel alcohol production. The physical procedures for making fuel alcohol from potatoes would be the same as for the dry milling process with corn, except for the first two steps. For corn, these steps are to mill and gelatinize the kernals, whereas for potatoes, these steps would be to pulp the tubers and dilute them with water.

The major difference in producing alcohol from the two crops, however, is that the beer from potatoes has a lower alcohol content than that from corn. Therefore, a larger volume of potato beer must be manufactured and distilled per time period to attain the same output of fuel alcohol as one would achieve using corn feedstock. It is estimated (roughly) that the processing of this larger volume of potato beer would cause an increase in operating costs of roughly 20% over that of corn beer, for each gallon of alcohol produced.

Another difference in <u>net</u> production costs between the two feedstocks appears in the credit for the feed byproduct. The feed byproduct credit for corn ($.30/gallon of alcohol) is largely due to the byproduct's high protein content, which makes it a good supplement in livestock rations. Since potatoes have about 85% of the protein content of corn on a per gallon of alcohol basis (USDA, 1980b), its feed byproduct credit is assumed to be about 85% of that for corn--or $.26/gallon of alcohol.

With the basic procedures for manufacturing fuel alcohol from potatoes being similar to those for corn, one can assume that the fixed costs would be similar, also, while operating costs would be higher, as described above. Using the SDSU data presented earlier for small-scale fuel alcohol production from corn, fixed costs for a 175,000 gallon/year plant using potatoes are $.33/gallon. The addition of operating costs and feedstock costs, under the assumptions stated, results in total costs of between $3.93 and $4.96/gallon for a plant of this size. After subtracting the byproduct credit of $.26/gallon, these costs are reduced to between $3.67 and $4.70/gallon.

Using potatoes for alcohol production in LDCs would likely be at least as costly as indicated by the figures above, and more costly in certain countries. Table 4-4 shows these cost estimates for alcohol plants located in LDCs categorized as low, medium, and high cost.

The lowest production costs shown in Table 4-4 are $3.67 to $4.70/gallon. Costs rise as one looks at medium and high cost countries. Production costs for "medium cost countries" range from $3.75 to $4.78/gallon. For "high cost countries", this range is from $3.96 to $4.99/gallon.

As was the case with rice, the high cost of potatoes as a feedstock causes fuel alcohol production costs to be quite high. This would seem to eliminate potatoes as an economically viable source of fuel alcohol in many countries.

5. Cassava

There has been much written recently on the potential of using cassava as a feedstock for fuel alcohol production. This has been due

Table 4-4. Estimate of Costs of Producing Fuel Alcohol in LDCs and the U.S. from Potatoes.

Country Type	Alcohol Plant 1/
	$/gallon
Low Cost Countries and the U.S.	$3.67 - $4.70
Medium Cost Countries	$3.75 - $4.78
High Cost Countries	$3.96 - $4.99

1/ The plant is assumed to produce 175,000 gallons of 185 proof alcohol annually (Hoffman and Dobbs). The range in costs represents a range in per hundredweight alcohol yield, from 1 to 1.4 gallons/cwt (Doney; Hanway and Harlon).

to the reported adaptability of cassava to many climates and soil types. This adaptability has fostered the idea that cassava can be grown on marginal lands not yet in food production. Therefore, it might be argued that it could be grown specifically for fuel and not crowd out land used to grow food crops.

This idea may well have merit in LDCs, since, at present, nearly all of the world's cassava production takes place in those countries (FAO, 1981a). However, in at least some LDCs, cassava is one of the main food staples.

Because cassava is not grown in the U.S., there is no market price to indicate the cost of cassava as an input into the alcohol production process. However, there are several articles in which the cost of obtaining the raw cassava has been estimated.

The first article (Florida Engineering Society) contains some facts on cassava and its potential as an alcohol fuel crop in Florida. The article states that (at that time, July 1979) Brazil had opened a 60,000 L/day alcohol fuel plant using cassava as a feedstock. The cassava roots were reported to cost $14.85/ton. Total costs of producing alcohol were estimated to be $1.43/gallon. Indexed to 1981, these costs become $17.52/ton of cassava and $1.60/gallon of alcohol.

Costs of growing cassava in the Philippines were reported in a 1981 study completed by the Institute of Energy Economics of Japan. According to this study, the cost of planting, harvesting, and transporting cassava to place of storage was $13.64/ton.

A study by McClure and Lipinsky estimated the cost of growing cassava in Brazil to be $7.78/ton in 1971. Through indexing, this cost is converted to be $20.23/ton in 1981 costs. The McClure-Lipinsky study did not give any total cost figures for alcohol production from cassava.

An article by Cecelski and Ramsay drew on data from other sources in estimating costs of ethanol production from various feedstocks. Cassava as a feedstock was estimated to cost $.87/gallon of ethanol produced. In addition, capital and non-feedstock operating costs equaled $.63/gallon. A $.06/gallon feed byproduct credit was estimated, leaving a total net production cost of $1.44/gallon of alcohol produced. These cost data were in 1975 dollars, and would be equal to $1.42/gallon for the cassava feedstock, $.85/gallon in processing costs, and $.08/gallon for the feed byproduct credit in 1981 dollars. Thus, net production costs in 1981 dollars would be $2.19/gallon.

In none of the above studies was the alcohol yield per unit of cassava noted, although it was implied in the Florida Engineering Society article. Two other studies do make such estimates, however. These estimates range from 37.3 gallons of alcohol/ton of cassava (Ueda, et al.) to 43.3 gallons/ton (Kosaric, et al.). Combining these alcohol yield estimates with the cost estimates for growing cassava for alcohol production from the Florida study, the Japanese study, and the McClure-Lipinsky study results in a range of cassava feedstock costs of from $.32 to $.54/gallon of alcohol (in 1981 terms). By comparison, the Cecelski-Ramsay study put cassava feedstock costs at $1.42/gallon (adjusted to 1981 prices), but that study did not state the assumptions about either per unit raw cassava cost or alcohol yield from cassava.

Table 4-5 combines the data on alcohol production from cassava according to the general range of cost estimates for the process. As with the other feedstocks discussed previously, the cost estimates for "low cost countries" represent estimated costs for alcohol production from cassava for both low cost LDCs and the U.S. The "medium" and "high" cost country estimates refer to the LDCs.

As can be seen in Table 4-5, the cost estimates for producing fuel alcohol from cassava look quite favorable in plant A in comparison to other feedstocks examined so far. Per gallon costs range from only $1.09/gallon in "low cost countries" to a high of $2.54/gallon in "high cost countries".

Plant B shows the cost of producing fuel alcohol in a plant that produces 175,000 gallons of 185 proof alcohol annually. The processing costs for this plant are taken from the SDSU study referred to in the previous analyses of other starch feedstocks. Although the SDSU plant was designed to dry mill corn feedstock, the same general equipment and procedures could be used in handling cassava, except for the initial feedstock preparation step. For corn, this was milling and gelatinizing, while for cassava, the initial preparation step would be to cut, pulp, and mix with water. Therefore, no significant difference would be expected in the level of fixed costs for a small plant using cassava as a feedstock compared to one using corn. However, some differences in operating costs would be expected.

As was the case with potatoes, beer made from cassava has a lower alcohol content than beer made from corn. This means processing a larger volume of cassava beer compared to corn beer to reach an equal

Table 4-5. Estimate of Costs of Producing Fuel Alcohol in LDCs and the U.S. from Cassava.

Country Type	Plant A[1/]	Plant B[2/]
	-----$/gallon-----	
Low Cost Countries and the U.S.	$1.09 - $2.19	$1.58 - $1.80
Medium Cost Countries	$1.19 - $2.29	$1.66 - $1.88
High Cost Countries	$1.44 - $2.54	$1.87 - $2.09

1/ The fixed and variable costs (other than feedstock cost) making up this cost estimate are for a plant of unspecified size producing alcohol that is assumed to be 200 proof (Cecelski and Ramsay). The range in costs represent a range in per ton alcohol yield of 37.3 to 43.3 gallons (Ueda, et al.; Kosaric, et al.). The range in per gallon costs is also affected by different raw cassava cost estimates. These range from $1.42/gallon (for feedstock alone) (Cecelski and Ramsay) to per ton of feedstock estimates of $13.64 to $20.28 (Institute of Energy Economics of Japan; McClure and Lipinsky). An $.08/gallon byproduct credit is assumed (McClure and Lipinsky).

2/ Plant B is assumed to produce 175,000 gallon of 185 proof alcohol annually (Hoffman and Dobbs). The range in per gallon costs is due to a range in per ton of feedstock alcohol yield of 37.3 to 43.3 gallons (Ueda, et al.; Kosaric, et al.). The range in per gallon costs is also affected by a range of raw cassava cost estimates of $13.64 to $20.23/ton (Institute of Energy Economics of Japan; McClure and Lipinsky). An $.08/gallon byproduct credit is assumed (McClure and Lipinsky).

annual alcohol output. The handling and processing of this larger volume is assumed to cause a 20% increase in operating costs per gallon of alcohol produced from cassava beer over the operating costs per gallon of alcohol produced from corn beer. Taking this into account, total production costs in plant B were estimated to range from a low of $1.58/ gallon of alcohol in "low cost countries" to a high of $2.09/gallon for alcohol produced in "high cost countries".

There is potential for reducing the cost of the raw cassava feedstock, if research on the crop is expanded. Up to now, there has been very little production of cassava in developed countries.

In LDCs, there is competition for cassava as a foodstuff. However, it may be possible to have expanded production of cassava on marginal lands not now being used intensively for food production. The better land could then be reserved for other crops such as corn, wheat, rice, etc.

6. Sweet potatoes

Sweet potatoes, like most tubers, are most commonly used as a source of human food. It is a common food in many less developed countries, where 98% of the world's production takes place (FAO, 1981a). However, there are enough sweet potatoes grown in the southeastern U.S. for a U.S. sweet potato market to exist. The average price U.S. farmers received for sweet potatoes from 1979 through 1981 was $12.07/cwt. (USDA, 1980 to 1982).

At that price, and given the fact that between 1.71 and 2.33 gallons of alcohol can be produced from each 100 pounds of sweet potatoes (USDA, 1980b; "Production Per Acre Equation"), the alcohol feedstock cost from sweet potatoes would be between \$5.18 and \$7.06/gallon. The protein content per gallon of alcohol of sweet potatoes is about 39% of that of corn (USDA, 1980b). Therefore, the feed byproduct credit is assumed to equal 39% of that of corn, or about \$.12/gallon of alcohol.

Thus, even after adjusting for the byproduct credit, the alcohol feedstock cost using sweet potatoes grown in the U.S. would be very high. However, a study done by the Institute of Energy Economics in Japan estimates the cost of growing sweet potatoes in the Philippines to be much lower than the price paid for them in the U.S. This cost was estimated to be \$16.40/ton, or only \$.82/cwt. The market price for sweet potatoes in the Philippines was not stated, but if it were to reflect the costs of growing the sweet potatoes, then the price an alcohol producer would expect to pay for sweet potato feedstock would be around \$.82/cwt. This would be equivalent to between \$.35 and \$.50/gallon of alcohol produced.

In Table 4-6, the sweet potato feedstock costs have been combined with the processing costs of the aforementioned SDSU alcohol plant, which has an annual output of 175,000 gallons. Sweet potatoes would be processed in the same manner as the other tubers discussed (dry milled) and, therefore, the assumptions concerning fixed and variable costs associated with the processing of potatoes and cassava are also applied here.

The lowest production cost shown in Table 4-6 is \$1.57/gallon. This figure represents production costs for "low cost" LDCs and for the U.S. under the assumption that the cost of growing sweet potatoes in the Philippines accurately reflects the price an alcohol producer would pay

Table 4-6. Estimate of Costs of Producing Fuel Alcohol in LDCs and the U.S. from Sweet Potatoes.

Country Type	Alcohol Plant 1/
	$/gallon-
Low Cost Countries and the U.S.	$1.57 - $8.28
Medium Cost Countries	$1.65 - $8.36
High Cost Countries	$1.86 - $8.57

1/ The plant is assumed to produce 175,000 gallons of 185 proof alcohol annually (Hoffman and Dobbs). The range in per gallon costs represent a range in alcohol yields per hundredweight of feedstock of 1.71 to 2.33 gallons (USDA, 1980b; Researchers Analyze Ethanol Production Costs). The per gallon costs are also affected by the difference in assumed feedstock cost between the U.S. market price, which is $12.07/cwt (USDA, 1980 to 1982), and the cost of growing sweet potatoes in the Philippines, which is $.82/cwt (Institute of Energy Economics in Japan).

for sweet potato feedstock. The $1.57 estimate includes a $.12/gallon food byproduct credit. However, if the alcohol producer were to pay U.S. market prices for sweet potatoes, then alcohol fuel production costs could be as high as $8.28/gallon. For "medium cost countries" and "high cost countries", the ranges in per gallon alcohol production costs are $1.65 to $8.36 and $1.86 to $8.57, respectively.

As with rice and potatoes, the high cost of procuring the raw sweet potatoes renders the use of sweet potatoes for alcohol production economically unsatisfactory in the U.S. in comparison to other, less expensive feedstocks. However, there appears to be the possibility of paying a much lower price for sweet potatoes in at least some countries--as evidenced by the Philippines data. If so, alcohol production from sweet potatoes could be cost competitive with production from other crops in some cases.

7. Yams

At present, little information is available concerning the production of fuel alcohol from yams. In 1978, some 21.5 million metric tons of yams were grown in LDCs (Goering). However, no information was found concerning the selling price of yams, the cost of growing yams, or the cost of processing yams into alcohol. Some data on crop yields and possible alcohol yields per ton of yams were cited in an earlier section of this report.

Since yams have nutrient characteristics similar to sweet potatoes and are also used for human food consuption, it is probable that the per unit cost of yams to the alcohol producer would be similar to that of sweet potatoes. If so, the findings for sweet potatoes may have some relevance for yams, as well. We did note in an earlier section, however, that the alcohol yield per ton of feedstock may be lower for yams than for sweet potatoes.

B. Sugar crops

The use of sugar crops for processing into alcohol has one potential advantage over the use of starch crops in that the cooking stage used to convert starch into sugar for fermentation can be eliminated. As with the starch crops, however, the two most important factors in terms of economic feasibility continue to be the raw feedstock cost and the per unit alcohol yield from the feedstock. The following section provides an examination of these factors and total alcohol fuel production costs for producers in the U.S. and in LDCs for five sugar crops: (1) sugar cane, (2) sweet sorghum, (3) sugar beets, (4) fodder beets, and (5) Jerusalem artichokes.

1. Sugar cane

Sugar cane is considered to be, potentially, one of the best feedstocks for fuel alcohol production, particularly in tropical and subtropical regions where per hectare yields are high. In fact, Brazil has made alcohol production from sugar cane a part of government policy which has been pursued since 1975 (Roy). Numerous analyses concerning the cost of producing fuel alcohol from sugar cane have been done. Because there has been a relatively large amount of research done with sugar cane, and because sugar cane is not adapted to growth in the Northern Plains region of the U.S., this report will only briefly summarize the results of a few of these studies.

Sugar cane feedstock costs per gallon of alcohol produced are dependent on the market price of sugar cane and on the alcohol yield from sugar cane. Estimated yields of alcohol from sugar cane vary according to the source, but are in the general range of 15 (Bagbey) to 20 gallons (Kampen)/ton.

The U.S. market price for sugar cane experienced some fluctuation from 1979 through 1981, but showed an overall average of $29.80/ton for that time period (USDA, 1980 to 1982). Using the above alcohol yields, this translates into a feedstock cost of $1.49 to $1.99/gallon of alcohol produced. This ignores, for the moment, any byproduct credit. That feedstock cost is used in our analysis; however, some sources have noted that the U.S. price is somewhat higher than the world price (Roy) and, therefore, that sugar cane feedstock costs may be lower in some LDCs.

Estimates of the cost of processing sugar cane into alcohol can be found in several sources. In a study using 1977 data for U.S. sugar cane production, James estimated this cost to be $.61/gallon, which is $.82/gallon if adjusted to 1981 price levels. Combining feedstock costs with processing costs results in total costs of between $2.31 and $2.81/gallon. No mention was made of a credit for bagasse or for any feed byproduct.

Another study (Celis U., et al.) estimated the cost of producing anhydrous alcohol in Costa Rica to be approximately $1.96/gallon (adjusted to 1981 dollars). Hydrous alcohol costs were estimated to be $1.80/gallon (in 1981 dollars). Of that total cost, the sugar cane feedstock was estimated to be $1.03/gallon of anhydrous alcohol and $.97/gallon of hydrous alcohol. Credits for bagasse or feed byproducts were not included in the Celis U., et al. estimates.

Cecelski and Ramsay provide three cost estimates of producing alcohol from sugar cane. Their figures are presented in 1975 dollars, which have been converted to 1981 dollars, by indexing, in this report. The first estimate put processing costs (capital and operating costs <u>not</u> including feedstock cost, <u>but including</u> bagasse credit) at \$.54/gallon. A byproduct credit of \$.08/gallon was provided for, also. The addition of our assumed cane feedstock costs based on U.S. market prices would result in total costs of \$1.95 to \$2.45/gallon of alcohol produced, after adjusting for the \$.08 credit.

The second Cecelski and Ramsay estimate indicated processing costs of \$.88/gallon. An \$.08/gallon byproduct credit was again also assumed. Thus total costs, including raw feedstocks at U.S. prices, would be in the range of \$2.29 to \$2.79/gallon using these data.

Processing costs using sugar cane feedstock were estimated to be \$.80/gallon of alcohol in the third Cecelski and Ramsay estimate. No byproduct credit was assumed in this third instance. Therefore, the total costs of purchasing sugar cane at U.S. prices and processing it into alcohol using this processing cost estimate would be between \$2.29 and \$2.79/gallon of alcohol.

The last study reviewed used 1978 cost estimates (SEIS). These estimates, updated to 1981, showed processing costs of converting sugar cane into 190 proof alcohol to be \$1.07/gallon--including a credit for bagasse as boiler fuel. The authors assumed that the plant would produce 25 million gallons of ethanol annually. Total production costs for this plant, including feedstock costs, would equal \$2.56 to \$3.06/gallon of alcohol.

Table 4-7 shows the results of each of the previous studies, for comparison purposes. The "low cost countries" cost estimates represent expected costs in both the U.S. and in LDCs with well-developed fuel alcohol production technologies.

The data in Table 4-7 indicate that alcohol production costs from sugar cane feedstock are relatively high in comparison to certain other feedstocks. The lowest cost estimates for the U.S. and "low cost" LDCs range from $1.80 to $3.06/gallon, depending on alcohol yield and on type or size of plant from which the estimate is taken. For "high cost" LDCs, these estimates are as high as $3.63/gallon. The reason for the relatively high production costs is primarily the high sugar cane feedstock cost. However, as noted in the Costa Rican study, sugar cane feedstock costs may be lower in some LDCs than is reflected in most of Table 4-7. The Costa Rican feedstock cost is included in Plant B of Table 4-7, whereas U.S. sugar cane prices are reflected in the other cost data contained in that table.

2. Sweet sorghum

Sweet sorghum has been produced in the U.S. on a limited scale for production of table syrup but has recently come under examination as a potential feedstock for fuel alcohol production (SERI, 1982). Because such a small amount of sweet sorghum is produced in the U.S., little data concerning alcohol yield from sweet sorghum or the cost of producing sweet sorghum are available. No major markets exist for sweet sorghum from which an established price can be derived to determine sweet sorghum feedstock costs.

Table 4-7. Estimate of Costs of Producing Fuel Alcohol in LDCs and the U.S. from Sugar cane.

Country Type	Plant A[1/]	Plant B[2/]	Plant C[3/]	Plant D[4/]	Plant E[5/]	Plant F[6/]
			-----$/gallon[7/]-----			
Low Cost Countries and U.S.	$2.31 - $2.81	$1.80 - $1.96	$1.95 - $2.45	$2.29 - $2.79	$2.29 - $2.79	$2.56 - $3.06
Medium Cost Countries	---	---	$2.01 - $2.51	$2.45 - $2.95	$2.43 - $2.93	$2.72 - $3.22
High Cost Countries	---	---	$2.16 - $2.66	$2.85 - $3.35	$2.79 - $3.29	$3.13 - $3.63

1/ The plant size and the proof of alcohol were not given. No byproduct credit was given. Estimates for medium and high cost LDCs could not be made because total costs were not broken down into fixed and variable costs (James).

2/ The plant size was not given. The $1.80 figure refers to hydrous alcohol, while the $1.96 figure refers to anhydrous alcohol. Estimates for medium and high cost LDCs could not be made because total costs were not broken down into fixed and variable costs. No byproduct credit was included. Feedstock costs were $1.03/gallon for anhydrous alcohol and $.97/gallon for hydrous alcohol and represent sugar cane feedstock grown in Costa Rica (Celis U., et al.).

3/ The plant size and the proof of alcohol were not given (Cecelski and Ramsay). A credit for bagasse was included in net costs, but the amount was unspecified. A byproduct credit of $.08/gallon was also included.

4/ The plant size and the proof of alcohol were not given (Cecelski and Ramsay). A credit for bagasse was included in net costs, but the amount was unspecified. A byproduct credit of $.08/gallon was also included.

5/ The plant size and the proof of alcohol were not given (Cecelski and Ramsay). A credit for bagasse was included in net costs, but the amount was unspecified. A byproduct credit of $.08/gallon was also included.

6/ Plant F is assumed to produce 25 million gallons of 190 proof annually (SEIS). An $.11/gallon credit for bagasse was included.

7/ The range in costs for each plant, except Plant B, represents a range in per ton alcohol yield of between 15 and 20 gallons (Bagbey; Kampen). Per ton cost is based on the U.S. sugar cane market for all plants except Plant B.

Most available studies estimating alcohol yield from sweet sorghum are based largely on theory, and the tonnage yields of sweet sorghum are based primarily on experiment plots. Estimated alcohol yields from sweet sorghum can range from 194 (McClure and Lipinsky) to 654 (Ricard, Martin, and Cochran) gallons/acre.[4/]

Per acre costs of producing sweet sorghum have been derived here from several sources. A California study (Hills, et al., 1983) estimated irrigated sweet sorghum production costs to be \$789/acre, including a \$50/acre return to the farmer. That study estimated alcohol yields of between 435 and 577 gallons/acre, which translated into a sweet sorghum feedstock cost of between \$1.37 and \$1.81/gallon of alcohol.

A study reviewed in the CRC Handbook of Biosolar Resources (McClure and Lipinsky) estimated 1978 dryland sweet sorghum production costs for the midwestern U.S. to be approximately \$347/acre. Indexed to 1981, these production costs would be \$475/acre. In the study referred to, sweet sorghum yield was approximately 19.4 tons of stalk/acre. Assuming an alcohol yield of 10 gallons/ton of stalk (the same yield reported in 1983 by Hills, et al.) sweet sorghum feedstock costs per gallon of alcohol produced would be \$2.45.

Two other studies examined the total costs of processing sweet sorghum into fuel alcohol. The first study, by Meo and Sachs, used 1980 to 1981 secondary data to estimate alcohol production costs from irrigated sweet sorghum in California. They assumed an alcohol plant which would produce 50,000 gallons of 190 proof alcohol annually. Using a 15%

[4/]The high end of this range exceeds the high end of the probable range cited earlier in this report.

amortization rate for capital equipment, they estimated total production costs (including feedstock) of \$1.65/gallon of alcohol. This included a \$.14/gallon credit for the feed byproduct. The sweet sorghum yield per acre, alcohol yield per ton of sweet sorghum, and the per acre cost of producing sweet sorghum were not given.

The other analysis (SEIS) assumed an alcohol plant producing 50 million gallons of 200 proof alcohol annually using both sweet sorghum and corn as feedstocks. Although not mentioned in the other studies, another feedstock may have to be used in conjunction with sweet sorghum in many regions in order to keep the alcohol plant in operation over a substantial portion of the year. There are some difficulties in storing sweet sorghum for lengthy time periods.

The SEIS study does, however, estimate total processing costs for an alcohol plant using sugar crops only. These costs, not including feedstock cost, were \$.40 to \$.73/gallon of alcohol in 1978, including a \$.09/gallon credit for the use of the bagasse as boiler fuel. On a 1981 basis, these costs would be \$.50 to \$.90/gallon, net of an \$.11/gallon bagasse credit.

Sweet sorghum feedstock costs vary according to geographic area and according to whether or not irrigation is used. Using the range of feedstock costs already cited (\$1.37 to \$2.45/gallon), total alcohol production costs, based on the SEIS processing cost data, would be between \$1.87 and \$3.35/gallon.

Data from the previously cited SDSU study can also be used to estimate the cost of converting sweet sorghum into fuel alcohol. The SDSU plant was built to utilize starch feedstocks, especially corn, in a dry milling process. However, with some adjustments in the physical plant and in operating procedures, it is possible that sugar crops could also be processed in that type of facility.

When using sugar crops such as sweet sorghum, some new capital equipment might be needed to chop the sweet sorghum into pieces. However, the need for a hammermill may be eliminated. Similarly, sugar crop conversion to alcohol might require a different fermentor (i.e., solid phase or continuous diffusion), however, some of the fermentation tanks used for corn would possibly not be needed. Because of these and other unknown, but possibly offsetting, differences in plant structure and costs, we assume first that the costs of processing corn into alcohol (not including feedstock cost) in a plant similar to that at SDSU would also apply to the cost of processing sweet sorghum and other sugar crops into alcohol.[5/]

Processing cost data from the SDSU research were available for a plant that could theoretically produce 175,000 gallons of 185 proof alcohol annually. The processing costs from this plant were estimated to be $1.17/gallon of alcohol (Hoffman and Dobbs). Combining this with our estimated sweet sorghum feedstock costs of $1.37 to $2.45/gallon results in total costs of $2.54 to $3.62/gallon. However, a byproduct credit of $.12/gallon is also assumed, thereby reducing per gallon costs of alcohol made from sweet sorghum in such a plant to from $2.42 to $3.50.[6/]

[5/] The SDSU plant data were not applied to alcohol production from sugar cane because of the large amount of research already completed for that feedstock.

[6/] The $.12/gallon credit is an average of the $.11/gallon credit found in the SEIS study and the $.14/gallon credit found in the Meo and Sachs study.

A summary of the range of costs reported in these studies is presented in Table 4-8. The lowest cost estimates of \$1.65 to \$3.50/gallon represent costs of alcohol production from sweet sorghum in the U.S. and in "low cost" LDCs. "High cost country" alcohol producers could expect production costs in the range of \$2.18 to \$4.06/gallon.

Whether estimates are on the lower or the upper end of the range depends primarily on the sweet sorghum feedstock cost, which, in turn, depends a great deal on geographic location and irrigation usage. Higher raw sweet sorghum yields were reported for producers climate of California who used irrigation than for midwestern U.S. sweet sorghum producers not using irrigation. The higher yields corresponded with lower per unit sweet sorghum production costs, which, in turn, provided for a lower feedstock cost per gallon of alcohol. It should be noted, however, that most sweet sorghum yield data are from experiments. Much research remains to be done to determine sweet sorghum yields under different soil and climatic conditions. Methods of harvesting, storing, and processing sweet sorghum also need further evaluation before the economic feasibility of processing sweet sorghum into alcohol can be ascertained with confidence.

Some recent, unpublished work done at SDSU resulted in preliminary estimates of about \$1.80/gallon in costs for producing alcohol from sweet sorghum in a small-scale plant. More detailed research is needed, however.

3. Sugar beets

The sugar beet is a crop already grown in the midwestern region of the U.S. for crystal sugar production. Its high sugar content also

Table 4-8. Estimate of Costs of Producing Fuel Alcohol in LDCs and the U.S. from Sweet Sorghum.

Country Type	Plant A[1/]	Plant B[2/]	Plant C[3/]
		-----$/gallon-----	
Low Cost Countries and the U.S.	$1.65	$1.87 - $3.35	$2.42 - $3.50
Medium Cost Countries	$1.80	$1.97 - $3.55	$2.50 - $3.58
High Cost Countries	$2.18	$2.23 - $4.06	$2.71 - $3.79

1/ Plant A is assumed to produce 50,000 gallons of 190 proof alcohol annually. The sweet sorghum yields were attained under irrigation in California. The authors did not explicitly state the yields and growing costs for sweet sorghum (Meo and Sachs).

2/ Plant B is assumed to produce 50 million gallons of 200 proof alcohol annually. An $.11/gallon credit for bagasse is included (SEIS). The range in cost estimates is due to different sweet sorghum yields and production costs under two different circumstances. The lowest cost estimate comes from sweet sorghum grown in California using irrigation. The cost of growing sweet sorghum there was estimated to be $789/acre, with an alcohol yield ranging from 435 to 577 gallons/acre (Hills, et al., 1983). The highest cost estimate for growing sweet sorghum comes from sweet sorghum grown in the midwestern U.S. without irrigation. Per acre costs were estimated to be $475/acre (McClure and Lipinsky). Alcohol yield was assumed to be 10 gallons/ton of stalk or 194 gallons/acre (Hills, et al., 1983). Fixed costs of the alcohol plant also ranged from $.41/gallons to $.81/gallons (SEIS).

3/ Plant C is assumed to produce 175,000 gallons of 185 proof alcohol annually (Hoffman and Dobbs). The range in cost estimates is due to the range in estimates of sweet sorghum production costs per acre, from $475 to $789/acre, with alcohol yields varying from 194 to 577 gallons/acre for each cost, respectively (McClure and Lipinsky; Hills, et al., 1983). A $.12/gallon credit for bagasse was assumed (SEIS; Meo and Sachs).

makes it a potential feedstock for fuel alcohol production. The sugar beet differs from sugar cane and sweet sorghum in that its sugar is stored in roots instead of in stalks. This means that the initial preparation stages for converting sugarbeets into alcohol will differ from those used in preparation of stalk sugar crops. However, we assume here that these differences in preparation do not cause major differences between the costs of processing sugar tubers into alcohol and the costs of processing sugar stalks into alcohol.

The cost of sugar beet feedstock to the alcohol producer is assumed equal to the price sugar beet farmers receive from raw sugar manufacturers. The average sugar beet price in the U.S. from 1979 though 1981 was \$36.77/ton (USDA, 1980 to 1982).

Alcohol yields from sugarbeets have been estimated to be between 20.3 (SERI, 1980) and 27 (Hanway and Harlon) gallons/ton. Therefore, sugar beet feedstock cost, assuming a price of \$36.77/ton of sugar beets, would be in the range of \$1.36 to \$1.81/gallon of alcohol produced.

The costs of processing sugar beets into fuel alcohol have been estimated in at least two studies. Doney put processing costs at \$.60/gallon of alcohol in 1979, with a feed byproduct credit of \$.25/gallon. In 1981 dollars, this processing cost would be \$.67/gallon, and the feed byproduct credit would be \$.28/gallon. Total costs of producing alcohol from sugar beets using data from the Doney study would range from \$1.75 to \$2.20/gallon when feedstock costs net of the feed byproduct credit are added to the other fixed and operation costs.

In another study (Gallian), the cost of converting sugar beets to alcohol was also estimated to be \$.60/gallon in 1979. The feed byproduct credit, however, was only \$.11/gallon in that study. After adding in feedstock costs, total alcohol production costs net of the feed byproduct credit in that study were between \$1.91 and \$2.36/gallon of alcohol, in 1981 dollars.

Processing costs for converting sugar beets to alcohol were also derived from the SDSU study (based on corn) mentioned in the sweet sorghum section. The operating procedures and capital equipment of the alcohol plant described in the SDSU study would need to be adjusted to handle sugar beets, but we assume here that no significant changes in operating or capital costs would be involved.

The SDSU alcohol plant (producing 175,000 gallons of 185 proof alcohol annually) had annual fixed and operating costs, not including feedstock costs, of \$1.17/gallon. With sugar beet feedstock costs of between \$1.36 and \$1.81/gallon, total costs for this size and type of alcohol plant would be between \$2.53 and \$2.98/gallon. Assuming a byproduct credit of \$.20/gallon[7/], total costs net of the byproduct credit would be from \$2.33 to \$2.78/gallon.

The cost data presented in this discussion have been condensed into the first row of Table 4-9, and are assumed to apply to alcohol production in the U.S. and "low cost" LDCs. Where fixed cost data existed, estimates of these costs were made for alcohol plants located in "medium cost" and "high cost" LDCs, as well.

[7/] The \$.20/gallon figure is the average of the sugar beet byproduct credits shown in the Doney and Gallian studies.

Table 4-9. Estimate of Costs of Producing Fuel Alcohol in LDCs and the U.S. from Sugar Beets.

Country Type	Plant A[1/]	Plant B[2/]	Plant C[3/]
		-----$/gallon-----	
Low Cost Countries and the U.S.	$1.75 - $2.20	$1.91 - $2.36	$2.33 - $2.78
Medium Cost Countries	---	---	$2.41 - $2.86
High Cost Countries	---	---	$2.62 - $3.07

1/ The annual output and alcohol proof of plant A is unknown (Doney). The range is due to a range in per ton alcohol yield estimates of between 20.3 (SERI, 1980) and 27 (Hanway and Harlon) gallons/ton. Processing costs were not broken down into fixed and variable costs; therefore, estimates for medium and high cost LDCs could not be made.

2/ The annual output and alcohol proof of plant B is unknown (Gallion). The range in costs is due to a range in per ton alcohol yield estimates of between 20.3 (SERI, 1980) and 27 (Hanway and Harlon) gallons/ton. Processing costs were not broken down into fixed and variable costs; therefore, estimates for medium and high cost LDCs could not be made.

3/ Plant C is assumed to produce 175,000 gallons of 185 proof alcohol annually (Hoffman and Dobbs). The range in costs is due to a range in per ton alcohol yield estimates of between 20.3 (SERI, 1980) and 27 (Hanway and Harlon) gallons/ton.

As shown in the table, per gallon costs range from a low estimate of $1.75 in plant A for "low cost" LDCs and the U.S. to a high of $2.78 for this group of countries in plant C. For "high cost" LDCs, costs of producing alcohol fuel from sugar beets are expected to range from $2.62 to $3.07/gallon. As with many of the other feedstocks discussed, if alcohol producers must pay the "food usage" price for sugar beets, the cost may be too high for economical fuel alcohol production. On the other hand, import restrictions on sugar probably cause the market price of sugar beets to exceed what a free market cost of production would be. Thus, if sugar beets were grown as an energy crop, costs to alcohol producers for the feedstock might be lower than those used in our economic calculations here.

4. Fodder beets

Because of their very high fermentable sugar content, fodder beets have potential to become an economical feedstock for fuel alcohol production. At present, however, fodder beets are not grown in large quantities. Therefore, data concerning fodder beet yields and alcohol yields from fodder beets are based on preliminary experimental trials.

One study presenting such data was completed in 1983 (Hills, et al., 1983). Fodder beets were grown on an experimental basis in Yolo County, California under irrigated conditions. Fodder beet production costs were estimated to be $912/acre, including a $50/acre charge representing return to the farm operator. Estimated per acre alcohol yields ranged from 611 to 811 gallons.[8/] Thus, fodder beet feedstock costs in this study were between \$1.12 and \$1.49/gallon of alcohol.

A study done in New Zealand (Earl) in 1979 resulted in estimated costs of producing 200 proof alcohol from fodder beets under four different levels of annual alcohol output (between 2.7 million and 5.5 million gallons). The fodder beet feedstock was assumed to cost \$80/ODt[9/], and the costs of capital equipment were amortized at 10% over each item's useful life. Depending upon the number of operating hours the plant was assumed to function annually (3,000 to 6,000 hours), total production costs ranged from NZ \$.29 to NZ \$.36/L of alcohol produced. In U.S. dollars[10/], indexed to 1981, those costs would be \$.34 to \$.43/L, or \$1.31 to \$1.65/gallon.

Meo and Sachs analyzed the economic feasibility of using fodder beets for fuel alcohol production (using 1981 data). In their study, they assumed that capital costs (amortized at 15%) would be the same as for an alcohol plant using grains for feedstock.

The alcohol plant was assumed to produce 50,000 gallons of 190 proof alcohol annually. Using fodder beet feedstock, total production costs for a plant of this type were estimated to be \$2.25/gallon of alcohol. This estimate included a credit for a feed byproduct, but the

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[8/] These experimental yields were achieved under irrigated conditions. They are relatively high compared to the alcohol yields reported earlier in this report; those yields reported earlier would represent less than optimal or more average growing conditions.

[9/] ODt = Oven Dried Metric Ton.

[10/] In 1979, New Zealand \$1.00 = U.S. \$1.05 (Earl and Brown).

amount of credit was not stated. Also not shown were the alcohol yields expected from fodder beets.

Although not specifically built to process fodder beets, the alcohol plant described in the SDSU study could be modified to do so. As was the case with sugar beets, such a modification was assumed not to cause significant changes in fixed or operating costs.

The SDSU plant is assumed to produce 175,000 gallons of 185 proof alcohol annually. Capital and non-feedstock operating costs for this plant are estimated to be $1.17/gallon of alcohol produced. Total costs, including the fodder beet feedstock costs estimated in the Hills, et al. study but no byproduct credit, would thus range from $2.29 to $2.66/gallon.

In neither the Meo-Sachs study nor the Earl study was the amount of byproduct credit stated when fodder beets were the feedstock. Fodder beets have roughly the same protein content per ton as sugar beets (Hayes; USDA, 1980b). For simplicity, the fodder beet byproduct credit is assumed here to be equal to that of sugar beets--$.20/gallon of alcohol--even though more fodder beets than sugar beets, by weight, are required to produce a gallon of alcohol. Therefore, the total alcohol production costs in the SDSU plant <u>net</u> of the byproduct credit would be $2.09 to $2.46/gallon.

More recent work on fodder beets at SDSU indicates preliminary cost estimates of around $1.75/gallon, or slightly higher, for alcohol produced from fodder beets using solid-phase fermentation technology in a small-scale plant (Gibbons, Westby, and Dobbs). The byproduct credit in these calculations was $.30/gallon of alcohol. These estimates need verification, however, through more detailed technical and economic studies.

Table 4-10 shows what the costs, from the above studies, might be for LDCs as well as for the U.S. For "low cost" LDCs and the U.S., per gallon costs of ethanol production from fodder beets range from $1.31 in the 2.7 million gallon/year plant to $2.46 in the 175,000 gallon/year plant. For "high cost" LDCs, the available data would suggest a range of alcohol production costs from $2.38 to $2.78/gallon.

5. Jerusalem artichokes

In the past two or three years, enthusiasm for growing Jerusalem artichokes for fuel alcohol production has at times been high in parts of the Dakotas and Minnesota. At present, there is a very limited U.S. market for Jerusalem artichokes. Consequently, information on per acre yields and growing costs for Jerusalem artichokes is based on experimental growing plots and is not yet well-documented for different growing conditions. Information on the costs of converting Jerusalem artichokes into fuel alcohol is even less readily available.

Estimated alcohol yields from Jerusalem artichokes range from 16.8 gallons/ton (Underkofler, McPherson, and Fulmer) to 30 gallons/ton (Sachs, et al.). Falling within that range were yields of 18 to 24 gallons/ton from artichokes grown in Nebraska test plots (University of Nebraska). No data concerning costs of growing Jerusalem artichokes were found. However, as of December 1982, Jerusalem artichokes were selling for seed at $1.20/pound (Walker). Obviously, this level of feedstock cost would be far too high for economical alcohol production

Table 4-10. Estimate of Costs of Producing Fuel Alcohol in LDCs and the U.S. from Fodder Beets.

Country Type	Plant A[1/]	Plant B[2/]	Plant C[3/]
		-----$/gallon-----	
Low Cost Countries and the U.S.	$1.31 - $1.65	$2.25	$2.09 - $2.46
Medium Cost Countries	---	$2.40	$2.17 - $2.54
High Cost Countries	---	$2.78	$2.38 - $2.75

[1/] Plant A is assumed to produce between 2.7 million and 5.5 million gallons of 200 proof alcohol annually (Earl). This range accounts for the range in cost estimates. The fodder beet yields were attained in New Zealand. Estimates for medium and high cost LDCs could not be made because total costs were not broken down into fixed and variable costs.

[2/] Plant B is assumed to produce 50,000 gallons of 190 proof alcohol annually. The fodder beet yields were attained under irrigation in California (Meo and Sachs).

[3/] Plant C is assumed to produce 175,000 gallons of 185 proof alcohol annually (Hoffman and Dobbs). The range in costs is due to the range in estimates of alcohol yield per acre (611 to 811 gallons, under irrigation in California) (Hills, et al., 1983).

($80 to $143/gallon). However, the price of Jerusalem artichokes would drop substantially if producers began to plant the crop in large quantity.

Only one study was found in which the total cost of producing fuel alcohol from Jerusalem artichokes was estimated. That study, by Meo and Sachs, involved an assumed plant with a standard dry milling process, in which 50,000 gallons of 190 proof alcohol would be produced annually. Capital costs were amortized at a 15% interest rate.

Results of the study showed total alcohol production costs of $2.06/ gallon. Credit for a feed byproduct was included in this figure, but the amount was not specified. Cost of the Jersalem artichoke raw feedstock also was not stated, but the cost was clearly far less than the $1.20/pound being paid for Jerusalem artichoke seed in late 1982 in South Dakota.

Cost figures from the Meo and Sachs study have been used to estimate alcohol production costs for low, medium, and high cost LDCs using Jerusalem artichoke feedstock. The costs, estimated using the procedures already established for other crops examined in this chapter, are presented in Table 4-11.

As shown in the table, "low cost" LDC and U.S. alcohol producers might expect costs of about $2.06/gallon, while "medium cost" LDC producers could have costs of $2.21/gallon, and "high cost" LDCs could have costs of $2.59/ gallon. As with the other "non-traditional" crops examined in this report, these cost estimates are preliminary and rough. More detailed research is needed to predict with any confidence the actual cost of producing fuel alcohol from Jerusalem artichokes.

Table 4-11. Estimate of Costs of Producing Fuel Alcohol in LDCs and the U.S. from Jerusalem Artichokes.

Country Type	Alcohol Plant A[1/]
	$/gallon
Low Cost Countries and the U.S.	$2.06
Medium Cost Countries	$2.21
High Cost Countries	$2.59

[1/] The plant is assumed to produce 50,000 gallons of 190 proof alcohol annually. The Jerusalem artichoke yields were attained under irrigation in California (Meo and Sachs).

C. Summary

Presented in this section have been data on costs of using alternative biomass feedstocks to produce fuel alcohol in the U.S. (particularly in the Northern Plains region) and in less developed countries. Twelve crops were examined in the analysis--seven starch crops and five sugar crops.

In every study reviewed for which processing costs were available, the cost of the feedstock was a large component of total alcohol production costs, regardless of the crop being considered. Feedstock costs per gallon of alcohol produced were generally dependent on two factors:

(1) the cost per unit for growing the crop, or the established market price for the crop, and

(2) the alcohol yield per unit of the crop.

If there is a well-established market for a particular crop that already pays farmers a price they consider to be profitable, then an alcohol producer can normally expect to pay at least that price for the crop. Paying a high per unit price for a feedstock may be acceptable if the per unit alcohol yield from that crop is high and processing costs are not especially high. However, if the per unit alcohol yield (or potential yield) is relatively low or even average for one of these crops, then the effect of competing against alternative uses for the crop may be to make the crop too expensive for fuel alcohol production. That situation often occurs for rice and potatoes, as well as for sweet potatoes if they are produced in the U.S. However, sweet potatoes grown in the Philippines may not be as expensive as in the U.S. As shown earlier in the text, the costs of producing fuel alcohol from rice and potatoes are over one and one-half times the cost estimates made for the other crops examined. This is due to the high value attached to them, through the market, as food crops.

The costs of producing fuel alcohol from most of the remaining crops examined are much lower[11/] and, depending upon local gasoline prices and other factors, may well be low enough to make production economically feasible in some countries. However, when selecting one crop as the "best" fuel alcohol crop in terms of the lowest production cost, several considerations must be kept in mind.

Estimates of the costs of producing fuel alcohol from these crops have been made in a very preliminary manner. Many estimates were made with assumptions based on theoretical feedstock and alcohol yields and on untested production procedures. For some crops, little empirical evidence was available with which to make these assumptions. As a result, we have presented a wide range of cost estimates for alcohol production for most of the crops.

When looking at cost estimates for the crops in this study, one must consider the assumptions on which each estimate was based. For example, three of the lowest cost estimates occurred in part because the author of the particular study estimated a byproduct credit significantly higher than that in most of the other studies. This was the case for grain sorghum, in which a $.95/gallon estimated net cost of producing alcohol included a $.52/gallon (1981 dollars) byproduct credit. For the

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[11/] One exception may be yams, for which there were no available cost estimates.

$1.17/gallon estimate using corn feedstock, a byproduct credit of $.47/gallon (1981 dollars) was assumed.

In addition, some cost estimates for producing alcohol from certain feedstocks were made assuming plants that produce as much as 50 million gallons/year. This was done for grain sorghum, corn, and sugar cane. Cost estimates using the other feedstocks were often limited to plants producing 50,000 to 175,000 gallons/year, because of lack of data for larger sized facilities, and because our principal interest in this report is in small-scale plants. Some studies cited gave total alcohol production cost estimates without stating the size of plant assumed.

A summary of the cost estimates for small-scale plants, and some of unspecified size, is presented in Table 4-12. The lowest alcohol production cost occurs when cassava is the feedstock ($1.09/gallon in low cost LDCs and the U.S.). However, the wide variation in estimates suggests that the differences in alcohol production costs between the nine crops with relatively low feedstock costs may not be significant, overall. Depending upon the circumstances, all should perhaps be considered as potential alcohol fuel feedstocks.

As already noted, the per unit cost (or price) of a particular commodity will be a major determinant of its attractiveness as a feedstock for fuel alcohol production. Many times, this price is based on already established alternative uses. It has already been indicated that the market price established for these alternate uses may often eliminate rice and potatoes as economical feedstocks for alcohol production. However, grain sorghum, corn, sugar cane, sweet potatoes, and sugar beets also have established markets as food and feed products. In

Table 4-12. Costs of Producing Fuel Alcohol in LDCs and the U.S. from Various Feedstocks[1/].

Crop	Low Cost Countries and the U.S.	Medium Cost Countries	High Cost Countries
		-----$/gallon-----	
Grain sorghum	$1.66 - $2.09	$1.74 - $2.25	$1.95 - $2.64
Corn	$1.80 - $1.88	$1.88 - $1.96	$2.09 - $2.17
Rice[2/]	$3.57	$3.65	$3.86
Potatoes	$3.67 - $4.70	$3.75 - $4.78	$3.96 - $4.99
Cassava[3/]	$1.09 - $2.19	$1.19 - $2.29	$1.44 - $2.54
Sweet potatoes[4/]	$1.57 - $8.28	$1.65 - $8.36	$1.86 - $8.57
Yams[5/]	---	---	---
Sugar cane[6/]	$1.80 - $2.81	$2.01 - $2.95	$2.16 - $3.35
Sweet sorghum	$1.65 - $3.50	$1.80 - $3.58	$2.18 - $4.06
Sugar beets[7/]	$1.75 - $2.78	$2.41 - $2.86	$2.62 - $3.07
Fodder beets	$2.09 - $2.46	$2.17 - $2.54	$2.38 - $2.78
Jerusalem artichokes[2/]	$2.06	$2.21	$2.59

[1/]Most of the estimates included here are for "small-scale" plants, defined generally as ones that produce less than 1 million gallons of alcohol annually. As noted in some of the other footnotes, however, costs for some plants of "unspecified" size are included.

[2/]Only one estimate of fuel alcohol production costs using these feedstocks was made for each country type.

[3/]The cost figures presented for alcohol production using cassava feedstocks are for a plant of unspecified size. The proof of alcohol is also unspecified.

[4/]The large range of cost estimates is due to the difference in feedstock cost between market prices for sweet potatoes in the U.S. and the cost of growing sweet potatoes in the Philippines, as well as to a range in estimates of alcohol yield from 1.71 to 2.33 gallons/cwt.

[5/]No estimates of fuel alcohol production costs using yam feedstocks were available.

[6/]The cost figures presented for alcohol production using sugar cane feedstocks are for plants of unspecified size. The proof of alcohol is also unspecified.

[7/]The lowest cost figure ($1.75/gallon) for alcohol production using sugar beet feedstocks is for a plant of unspecified size. The proof of alcohol is also unspecified for that estimate.

all but the largest plants, their use as feedstocks for alcohol production may also be questionable on economic grounds.[12/] This relatively high opportunity cost for conventional food and feed crops has caused attention to be given recently to specialized "energy" crops. Some of these might not necessarily compete extensively with food and feed crops for prime land, water, and other extremely scarce inputs.

In the cases of cassava, sweet sorghum, and fodder beets, the price an alcohol manufacturer would pay for raw feedstock has been assumed in this report to be equal to the cost of growing the feedstocks.[13/] For the feedstock to be produced, the net return to the farmer for producing the crop for alcohol production must be greater than the net return for producing that crop or <u>any other</u> crop for <u>any other</u> use (feed, food, etc.) with the same land or other limiting resources. Caution is therefore needed in interpreting the data from this study. For example, sugar beets were valued on the basis of food-related market prices, whereas fodder beets were valued on the basis of their production costs. The sugar from fodder beets also has potential food use, however. Thus, a direct comparison of the fodder beet and sugar beet feedstock costs found in this report could overstate any cost advantage of fodder beets over sugar beets as an alcohol feedstock.

[12/] They are even expensive in the large plants if conservative estimates of byproduct credits are assumed.

[13/] The same holds true for Jerusalem artichokes. However, because so little data were available to estimate the cost of growing Jerusalem artichokes, they are not included in this discussion.

It may be possible for farmers to grow energy crops and to equal or exceed the net returns they received from growing traditional (non-energy) crops and, at the same time, for alcohol producers to obtain feedstocks at affordable prices if one or both of the following should come about:

(1) if the yield of fermentable biomass from cassava, sweet sorghum, or fodder beets could be increased on a per acre basis without proportional increases in growing costs. Under this condition, it may be possible for farmers to accept less money per ton of energy crop but to increase total net returns per acre, due to the increased volume of biomass they would harvest. If the increase in biomass yield is large enough, per acre net returns from producing energy crops may exceed that of producing traditional crops. At the same time, the feedstock cost per gallon of alcohol produced could decline for the alcohol manufacturer.

(2) if the alcohol yield per ton of fermentable biomass from cassava, sweet sorghum, or fodder beets could be increased relative to their present yields without proportional increases in processing costs. Thus, at any given price per unit of biomass, the cost per gallon of alcohol would be reduced.

Of course, the same conditions could be also said to hold true for traditional food and feed crops (corn, sorghum, etc.). However, much more of the agronomic research necessary to achieve such accomplishments has been done for traditional crops than has been done for new, "energy" crops.

In addition to research on increasing biomass and alcohol yields, more detailed research is required to determine processing costs for fuel alcohol made from non-traditional crops. Research on practical harvesting and storage methods for specialized energy crops is also needed.

D. Final remarks

It is obvious from the preceding discussion that there remain many unknowns about alcohol production from the various crops analyzed. Further research is needed to answer many questions. However, the following preliminary general conclusions can be drawn:

(1) There seems to be potential for economic production of fuel alcohol from "energy" crops such as cassava, sweet sorghum, and fodder beets--under some circumstances.

(2) Not enough is known about Jerusalem artichokes at this point in time to draw definite conclusions about its feasibility as a fuel alcohol feedstock.

(3) Because of possible harvesting and storage problems, sweet sorghum does not yet look as attractive for alcohol production as do cassava or fodder beets. Also, in the Northern Plains region of the U.S., the climate may not be as conducive to sweet sorghum as it is to fodder beet production, and cassava is restricted to warmer climates.

(4) Preliminary cost data indicate that small-scale alcohol production from cassava is relatively low cost, at least in some countries, compared to other crops for which cost

estimates were available. Cassava is reported to produce well on marginal soils and in varied tropical and subtropical climates. If so, it may well provide a better return on these lands to farmers than do more traditional crops in those areas. However, cassava is already grown in many LDCs as a food crop.

In examining the data presented in Table 4-12, it appears that cassava would often be the best economic choice for an alcohol fuel feedstock, at least in the tropical or subtropical climates where it can be grown. Total production costs using cassava feedstock are as low as \$1.09/gallon in "low cost" LDCs.

For the Northern Plains region of the U.S., including South Dakota, grain sorghum, corn, sweet sorghum, and sugar beet feedstocks provide for fuel alcohol production at low per gallon costs relative to other feedstocks examined. The lowest per gallon costs using these feedstocks are in the \$1.65 to \$1.80 range.

Per gallon costs using sweet potatoes are in the same range when the sweet potatoes are purchased at the growing cost in the Philippines. However, if they must be purchased at recent U.S. market prices, then the use of sweet potatoes as an alcohol fuel feedstock is definitely not likely to be economical.

The estimates mentioned above were for the U.S. and "low cost" LDCs such as Brazil, where alcohol technology is reasonably well-developed. For "medium cost" LDCs such as Thailand, where costs of constructing plant facilities may be somewhat higher, estimated alcohol production costs for cassava are \$1.19 to \$2.29/gallon. For grain sorghum, corn, sweet sorghum, and sugar beets, the costs range from \$1.74 to \$3.58/gallon. Finally, for "high cost" LDCs such as the Sudan, where construction costs are presumably higher still, alcohol production costs using cassava feedstock are estimated to be between \$1.44 and \$2.54/gallon. For grain sorghum, corn, sweet sorghum, and sugar beet feedstocks, these costs rise to between \$1.95 and \$4.06/gallon.

It should be noted that, although most of the cost data presented in Table 4-12 are for small-scale plants, some are for plants of "unspecified" size (see table footnotes). Thus, appropriate caution should be exercised in making cost comparisons among feedstocks in the table.

Are any of these costs low enough to make alcohol production feasible? Alcohol produced and sold at a price covering the lower cost estimates could be competitively priced relative to 1981 U.S. gasoline prices if it could replace gasoline on a one-to-one basis. However, the substitution ratio for hydrous alcohol is more like 1.5 or 1.6. Alcohol priced at the highest cost estimates certainly would not have been economically competitive with gasoline in the U.S. in 1981, even if it were anhydrous and substitutable on a one-to-one basis.

Generally speaking, gasoline prices are higher in most LDCs than in the U.S. Therefore, it is possible that alcohol priced at the lowest cost estimates would make alcohol production economically viable in some LDCs. Depending upon the local conditions that affect gasoline prices (quantity demanded, gasoline transportation costs, storage costs, etc.), even alcohol priced at some of the medium or higher cost estimates may prove to be economically competitive as a substitute for gasoline in certain LDCs. Of course, the cost of growing crops may also currently be higher in many or most LDCs than we have assumed here. Food prices and, hence, prices of crops that can be used for food, are higher in many LDCs than in the U.S. Therefore, our feedstock cost estimates could be lower than would actually be the case in some LDCs. If so, per gallon alcohol production costs would be higher than we have shown.

V. Food-Fuel Conflicts*

In the U.S., most of the discussion and controversy surrounding alcohol fuels has centered on the economic profitability of alcohol production and on the energy balance achieved through alcohol production. One other issue, which is often overlooked in time of grain surpluses, is the impact on food production and prices of diverting cropland from food production to fuel production. The "food-fuel conflict" issue is of particular importance to countries which are net grain importers. Many of the less developed nations of the world fall into this category.

A. Overview

Depending upon a particular country's national policies and its agricultural and energy production situation, the production of alcohol fuels may provide some national economic benefits. Norman Rask has developed a grid that classifies various countries according to their positions as: (a) surplus agricultural producers, (b) deficit agricultural producers, (c) surplus energy producers, and (d) deficit energy producers. That grid has been reproduced in Figure 5-1.

The countries in the upper lefthand corner of the grid in Figure 5-1 are the ones most likely to favor alcohol fuel production from agricultural products. These countries produce more agricultural commodities than they consume, but consume more energy than they produce.

For these countries, in particular, a policy that encourages the development of an alcohol fuels industry might provide several favorable impacts. First, money formerly funneled to energy exporting countries

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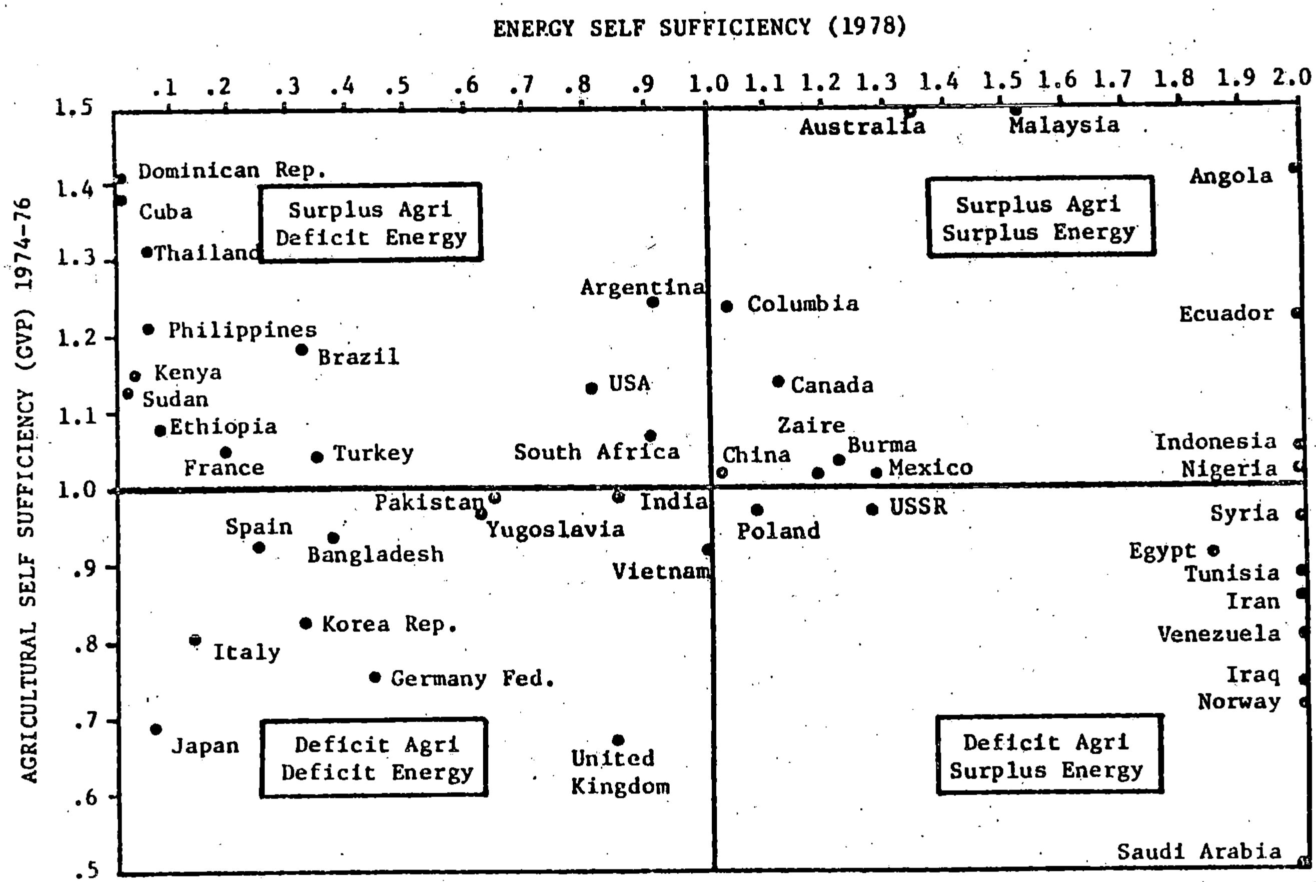
*Principal authors: Randy Hoffman and Thomas Dobbs.

Figure 5-1. Energy and Agricultural Self Sufficiency Characteristics of Selected Countries.



Source: Reproduced from page 2 in Norman Rask, "Food-Fuel Conflicts--The Brazil Case." a paper presented at the 1981 Annual Meeting of the Association for the Advancement of Science, Toronto, Canada, January 1981; Rask's figure is based on FAO data.

would stay at home, improving foreign exchange problems, if any exist. As a result, more money could be available for rural development. In addition, an alcohol fuels industry could provide more rural employment and could also provide higher income for farmers, through higher prices for agricultural commodities.

There could also be several negative impacts associated with such an alcohol fuels policy. The first and foremost could be a reduction in food supply, with a resulting rise in food prices. If crops are used for fuel, then they cannot be fully utilized for food, though some byproducts have potential use as feed or food. Or, if food crops are replaced by energy crops, then the amount of land, fertilizer, water, and other inputs available for food crops is reduced. In either case, the food supply is cut back relative to potential, at least, and food prices are likely to climb. The extent to which they rise in any specific country is dependent on that country's total agricultural production and consumption. However, even if the country in which alchohol fuel production is taking place has a surplus of agricultural commodities, the world supply of food will decrease, causing general rises in food prices in all countries which participate in international agricultural trade.

Cecelski and Ramsay, in a 1981 report, provide data which help to put into perspective the amount of biomass and land area needed to replace conventional liquid fuels in various countries throughout the world. Their data also indicate the possible reduction in acres of food-producing land resulting from significantly expanded alcohol production.

In their study, hypothetical land use requirements to replace conventional liquid fuels with biomass fuels were computed for different countries using sugar cane, sweet sorghum, corn, and cassava as alcohol feedstocks. The results are reproduced in Table 5-1.

The data in Table 5-1 are only illustrative of general relationships between alcohol production and land use, and some of the estimates of crop yields are highly speculative. It was assumed that approximately 1.5 L of alcohol would be required to replace each liter of conventional liquid fuel. This substitution rate represents approximate relative BTU values of conventional fuels and alcohol. The actual substitution rate in any given situation can depend on the type of conventional fuel being replaced, the design of engines, the extent of substitution, and other factors. The authors point out that "some countries with low liquid fuel requirements relative to their available land areas--such as India, Argentina, and Ethiopia--appear, a priori, to be capable of fulfilling their liquid energy consumption from biomass utilizing a relatively small part of their total available arable or forest land..." (Cecelski and Ramsay, p. 1003). Thus, in countries like these, the production of fuel alcohol from biomass may not have a large impact on food production and food prices.

For countries with large liquid fuel consumption relative to their available land--like the United States, Egypt, and Cuba--a significant portion of both their total land area and of their current (1976) arable and permanent croplands would be needed to produce enough alcohol fuel to provide their total liquid fuel needs. This would probably result in

Table 5-1. Hypothetical Land Use Requirements to Replace Liquid Fuels with Biomass Alcohol Fuels.

Ethanol From Agricultural Crops

Feedstock & Country Ethanol	(FAO.1976) Average Yields mt/ha	Alcohol 2/ Production Liters/ha	(UN, 1976) Liquid Fuel Consumption 1976 (mil. liters)	% "Available" 3/ Land Required To Meet 1976 Liquid Fuel Consumption
Sugarcane				
Brazil	46	2990	53923	51-74
Cuba	45	2925	9918	120-160
Dom. Rep.	64	4160	2841	49-100
USA	85	5525	977187	51-150
Egypt	79	5135	12597	130
India	51	3315	24959	5-7
Indonesia	84	5460	22220	4-33
Philippines	49	3185	11791	27-70
Sweet Sorghum 1/				
Ethiopia	52	4044	620	1-2
Nigeria	52	4044	4020	3-6
Sudan	52	4044	2206	1-11
Upper Volta	52	4044	98	0.4-0.6
India	52	4044	24959	4-6
Argentina	52	4044	9894	4-11
USA	52	4044	977187	70-170
Corn				
Kenya	1	340	1668	200-420
Malawi	1	340	164	16-32
Tanzania	1	340	870	10-63
USA	5	1700	977187	170-410
El Salvador	2	680	854	210-290
Argentina	2	680	9894	23-63
Turkey	2	680	18321	83-140
Thailand	2	680	10828	64-140
Cassava				
Cameroon	4	696	420	2-12
Ghana	9	1566	969	18-34
Nigeria	10	1740	4020	6-15
Indonesia	8	1392	22220	17-130
Sri Lanka	5	870	1135	40-98
Thailand	18	3132	10828	14-31
Brazil	13	2262	53923	7-97

1/ Sweet sorghum has not been widely produced commercially; yields are assumed constant (see Fn. 2).

2/ Alcohol production per ton of feedstocks based on reported current yields as follows:

ethanol	L/t
sugar cane, fresh stalks	65
sweet sorghum, fresh stalks (sweet sorghum is not presently widely produced commercially; yields are based on Lipinsky, 1978, projected 1980 yields of 52 t/ha in southern U.S., 6.8 t/ha fermentable sugars; assuming 50 percent conversion into ethanol yields 3.2 t/ha, ethanol = 4,044 L/ha).	78
corn, grain	340
cassava, fresh	174

3/ Lower percentage is of total arable, permanent crop, forest, and woodlands; higher figure is of only currently arable and permanent croplands.

Source: Adapted from Cecelski, Elizabeth and William Ramsay. "Prospects for Fuel Alcohols from Biomss in Developing Countries." Long-Term Energy Resources, Volume II, An International Conference sponsored by the United Nations Institute for Training and Research and Petro-Canada, Marshfield, Massachusetts: Pitman Publishing Inc., reprint ed., Washington, DC: Resources for the Future, Reprint 197, 1982.

a significant reduction in food or feed production and a corresponding rise in prices.

A study done in Costa Rica (Celis U., et al.) used a general equilibrium model to simulate the effects of alcohol fuel production on food production and prices in that country. In the simulation, there were four distilleries available for alcohol production--each capable of producing 36 million liters of alcohol annually from sugar cane feedstocks.

The simulations showed that as the first plant was utilized to full capacity, no displacement of other crops was observed, but new lands were developed for sugar cane cultivation. Rice porducers adopted new technologies that enabled them to produce a larger volume of rice, resulting in lower rice prices. "This phenomenon . . . reflects the fact that through competition for productive resources brought about by sugar production for alcohol, the large rice producers that have investments in machines and processing plants try to improve agricultural production to make more efficient use of scarce resources and to maintain a level of income attractive enough for them to continue the activity" (Celis U., et al., p. 47).

When the second alcohol plant was fully utilized, new lands were again developed for sugar cane cultivation; also, other sugar cane cropland was used to grow sugar cane for alcohol instead of for sugar. This caused an increase in sugar prices. However, corn producers adopted new technologies and increased the volume of corn, resulting in lower corn prices.

As the third alcohol plant was brought into production, more new land was developed for sugar cane production. More of the original sugar cane cropland was switched from cane for sugar production to cane for alcohol production. Rice growers again adopted new technologies, attaining a greater volume of production.

Finally, when the fourth plant came on line (producing a cumulative total of 144 million L of alcohol/year), areas for the majority of crops diminished, resulting in decreases in the food supply. Most crop prices increased, with corn prices rising 45%. The use of resources for cane production forced 6,570 ha that had been previously used for agricultural activities to be left uncultivated. Thus, in this study, production of <u>large</u> volumes of fuel alcohol caused large disruptions in food production and food prices.

In the Costa Rican study, the cost of importing parts and equipment for producing alcohol, inputs for growing more sugar cane, and parts and equipment for distributing and utilizing fuel alcohol resulted in a loss of foreign exchange that exceeded the gain in foreign exchange associated with the reduced imports of petroleum based fuels.

Some researchers, such as Lester Brown (1980b), have hypothesized that using crops for alcohol fuel production would add to the spreading gap in income and quality of life that now exists between rich and poor peoples, especially in the LDCs. He argues that the alcohol fuel produced would be used by the affluent minority in these countries who own automobiles, while the millions of people who already spend the majority of their incomes on food would be faced with even higher food prices.

Brown (1980a) illustrates the effect on food producing resources that alcohol fuel production could have by comparing human grain consumption with automobile grain consumption via the burning of alcohol. Average per capita grain consumption in developing countries is about 400 pounds per year, compared to 1,600 pounds in affluent countries. Based on 1978 average world grain yields, 0.2 acres would be needed to satisfy the grain demands of a typical LDC consumer and 0.9 acres would be needed for the consumer in more affluent countries.

Brown reports that to run a typical American car totally on ethanol would require over 7 tons of grain per year, or about 8 acres of land. An average European car would require less--about 3 tons of grain annually, or just over 3 acres of land. Using gasohol at a 10 to 90 mix to fuel American cars would require 1,460 pounds of grain, or 1.7 acres of land.

Obviously, a policy of energy crop production on a world-wide scale (or even in North America, where much of the world's grain imports originate) would result in substantially reduced acreages for food production.

There are some arguments that energy crops could be grown without competing with food production. These arguments are expressed in one of the following ways:

(1) a particular country has idle (perhaps economically marginal) land that could be put into energy crop production;

(2) if very high yielding energy crops could be developed, then fewer acres of food producing land would be needed for alcohol production.

The argument that idle land can be put into energy crop production has some potential shortcomings. Land that is idle now may be that way because of land tenure systems or various cost factors (lack of roads, drainage, etc.) that make it uneconomical to farm either for food or fuel. Removing those constraints might make the land more economical to expand food production on than to use for fuel production. However, if energy crops can be developed that are adapted to soils and climates which are economically <u>un</u>suited for food crop production, then alcohol fuel production might proceed without diverting land from food production. Avoidance of any food-fuel conflict would also depend on other scarce resources (water, fertilizer, etc.) not being diverted from food production to energy crops on the previously idle land. These other resources may be limited in some absolute sense <u>or</u> available in increased quantities only at higher prices.

The idea of growing energy crops which are very high yielding in terms of alcohol production would seem to provide a plausible scenario in which alcohol could be produced without diverting large portions of land from food production. Thus, there might not be a significant reduction in the food supply. However, there are two opposing arguments to this thought. First, land is not the only resource diverted from crop production when energy crops are produced. High yielding energy crops may require large amounts of fertilizer, water, labor, or machinery that might have to be taken from food crop enterprises. If so, the likely result would be a decrease in food crop yields and an increase in food prices. Second, if energy crops provided a higher net return per hectare than food crops, then what is to stop farmers from diverting their land from food to energy production? This conversion would increase until the resulting rise in food crop prices and fall in energy crop prices provided a new equilibrium between food crop acreage and energy crop acreage--where planting an additional acre to either food or energy crops would provide the same net return. Although the exact point at which this new equilibrium would be reached is unknown, the general outcome would probably be lower food supplies and higher food prices. However, one needs to consider the amount of biomass needed for a country's fuel alcohol program before drawing solid conclusions about impacts on food prices. Depending on the alcohol fuel production targets and on the food deficit-surplus situation in a country, a very high yielding energy crop grown on a relatively small land area might provide the necessary alcohol feedstock amounts without making significant dents in the food supply.

B. Examination of particular crops

We turn now to an examination of how particular crops might fit into the "food-fuel" equation.

Of the starch crops analyzed in this report, all are presently being grown for food or feed somewhere in the world. Therefore, without an expansion in acres or improvement in yields of these crops, their use for alcohol production would certainly cut into existing world food supplies.

One possibility for producing fuel alcohol without having major effects on food production might be to use a crop that is relatively unfamiliar to some parts of the world and upon which little yield improvement research has been done. Among the starch crops, only cassava can be placed in this category.

Cassava is reported to be adaptable to a wide variety of soil and climatic conditions (Rask). Currently, it is grown mainly as a subsistence crop for rural poor in tropical countries (Goering). Obviously, using cassava at present to manufacture alcohol fuel in these countries would cut into the existing local food supply. However, if it could be introduced into new regions where it could be grown on poorer soils (leaving the better soils in their present use for food production), then cassava could possibly serve as an alcohol feedstock without causing a major disruption in food supplies and prices. However, if cassava growth on poor soils requires large amounts of other inputs (fertilizer, water, etc.), then those resources would not be available for food production. Some reports indicate that cassava does not, at present, require modern production inputs (Brown, 1980a).

The production of fuel alcohol from any of the starch crops would also result in protein food or feed byproducts. To the extent that these byproducts provide human food--either directly or through animals--they reduce the food-fuel conflict. They do not eliminate the conflict, however, since the energy portion of these starch crops can be used for food/feed or fuel, but not both. Little information was discovered on the palatability of the byproducts for direct human consumption.

Major problems still exist in handling and storing these byproducts when they have high moisture content. In addition, their use as livestock feeds is more applicable to developed nations than to LDCs, where the consumption of animal protein is too expensive for many of the people. Moreover, in most countries where the malnutrition problem is widespread, the problem is one of energy and protein deficiency, not just of protein deficiency.

There are several sugar crops that could be placed in the same category as cassava--that is, they have not been produced over a widespread area and there has not been extensive research on improving their yields. Of the five sugar crops examined in this report, sweet sorghum, fodder beets, and Jerusalem artichokes fall into this category. The other two sugar crops examined, sugar cane and sugar beets, are currently used as food crops. Therefore, their use for fuel alcohol production would directly cut into world food supplies unless their acreages were expanded.

Not surprisingly, initial experimentation indicates that the best yields for sweet sorghum, fodder beets, and Jerusalem artichokes are likely to occur on soils that are also best for food and feed crops. Whether these sugar crops can produce satisfactory levels of fermentables for alcohol production on more marginal soils is a question that remains to be answered. Sugar beets, for example, are more salt tolerant than many other crops. For that reason, they can sometimes be grown in circumstances where other food crops cannot be grown economically. Perhaps additional research might show that to also be the case with some of the other potential energy crops.

As is the case with starch crops, byproducts produced when alcohol is made from sugar crops may partially offset the acreage diversions from food or feed crops. In this regard, sweet sorghum may hold particular promise. There exists the possibility of improving sweet sorghum varieties to increase the grain yield. If this could be accomplished, more grain from the crop would be available for food or feed, while the sugar in the stalk could be used for fuel alcohol production. However, some present varieties which have been developed to increase grain production have shown decreases in sugar yield. Thus, there would be lower alcohol yields from these varieties. Further research might be sucessful in increasing grain yields without sacrificing stalk sugar yields.

It is sometimes proposed that the leafy tops of fodder beets and Jerusalem artichokes be used as livestock feeds, while the tubers are used for alcohol. However, at least for Jerusalem artichokes, research has shown that one cannot harvest maximum yields of both tops and tubers ("JA - The Myth and the Reality Explained"). The yield trade-off between tops and tubers is likely to be quite substantial for any such energy crops. Thus, any argument that use of the tops substantially mitigates the food-fuel conflict must be regarded with extreme caution.

REFERENCES

Adesuyi, S. A. "Advances in Yam Storage Research in Nigeria." 3rd International Symposium on Tropical Root Crops. Ibadan, Nigeria: 1973.

Agency for International Development (AID), Office of Development Information. Development Information on Appropriate Rural Technology, Tropical Summary Series No. 1, 1977.

Aidoo, K. E., R. Hendry, and D. J. B. Wood. "Solid State Fermentations." Advances in Applied Microbiology. 28(1982):201-237.

Aldrick, Samuel R., Walter O. Scott, and Earl R. Leng. Modern Corn Production. 2nd ed. Champaign, Illinois: A and L Publications, 1975.

Alsina, E., S. Valle-Lamboy, A. V. Mendex-Cruz. "Preliminary Evaluation of Ten Sweet Sorghum Varieties for Sugar Production." Puerto Rico University Journal of Agriculture. 59(1975):5-14.

Atienza, J. C., and J. K. Demeterio. "The Sugar Industry of the Philippines." Sugar y Azucar 75(1980):195-210.

Bagbey, Marvin O. "Comparison of Potential Feedstocks." Proceedings of Regional Workshops on Alcohol and Vegetable Oil as Alternative Fuels. Raleigh, North Carolina: April 7-9, 1981; Sacramento, California: April 21-23, 1981; Peoria, Illinois: April 28-30, 1981.

Barnes, A. C. The Sugar Cane. New York: Interscience Publishers, Inc., 1964.

Baxter, S. W. D. "The Mechanical Harvesting of Green Cane." Sugar y Azucar 75(1980):43-47.

Bennett, Merrill K. "A World Map of Foodcrop Climates." Food Research Institute Studies 1(1960):285-295.

Broadhead, Dempsey M. "Effects of Stalk Chopping of Leaf Removal and Juice Quality of Rio Sweet Sorghum." Agronomy Journal 64(1972):306-311.

Brown, Lester R. Food or Fuel: New Competition for the World's Cropland. World Watch Paper 35 Washington, D. C.: Worldwatch Institute, March 1980a.

Brown, Lester R. "Food Versus Fuel." Environment 22(May 1980b): 32-40.

Bryan, W. L., et al. "Evaluation of Sweet Sorghum for Fuel Ethanol." Paper No. 81-3571 presented at the Winter Meeting of the American Society of Agricultural Engineering, Chicago, Illinois, 1981.

Bryan, W. L., and R. L. Parrish. "Solid-phase Fermentation of Sweet Sorghum." Paper No. 82-3603 presented at the Winter Meeting of the American Society of Agricultural Engineering, Chicago, Illinois, 1982.

Casey, J. P. "The Future of Corn Wet Milling." Food Technology 32(1978):72-82.

Cecelski, Elizabeth and William Ramsay. "Prospects for Fuel Alcohols from Biomass in Developing Countries." Long-Term Energy Resources, Volume II, An International Conference Sponsored by the United Nations Institute for Training and Research and Petro-Canada. Marshfield, Massachusetts: Pitman Publishing Inc., 1981. Reprint ed., Washington, D.C.: Resources for the Future, Reprint 197, 1982.

Celis U., Rafael, et al. The Foreign Trade Deficit and the Food Crisis: Anticipated Results of an Aggressive Program of Alcohol Fuel Production in Costa Rica. Energy in Developing Countries Series, Discussion Paper D-73H. Washington, D.C.: Resources for the Future, July 1982.

Chubey, B. B. and D. G. Dorrell. "Jerusalem Artichoke, a Potential Fructose Crop for the Prairies." Canadian Institute of Food Science Technology Journal 7(1974):98-100.

Clegg, M. D. Department of Agronomy, University of Nebraska, Lincoln, Nebraska. Personal conversation, May 1983.

Clements, Harold M., Sr. The Mechanization of Agriculture in Brazil. Gainesville, Florida: University of Florida Press, 1969.

Cobley, Leslie S. An Introduction to the Botany of Tropical Crops. 2nd ed. New York: Longman, 1956; revised by H. M. Steele, 1976.

Congdon, R. J., ed. Lectures of Socially Appropriate Technology. Eindhoven, The Netherlands: Committee for International Cooperation Activities, Technische Hogeschool, 1975.

de Alvim, Paulo T., and T. T. Kozlowski, eds. Ecophysiology of Tropical Crops. New York, San Francisco, and London: Academic Press, 1977.

De Datta, Surajit K. Principles and Practices of Rice Production. New York: John Wiley and Sons, 1981.

Dhawale, M. R., and W. M. Ingledew. "Starch Hydrolysis by Derepressed Mutants of Schwanniomyces Castellii." Biotechnology Letters 5(1983):185-190.

Doggett, H. Sorghum. London: Longmans, Green, and Co. Ltd., 1970.

Doney, Devon L. "Sugar Beet-Fodder Beet as a Source of Alcohol Fuel." Proceedings Bio-Energy '80 World Congress and Exposition. The Georgia World Congress Center, Altanta, Georgia, April 21-24, 1980.

Dorband, Wayne. "Culturing and Harvesting the Jerusalem Artichoke." Informational Sheet of America Energy Farming Systems, Inc. Marshall, Minnesota, 1982.

Dowling, R. N. Sugar Beet and Beet Sugar. London: Ernest Benn Limited, 1928.

Dykins, F. A., et al. "Production of a Palatable Artichoke Syrup, I, General Procedure." Industrial Engineering Chemistry 25(1933):937.

Earl, W. B. Ethanol from Fodder Beet. Department of Chemical Engineering. University of Canterbury. n.d.

Earl, W. B. and W. A. N. Brown. "Alcohol Fuels from Biomass in New Zealand--the Energetics and Economics of Production and Processing." Alcohol Fuels Technology Third International Symposium. Vol. 1, Asilomar, California: May 28-31, 1979.

Echevarria, Sinforiana F. "A Report on the Mechanization of the Sugar Industry in Mexico." Sugar y Azucar 74(1979):25-32.

Edmond, J. B., and G. R. Ammerman. Sweet Potatoes: Production, Processing, and Marketing. Westport, Connecticut: The AVI Publishing Company, Inc., 1971.

Ferraris, R., and G. A. Stewart. "New Options for Sweet Sorghum." Journal of the Australian Institute of Agricultural Science 45(1979):156-164.

"Field Mechanization." Sugar y Azucar 74(1979):23.

Fleming, S. E., and J. W. D. Groot Wassink. Preparation of High-Fructose Syrup from the Tubers of the Jerusalem Artichoke (Helianthus tuberosus L.). CRC Critical Reviews in Food Science and Nutrition. Boca Raton, Florida: CRC Press Inc., 1979.

Florida Engineering Society. "Cassava - Florida's Future Fuel?" Journal of Florida Engineering Society 33(July 1979):15, 34.

Food and Agriculture Organization of the United Nations (FAO). Cassava Processing, by M. R. Grace. Rome:FAO, 1977.

Food and Agriculture Organization of the United Nations (FAO). Crop Calendars. FAO Plant Production and Protection Paper No. 12, Rome: FAO, 1978.

Food and Agriculture Organization of the United Nations (FAO). 1980 FAO Production Yearbook. Vol. 34, Rome:FAO, 1981a.

Food and Agriculture Organization of the United Nations (FAO). "Seed Production of Specific Crops," by M. D. Kernick. Agricultural and Horticultural Seeds - Their Production, Control and Distribution. FAO Agricultural Studies No. 55, Rome:FAO, 1961.

Food and Agriculture Organization of the United Nations (FAO). The State of Food and Agriculture, 1980. Rome:FAO, 1981b.

Fox, S. D. "Economic Significance of Quality Losses in Commercial Piles." Proceedings of BSDF Conference. 1973.

Froid, Oscar. "Feedstock - the Jerusalem Artichoke." Fuel Alcohol USA, January 1982, pp. 29-33.

Gabel, Medard. Ho-Ping: Food for Everyone. Garden City, New York: Anchor Press and Doubleday, 1979.

Gallion, John J. "Biomass Research in Idaho." Gasohol USA, January 1980, pp. 28-29, 35.

Gibbons, William R., and Carl A. Westby. "Fuel Ethanol and High Protein Feed from Corn and Corn-Whey Mixtures in a Farm-Scale Plant." Biotechnology and Bioengineering 25(1982a):2127-2148.

Gibbons, William R., and Carl A. Westby. "Novel Farm-Community Scale Processes for the Conversation of Fodder Beets and Sweet Sorghum to Fuel Grade Ethanol." Paper No. 024 from Abstracts of the Annual Meeting of the American Society for Microbiology, New Orleans, Louisiana, 1983b.

Gibbons, William R., Carl A. Westby, and Thomas L. Dobbs. "A Continuous, Farm-Scale Solid Phase Fermentation Process for Fuel Ethanol and Protein Feed Production from Fodder Beets." Accepted for publication in Biotechnology and Bioengineering (1984).

Goering, T. J. "Root Crops: Potential for Food and Energy." Finance and Development 17(June 1980):32-35.

Hafliger, Ernst., ed. Maize - Ciba Geigy Agrochemicals. Ciba Geigy Ltd., Basle, Switzerland, 1979.

Hall, Marvin D. "Energy Alternatives and Potential." Proceedings of Regional Workshops on Alcohol and Vegetable Oil as Alternative Fuels. Raleigh, North Carolina: April 7-9, 1981; Sacramento, California: April 21-23, 1981; Peoria, Illinois: April 28-30, 1981.

Hanis, P. M., ed. The Potato Crop - The Scientific Basis for Improvement. Cooperative Extension Service, University of Nebraska, Lincoln, Nebraska, n.d.

Hanway, D. G., and P. W. Harlon. "Raw Materials for Fuel Alcohol Production." Ethanol Production and Utilization for Fuel. Cooperative Extension Service, University of Nebraska, Lincoln, Nebraska, n.d.

"Harvester for Recumbent Cane Used by U.S. Sugar Corporation." Sugar y Azucar 74(1979):46.

Hayes, David J. Fodder Beets for Alcohol Production. Pacific Seed Production Company, Albany, Oregon, 1981.

Hills, Jack F., et al. "Comparison of Four Crops for Alcohol Yield." California Agriculture, March-April 1983, pp. 17-19.

Hills, Jack F., et al. "Comparison of High Energy Crops for Alcohol Production." California Agriculture, November-December 1981, pp. 14-16.

Hoffman, Randy, and Thomas L. Dobbs. A Small-Scale Plant: Costs of Making Fuel Alcohol. South Dakota State University Agricultural Experiment Station Bulletin 686, September 1982.

House, Leland H. A Guide to Sorghum Breeding. Patancheru, Andra Pradesh, India: Inernational Crops Research Institute for the Semi-Arid Tropics, n.d.

Humbert, Roger P. The Growing of Sugar Cane. New York: Elsevier Publishing Company, 1968.

Institute of Energy Economics of Japan. The Alcohol Fuels from Energy Farming, II. Tokyo: The Institute of Energy Economics, 1981.

International Land Development Consultants. Agriculture Compendium for Rural Development in the Tropics and Subtropics. Amsterdam: Elsevier Scientific Publishing Company, 1981.

Islam, Shafigul, and William Ramsay. Fuel Alcohol: Some Economic Complexities in Brazil and in the United States. Energy in Developing Countries Series, Discussion Paper D-73G. Washington, DC: Resources for the Future, April 1982.

Jackson, Danny R., and Mickey F. Arthur. "Sweet Sorghum: An Alcohol Crop for the U.S." Gasohol U.S.A., December 1980, pp. 16-19.

Jackson, Danny R. and William T. Lawhon. "Development of Sweet Sorghum for Alcohol Production." Gasohol U.S.A., April 1981, pp. 10-12.

James, Norman I. "Potential of Sugarcane as an Energy Crop." Proceedings Bio-Energy '80 World Congress and Exposition. The Georgia World Congress Center, Atlanta, Georgia, April 21-24, 1980.

"JA - the Myth and the Reality Explained." Fuel Alcohol U.S.A., April 1982, pp. 20-26.

Johnson, Russell T., et al. Advances in Sugar Beet Production: Principles and Practices. Ames, Iowa: Iowa State University Press, 1971.

Kampen, W. H. "Ethyl Alcohol - The Automobile Fuel of the Future." Sugar y Azucar (1978):18-30.

Kay, E. E. TPI Crop and Product Digest No. 2: Root Crops. London: The Tropical Products Institute, 1973.

Kingsley, Q., and L. Evjen. "Miscellaneous Crops." Northeast Research Station Annual Progress Report. Plant Science Pamphlet No. 70. South Dakota State University, Brookings, South Dakota, 1982.

Kingsley, Q., and M. Volek. "Miscellaneous Observations." Central Crops and Soils Research Station Annual Progress Report. Plant Science Pamphlet No. 71. South Dakota State University, Brookings, South Dakota, 1982.

Kirby, K. D., and C. J. Mardon. "Production of Fuel Ethanol by Solid-Phase Fermentation." Biotechnology and Bioengineering 22(1980):2425-2427.

Klages, K. H. W. Ecological Crop Geography. New York: Macmillan Company, 1942.

Kosaric, N., et al. "Ethanol Production by Fermentation: An Alternative Liquid Fuel." Advances in Applied Microbiology 26(1980):145-227.

Lamb, M. E., K. Von Bargen, and L. L. Bashford. "Mechanical Expression of Sweet Sorghum Juice." Paper No. 82-3110 presented at the Summer Meeting of the American Society of Agricultural Engineering, University of Wisconsin, Madison, Wisconsin, 1982.

Law, J. B. "Methods of Measuring Quality Losses in Commercial Sugar Beet Storage Piles." Proceedings of BSDF Conference, 1973.

Leffingwell, Roy J. "The Hawaiian Sugar Industry." Sugar y Azucar 74(1979):25-33.

Lipinsky, E. S. "Fuels from Biomass: Integration with Food and Material Systems." Science 199(February 1978):644-651.

Lipinsky, E. S., and S. Kresovich. "Sorghums as Energy Crops." Proceedings of Bio-Energy '80 World Congress and Exposition. The Georgia World Congress Center, Atlanta, Georgia, April 21-24, 1980.

Lipinsky, E. S., et al. "Systems Study of Fuels from Sugar Cane, Sweet Sorghum, and Sugar Beets." Final Report BMI-1957, Vol. 2, Battelle Columbus Laboratories, Columbus, Ohio, December 31, 1976.

Luh, B. S., ed. Rice: Production and Utilization. Westport, Connecticut: The AVI Publishing Company, Inc., 1980.

Lukens, Thomas. "The Jerusalem Artichoke - A Special Crop for Alcohol." Gasohol U.S.A., May 1981, pp. 20-21.

Martin, G. H., Warren H. Leonard, and David L. Stamp. Principles of Field Crop Production. 3rd ed. New York: Macmillan Publishing Co. Inc., 1976.

McClure, Thomas A., and Edward S. Lipinsky, eds. CRC Handbook of Biosolar Resources, Volume II, Resource Materials. Boca Raton, Florida: CRC Press Inc., 1981.

Mcglumphy, J. H., et al. "Commercial Production of Levulose, I, General Considerations." Industrial Engineering Chemistry 23(1933): 1202.

Meo, Mark and Scott Sachs. "On-farm Alcohol Fuel Production." California Agriculture, July 1982, pp. 9-11.

National Research Council, National Academy of Sciences. Alcohol Fuels: Options for Developing Countries. Washington, D.C.: National Academy Press, 1983.

Onwueme, I. C. The Tropical Tuber Crops-Yams, Cassava, Sweet Potato, and Cocoyams. New York: John Wiley and Sons, 1978.

Papadakis, J. Agricultural Potentialities of World Climates. Buenos Aires, Argentina: n.p., 1970.

Papadakis, J. Climates of the World and Their Agricultural Pontentialities (sic). Buenos Aires, Argentina: n.p., 1966.

Paul, J. K., ed. Ethyl Alcohol Production and Use As A Motor Fuel. Park Ridge, New Jersey: Noyes Data Corporation, 1979.

Posler, Gerry L., and Nicholas S. Hill, "Sweet Sorghum Potential Feedstock for Alcohol." Proceedings: Alcohol Fuel Workshop. Manhattan, Kansas: Great Plains Agricultural Council Publication No. 94, May 13-14, 1980.

"Production Per Acre Equation." Gasohol U.S.A., 1980, pp. 6-8.

Rask, Norman. "Food-Fuel Conflicts - The Brazil Case." Paper presented at the 1981 annual meeting of the Association for the Advancement of Science, Toronto, Canada, January 1981.

"Researchers Analyze Ethanol Production and Costs." Gasohol U.S.A., July 1981, pp. 22-23.

Ricard, R., F. A. Martin, and B. J. Cochran. "Sweet Sorghum for Biomass and Alcohol Production." Louisiana Agriculture 24(1980):18-19.

Rolz, C., S. de Cabrera, and R. Garcia. "Ethanol from Sugar Cane: EX-FERM Concept." Biotechnology and Bioengineering 21(1979):2347.

Rolz, C. "A New Technology to Ferment Sugarcane Directly: The EX-FERM Process." International Sugar Journal 82(1980):47.

Routley, D. G. "Jersalem Artichoke." American Horticulturalist 56(August 1977):12-13.

Roy, Ewell P. "The Brazilian Sugarcane-to-Alcohol Program." Louisiana Rural Economist 41(August 1979):9-13.

Sach, Ray M. "Crop Feedstocks for Fuel Alcohol Production in California." Proceedings. Biomass Alcohol for California: A Potential for the 1980's. Davis, California: University of California Agricultural Engineering Extension, January 18, 1980.

Sachs, Roy M., et al. "Fuel Alcohol from Jerusalem Artichokes." California Agriculture, September - October 1981, pp. 4-6.

Serra, G. E. "Agricultural and Industrial Overview of Brazilian Alcohol Program." Proceedings of Bio-Energy '80 World Congress and Exposition. The Georgia World Congress Center, Atlanta, Georgia, April 21-24, 1980.

Shelef, Gedabiah, Y. Azoc, and R. Moraine. "Algae Biomass Production in High-Rate Wastewater Treatment Ponds." Proceedings Bio-Energy '80 World Congress and Exposition. The Georgia World Congress Center, Atlanta, Georgia, April 21-24, 1980.

Sinha, R. N., and W. E. Muir. Grain Storage: Part of a System. Westport, Connecticut: AVI Publishing Company, Inc., 1973.

Smith, Ora. Potatoes: Production, Storing, Processing. Westport, Connecticut: AVI Publishing Company, Inc., 1968.

Solar Energy Information Services (SEIS). Alcohol Fuels Reprint Series, Vol. I, U.S. Government Overviews. San Mateo, California, 1980.

Solar Energy Research Institute (SERI). Fuel From Farms - A Guide to Small-Scale Ethanol Production. Prepared by the Midwest Research Institute, Operated for the U.S. Dept. of Energy, February, 1980.

Solar Energy Research Institute (SERI). Fuel From Farms - A Guide to Small-Scale Ethanol Production. 2nd ed. Prepared by the Midwest Research Institute, Operated for the U.S. Dept. of Energy, 1982.

Solar Energy Research Institute (SERI). Harvest and Ethanol Yields from Selected Feedstocks, a Summary of Representative Data, by P. H. Kellough and C. L. Knapp. SERI/SP-755-1033. Golden, Colorado: Solar Energy Research Institute, 1981.

Stampe, S., et al. "Energy Consumption of a Farm Scale Ethanol Distillation System." Energy in Agriculture 2(1983):355-368.

Stauffer, M. D., B. B. Chubey, and D. F. Dorrell. "Jerusalem Artichoke: Formulating the Potential of a New Crop." n.d. (Mimeographed).

Steele, Peter. "Fodder Beet: How Will We Harvest It?" New Zealand Journal of Argiculture 139(1979):27-29.

Swift, F. L. "Losses of Sugar From American Crystal Sugar Company Commercial Storage Pile." Proceedings of BSDF Conference. 1973.

"Technical Section - Fodder Beet Research," Data sheet of farmer trials sponsored by Argonne National Laboratory, Idaho Falls, Idaho.

Theurer, Clair S., Devon L. Doney, and John Gallian. "Fodder Beet - Potential Alcohol Fuel Crop." Utah Science (1981):63-67.

Tindall, H. D. Commercial Vegetable Growing. Ibadan, Nigeria: Oxford University Press, 1968.

Trewartha, Glenn T. An Introduction to Climates. New York, St. Louis, and San Francisco: McGraw-Hill Book Company, 1968.

Ueda, S., et al. "Production of Ethanol from Raw Cassava Starch by a Nonconventional Fermentation Method." Biotechnology and Bioengineering. 23(1981):291-299.

Underkofler, L. A., W. K. McPherson, and E. I. Fulmer. "Alcoholic Fermentation of Jerusalem Artichokes." Industrial Engineering Chemistry 29(1937):1160-1164.

University of Nebraska-Lincoln Cooperative Extension Service. The Monday Morning Report, by Robert B. O'Keefe. Lincoln, Nebraska: Institute of Agriculture and Natural Resources, Cooperative Extension Service, November 30, 1982.

"U.S. Beets Top Europe's for Alcohol Production." Crop and Soils Magazine, Vol. 35, No. 6, 1983, p. 12.

U.S. Department of Agriculture (USDA). Agricultural Prices Annual Summary, 1979, 1980, and 1981 issues. Washington, D.C., June 1980a, June 1981a, June 1982.

U.S. Department of Agriculture (USDA). Agricultural Statistics. Washington, D.C.: United States Government Printing Office, 1981b.

U.S. Department of Agriculture (USDA). Culture of Sweet Sorghum for Sirup Production, by K. C. Freeman, D. N. Broadhead, and Natale Zummo. Agriculture Handbook No. 441, USDA Agricultural Research Service, Washington, D.C.: U.S. Government Printing Office, 1973.

U.S. Department of Agriculture (USDA). Growing the Jerusalem Artichoke, by Victor R. Boswell. Leaflet No. 116. Washington, D.C.: U.S. Government Printing Office, 1936, revised 1959.

U.S. Department of Agriculture (USDA). "Miscellany, Including Celeriac, Horseradish, Artichoke, Peanuts, Vegetable Soybeans," by Homer N. Metcalf and Milo Burnham. 1977 Yearbook of Agriculture, Gardening for Food and Fun. Washington, D.C.: U.S. Government Printing Office, 1977a.

U.S. Department of Agriculture (USDA). Motor Fuels from Farm Products, by P. Burke Jacobs and Harry P. Newton, USDA Miscellaneous Publication No. 327. Washington, D.C.: U.S. Government Printing Office, 1938.

U.S. Department of Agriculture (USDA). Small-Scale Fuel Alcohol Production. Prepared with the Assistance of Development Planning and Research Associates, Inc., Washington, D.C., March 1980b.

U.S. Department of Agriculture (USDA). Tropical Yams and Their Potential, Part 1, Dioscorea esuilenta, by Franklin W. Martin. Agriculture Handbook No. 457. Washington, D.C.: U.S. Government Printing Office, 1974a.

U.S. Department of Agriculture (USDA). Tropical Yams and Their Potential, Part 2, Dioscorea bulbifers, by Franklin W. Martin. Agriculture Handbook No. 466. Washington, D.C.: U.S. Government Printing Office, 1974b.

U.S. Department of Agriculture (USDA). Tropical Yams and Their Potential, Part 3, Dioscorea alata, by Franklin W. Martin. Agriculture Handbook No. 495. Washington, D.C.: U.S. Government Printing Office, 1976.

U.S. Department of Agriculture (USDA). Tropical Yams and Their Potential, Part 4, Dioscorea rotundata and Dioscorea cayenensis, by Franklin W. Martin. Agriculture Handbook No. 502. Washington, D.C.: U.S. Government Printing Office, 1977b.

Walker, Jon. "Farmers Rest Their Hopes in Jerusalem Artichokes," Sioux Falls, (S.D) Argus Leader, December 19, 1982, p. E1.

Wall, Joesph S., and William M. Ross, eds. Sorghum Production and Utilization. Westport, Connecticut: AVI Publishing Company, Inc., 1970.

Waters, L., D. Davis, and J. Richle. A letter to county extension agents reporting the results of Jerusalem artichoke trials sponsored by the Department of Horticulture, University of Minnesota, St. Paul, Minnesota, 1981.

Westby, Carl A., and William R. Gibbons. "Farm-Scale Production of Fuel Ethanol and Wet Grain from Corn in a Batch Process." Biotechnology and Bioengineering 24(1982):1681-1699.

"What's With the Specialty Crops? Interest in Safflower Lessens, Potential of Other Crops Bright." Dakota Farmer, December 12, 1962, pp. 13-14.

Wiedmeier, Floyd F. "Cultural Practices and Management of Sunchokes," Departmental Correspondence, South Dakota State University Plant Science Department, October 28, 1982.

Williams, C. N. The Agronomy of the Major Tropical Crops. Selangor, Malaysia: Oxford University Press, 1975.

Wilsie, Carroll P. Crop Adaptation and Distribution. San Francisco: W. H. Freeman and Company, 1962.

World Bank. Alcohol Production from Biomass in the Developing Countries. September 1980.

Wright, Malcolm E., et al. "Development of a Community-Size Sorghum Syrup Plant." Transactions of the American Society of Agricultural Engineers 20(1977):786-791.

Wyse, D. L. and Lori Wilfahrt. "Jerusalem Artichoke." Weeds Today, 1982, pp. 14-16.

Yoshida, Layne. Fuels from Biomass: Plants for Ethanol Production. Technical Report No. 4, Hawaii Biomass Program. Hawaii Natural Energy Institute, University of Hawaii, Honolulu, Hawaii, November, 1977.

ANNEX A

Measurement Conversions

Contained here are certain conversions of United States and metric measurement units. These conversions will be of use to individuals wishing to determine and state inputs, outputs, or costs found in this report either in metric units or in U.S. units.

Symbol	When You Know	Multiply By	To Find	Symbol
MASS (WGT)				
oz	ounces	28.0	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2,000 lb)	0.9	metric tons	t
	long tons (2,240 lb)	1.01	metric tons	t
g	grams	0.035	ounce	oz
kg	kilograms	2.2	pounds	lb
t	metric tons (1,000 kg)	1.1	short tons	
t	metric tons (1,000 kg)	0.98	long tons	
VOLUME				
tsp	teaspoons	5.0	milliliters	ml
tbsp	tablespoons	15.0	milliliters	ml
fl oz	fluid ounces	30.0	milliliters	ml
c	cups	0.24	liters	L
pt	pints	0.47	liters	L
qt	quarts	0.95	liters	L
gal	gallons (U.S.)	3.8	liters	L
gal	gallons (Imp)	4.5	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
ml	milliliters	0.03	fluid ounces	fl oz
L	liters	2.1	pints	pt
L	liters	1.06	quarts	qt
L	liters	0.26	gallons (U.S.)	gal (U.S.)
L	liters	0.22	gallons (Imp)	gal (Imp)
m^3	cubic meters	35.0	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3

ANNEX B

Fuel Alcohol Cost Tables in Terms of U.S. Dollars per Liter*

*Explanatory footnotes to the tables are not included, since they would be the same as for corresponding tables in the text. Table B-1 in this annex, for example, corresponds to Table 4-1 in the text; i.e., these annex tables correspond to the tables in Chapter IV of the text.

Table B-1. Estimate of Costs of Producing Fuel Alcohol in LDCs and the U.S. from Grain Sorghum.

Country Type	Plant A	Plant B	Plant C
		----------$/L----------	
Low Cost Countries and the U.S.	$ .55	$ .44 - $ .48	$ .25 - $ .30
Medium Cost Countries	$ .59	$ .46 - $ .50	$ .27 - $ .32
High Cost Countires	$ .70	$ .52 - $ .56	$ .33 - $ .38

Table B-2. Estimate of Costs of Producing Fuel Alcohol in LDCs and the U.S. from Corn.

Country Type	Plant A	Plant B
	---------$/L---------	
Low Cost Countries and the U.S.	$ .48 - $ .50	$ .31 - $ .33
Medium Cost Countries	$ .50 - $ .52	$ .33 - $ .35
High Cost Countries	$ .55 - $ .57	$ .39 - $ .41

Table B-3. Estimate of Costs of Producing Fuel Alcohol in LDCs and the U.S. from Rice.

Country Type	$/L
Low Cost Countries and the U.S.	$ .94
Medium Cost Countries	$ .96
High Cost Countries	$1.02

Table B-4. Estimate of Costs of Producing Fuel Alcohol in LDCs and the U.S. from Potatoes.

Country Type	$/L
Low Cost Countries and the U.S.	$ .97 - $1.24
Medium Cost Countries	$ .99 - $1.26
High Cost Countries	$1.05 - $1.32

Table B-5. Estimate of Costs of Producing Fuel Alcohol in LDCs and the U.S. from Cassava.

Country Type	Plant A	Plant B
	--------$/L--------	
Low Cost Countries and the U.S.	$ .29 - $ .58	$ .42 - $ .48
Medium Cost Countries	$ .31 - $ .60	$ .44 - $ .50
High Cost Countries	$ .38 - $ .67	$ .49 - $ .55

Table B-6. Estimate of Costs of Producing Fuel Alcohol in LDCs and the U.S. from Sweet Potatoes.

Country Type	
	$/L
Low Cost Countries and the U.S.	$ .41 - $2.19
Medium Cost Countries	$ .44 - $2.21
High Cost Countries	$ .49 - $2.26

Table B-7. Estimate of Costs of Producing Fuel Alcohol in LDCs and the U.S. from Sugar Cane.

Country Type	Plant A	Plant B	Plant C	Plant D	Plant E	Plant F
		$/L				
Low Cost Countries and the U.S.	\$ .61 - \$ .74	\$ .48 - \$ .52	\$ .52 - \$ .65	\$ .61 - \$ .74	\$ .61 - \$ .74	\$ .68 - \$ .87
Medium Cost Countries	---	---	\$ .53 - \$ .66	\$ .65 - \$ .78	\$ .64 - \$ .77	\$ .72 - \$ .85
High Cost Countries	---	---	\$ .57 - \$ .70	\$ .75 - \$ .88	\$ .74 - \$ .83	\$ .83 - \$ .96

Table B-8. Estimate of Costs of Producing Fuel Alcohol in LDCs and the U.S. from Sweet Sorghum.

Country Type	Plant A	Plant B	Plant C
		----------$/L----------	
Low Cost Countries and the U.S.	$ .44	$ .49 - $ .89	$ .64 - $ .92
Medium Cost Countries	$ .48	$ .52 - $ .94	$ .66 - $ .95
High Cost Countries	$ .58	$ .59 - $1.08	$ .72 - $1.00

Table B-9. Estimate of Costs of Producing Fuel Alcohol in LDCs and the U.S. from Sugar Beets.

Country Type	Plant A	Plant B	Plant C
		----------$/L----------	
Low Cost Countries and the U.S.	$ .46 - $ .58	$ .50 - $ .62	$ .62 - $ .73
Medium Cost Countries	---	---	$ .64 - $ .76
High Cost Countries	---	---	$ .69 - $ .81

Table B-10. Estimate of Costs of Producing Fuel Alcohol in LDCs and the U.S. from Fodder Beets.

Country Type	Plant A	Plant B	Plant C
		----------$/L----------	
Low Cost Countries and the U.S.	\$ .35 - \$ .44	\$ .59	\$ .55 - \$ .65
Medium Cost Countries	---	\$ .63	\$ .57 - \$ .67
High Cost Countries	---	\$ .73	\$ .63 - \$ .73

Table B-11. Estimate of Costs of Producing Fuel Alcohol in LDCs and the U.S. from Jerusalem Artichokes.

Country Type	
	$/L
Low Cost Countries and the U.S.	\$ .54
Medium Cost Countries	\$ .58
High Cost Countries	\$ .68

Table B-12. Costs of Producing Fuel Alcohol in LDCs and the U.S. from Various Feedstocks.

Crop	Country Type: Low Cost Countries and the U.S.	Medium Cost Counties	High Cost Counties
	$/L		
Grain Sorghum	\$ .44 - \$ .55	\$ .46 - \$ .59	\$ .52 - \$ .70
Corn	\$ .48 - \$ .50	\$ .50 - \$ .52	\$ .55 - \$ .57
Rice	\$ .94	\$ .96	\$1.02
Potaotes	\$ .97 - \$1.24	\$ .99 - \$1.26	\$1.05 - \$1.32
Cassava	\$ .29 - \$ .58	\$ .31 - \$ .60	\$ .38 - \$ .67
Sweet Potatoes	\$ .41 - \$2.19	\$ .44 - \$2.21	\$ .49 - \$2.26
Yams	---	---	---
Sugar Cane	\$ .48 - \$ .74	\$ .53 - \$ .78	\$ .57 - \$ .88
Sweet Sorghum	\$ .44 - \$ .92	\$ .48 - \$ .95	\$ .58 - \$1.08
Sugar Beets	\$ .46 - \$ .73	\$ .64 - \$ .76	\$ .69 - \$ .81
Fodder Beets	\$ .55 - \$ .65	\$ .57 - \$ .67	\$ .63 - \$ .73
Jerusalem Artichokes	\$ .54	\$ .58	\$ .68