Energy Balance for Ethyl Alcohol Production from Crops

Abstract. *Energy requirements to produce ethyl alcohol from three different crops in Brazil (sugarcane, cassava, and sweet sorghum) were calculated. Figures are presented for the agricultural and industrial phases. The industrial phase is always more energy-intensive, consuming from 60 to 75 percent of the total energy. Sugarcane is the more efficient crop for ethyl alcohol production, followed by sweet sorghum and cassava from a net energy viewpoint. The utilization of sweet sorghum stems might increase the total energy gain from this crop to almost the same level as sugarcane. Cassava has a lower energy gain at the present state of agriculture in Brazil.*

The difference between the energy available from crops and the energy expended in producing them was analyzed previously by Heichel (*1, 2*) and Pimentel *et al.* (*3*). The energy expended in crop production includes all the forms of energy used in agricultural and industrial processing, except the solar energy that the plants use for growth. Moreira and Goldemberg (*4*) in Brazil did a similar analysis, taking into account the native technology, to estimate the possibility of using ethyl alcohol produced from crops to replace oil.

In this report we present the cultural energy balance of three different crops and analyze the possibilities of using these crops in Brazil to produce ethyl alcohol: sugarcane, cassava, and sweet sorghum.

The National Alcohol Program (PNA) was started in Brazil in November 1975 for the purpose of increasing ethyl alcohol production so that it might be used to replace automotive gasoline, diesel oil, and several other synthetic products (*5, 6*). The choice of the best raw material for alcohol production is an important part of the program. Sugarcane, cassava and, more recently, sweet sorghum (*7, 8*) are now being considered as suitable crops. This is the reason for centering the present study on them.

Data on crops and yields must be selected carefully since they must represent the real average production in the country. There are large differences in the types and levels of technology used for different crops in different regions of the country. Since the PNA is a large-scale agricultural project supported by government funds, for any of the crops selected it will be possible to use the most advanced technology available. Taking this fact into consideration we assume the same technological level for all three different crops.

For sugarcane and cassava we used crop data and yields of Nascimento de Toledo (*9*). Because such information is not yet available for sweet sorghum in Brazil, we used data on corn crops, taken from the same source, because very similar agricultural practices are used for sorghum and corn (*9, 10*).

Total manpower, oil-consuming machinery, fertilizers, insecticides, and herbicides were translated into an energy equivalent by using the data of Heichel (*2*) and Pimentel *et al.* (*3*). Human labor was translated into energy by assuming an energy consumption of 544 kcal per work-hour for a farm laborer [see (*3, 11*)].

The total weight of the farm equipment (tractors, trucks, and miscellanea) required for the production of 1 ha of plant cane, on a farm where high technology is used, was estimated to be 0.5 metric ton. This figure is very similar to the one obtained by Pimentel *et al.* (*3*) for corn crops in the United States. Since data on energy consumption for equipment fabrication and maintenance are not available in Brazil, we used the figure reported in (*3*), that is, 1,050,000 kcal/ha. This energy component was calculated for ratoon cane, cassava, and sweet sorghum, the energy equivalent being scaled down according to the weight of equipment used per hectare.

The only cultural energy computed in the industrial stage was the energy necessary for raw material processing and absolute alcohol distillation, which is accomplished by steam generation. The energy embodied in the equipment for alcohol production also should have been taken into account, as explained in (*12*). This was not done, however, because raw data for input-output or process energy analysis is not yet available in Brazil. Since capital costs of the processing plants are very similar for the three raw materials under consideration we still can make a proper evaluation of the differences between net energy performance indices. These differences may have more meaning than the absolute values of the indices (*12*).

Distillery effluent, in spite of its recognized value as a fertilizer, was not considered in our calculations, since there is a lack of information on the total amount and composition of this residue for cassava and sorghum processing.

The following data supply more details on the cultural techniques and assumptions used in our calculations.

Sugarcane. The calculations were based on a sugarcane plantation and the two ratoon crops with yields of 103, 62, and 50 tons, respectively, per hectare (*9*), averaging 72 ton/ha. This is equivalent to 54 tons per hectare per year, since plant cane is harvested 18 months after plantation and uses the soil for 2 years

Table 1. Energy expended in the agricultural production of sugarcane.

Inputs: Item	Inputs: Amount (per hectare)	Plant cane: Mcal/ha	Plant cane: %	First ratoon: Mcal/ha	First ratoon: %	Second ratoon: Mcal/ha	Second ratoon: %	Total: Mcal/ha	Total: %	Average: Mcal/ha	Average: %
Manual labor*		234	2.94	120	2.79	120	2.79	474	2.86	158	2.86
Machines*		1,050	13.21	750	17.43	750	17.43	2,550	15.41	850	15.41
Combustibles*		4,065	51.16	1,920	44.62	1,920	44.62	7,905	47.76	2,635	47.76
Nitrogen	65 kg of N	1,204	15.15	1,204	27.98	1,204	27.98	3,612	21.82	1,204	21.82
Phosphorus†		146	1.84	44	1.02	44	1.02	234	1.41	78	1.41
Potassium	100 kg of K_2O	192	2.42	192	4.46	192	4.46	576	3.50	192	3.50
Lime	100 kg of K_2O	150	1.89					150	.91	50	.91
Seed		820	10.32					820	4.95	273	4.95
Insecticide	0.5 kg	12	.15					12	.07	4	.07
Herbicide	3.0 kg	73	.92	73	1.70	73	73	219	1.32	73	1.32
Total		7,946	100.0	4,303	100.0	4,303	100.0	16,552	100.0	5,517	100.0

*Includes transportation to industry. †Amount: 100 kg of P_2O_5 for plant cane; 30 kg of P_2O_5 for the first and second ratoon crops.

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for all practical purposes; ratoon cane has a 12-month crop period.

Table 1 shows the coefficients of energy conversion and the materials used in the agricultural stage for plant cane and the first and second ratoon crops. Similar tables containing more detail can be found elsewhere (*13*). Manual cutting and mechanical loading were assumed; an average distance of 10 km was chosen between the farm and alcohol distillery. The transportation of laborers by trucks was taken into account in accordance with conventional practice.

Energy is produced in distilleries by burning the crop residues (mainly bagasse), and we assumed that each ton of sugarcane produces 250 kg of bagasse with 50 percent moisture, and that 1 kg of this bagasse produces 2.4 kg of steam. The average amount of heat that can be obtained from bagasse is around 1300 kcal per kilogram of bagasse (*14*), or 540 kcal per kilogram of steam.

For the industrial process we assumed a total production of 66 liters of alcohol per ton of sugarcane (*15*), with a consumption of 5.5 kg of steam per liter of alcohol (*16*).

Cassava. We assumed a root yield of 29 tons per hectare (*10*); since the plant requires 2 years in which to grow, the average yield is 14.5 tons per hectare per year. Cassava is harvested manually. However, soil preparation and crop transportation are achieved by means of machinery. Raw material from farm to factory travels an average of 20 km, since the yield per hectare is lower than sugarcane.

The third column of Table 2 lists all requirements and their energy equivalence for cassava production. If one assumes that 22 tons of stem are produced per hectare (*17*), then one requires 2578 Mcal/ha for harvest and transport, and 3600 Mcal/ha for drying to 50 percent moisture content. The average amount of heat that can be obtained from stems is 5512 Mcal/ha. Therefore, there is no energy gain from stem utilization.

The industrial stage, including extraction and hydrolysis of starch, alcoholic fermentation, and distillation, requires 6.5 kg of steam per liter of alcohol (*16*). Alcohol production was assumed to be 174 liters per ton of cassava (*15*).

Table 2. Expended energy average in the agricultural phase of energy production from sugarcane, cassava, and sweet sorghum. On an average, plant cane requires 2 years to grow, ratoon cane requires 1 year. Cassava requires 2 years in which to grow. From sweet sorghum one can obtain two crops per year, one being a ratoon crop.

Inputs	Sugarcane		Cassava		Sweet sorghum	
	Mcal/ha	%	Mcal/ha	%	Mcal/ha	%
Manual labor	158	2.86	273	5.31	52	1.29
Machines	850	15.41	400	7.77	625	15.58
Combustibles	2635	47.76	2654	51.58	1861	46.40
Nitrogen	1204	21.82	1111	21.59	1111	27.70
Phosphorus	78	1.41	146	2.84	88	2.19
Potassium	192	3.48	115	2.24	115	2.87
Lime	50	0.91	100	1.95	25	0.62
Seed	273	4.95	250	4.86	13	0.32
Insecticides	4	0.07	48	0.93	73	1.82
Herbicides	73	1.32	48	0.93	48	1.20
Total*	5517	100.00	5145†	100.00	4011	100.00

*The totals, in megacalories per hectare per year are: sugarcane, 4138; cassava, 2573; and sweet sorghum, 4011. †If stems are harvested and transported for steam generation this number will rise to 7723 Mcal/ha, since 2578 Mcal/ha is the cultural energy expended.

Table 3. Expended energy in agricultural processing of sweet sorghum culture.

Input		Plant sorghum		First ratoon		Total		Average (Mcal/ha)
Item	Amount (per hectare)	Mcal/ha	%	Mcal/ha	%	Mcal/ha	%	
Manual labor *		57	1.22	48	1.43	105	1.31	52
Machines*		750	16.06	500	14.93	1250	15.59	625
Combustible		2284	48.90	1438	42.93	3722	46.40	1861
Nitrogen	60 kg of N	1111	23.79	1111	33.16	2222	27.70	1111
Phosphorus†		146	3.13	30	0.90	176	2.19	88
Potassium	60 kg of K_2O	115	2.46	115	3.43	230	2.87	115
Lime	500 kg	50	1.06			50	0.62	25
Seed		25	0.54			25	0.32	13
Insecticide	3.5 to 2.5 kg	85	1.82	60	1.79	145	1.81	73
Herbicide	2 kg	48	1.02	48	1.43	96	1.20	48
Total		4671	100.00	3350	100.00	8021	100.00	4011

*Includes transportation to industry. †Amount: 100 kg of P_2O_5 for plant sorghum; 20 kg of P_2O_5 for the first ratoon crop.

Table 4. The energy balance of ethyl alcohol production.

Crop	Agricultural yield (tons)		Alcohol production (liters)			Energy (Mcal $ha^{-1}year^{-1}$)						
						Produced			Expended			
	Per hectare	Per hectare per year	Per ton	Per hectare	Per hectare per year	Alcohol	Residue	Total	Agriculture	Industry	Total	Balance
Sugarcane	72	54	66	4,752	3,564	18,747	17,500	36,297	4,138	10,814	14,952	21,345
Cassava	29	14.5	174	5,046	2,523	13,271	—	13,271	2,573	8,883	11,456	1,815
Sweet sorghum*												
Plant	†			3,165	3,165	16,648	11,830	28,478	4,671	10,100	14,771	13,707
Ratoon	‡		§	2,000	2,000	10,520	7,280	17,800	3,350	6,400	9,750	8,050
Total	62.5	62.5		5,165	5,165	27,168	19,110	46,278	8,021	16,500	24,521	21,757
Sweet sorghum‖												
Plant	32.5	32.5		2,145	2,145	11,283	11,830	23,113	4,671	6,508	11,179	11,934
Ratoon	20.0	20.0		1,320	1,320	6,943	7,280	14,223	3,350	4,005	7,355	6,868
Total	52.5	52.5		3,465	3,465	18,226	19,110	37,336	8,021	10,513	18,534	18,802

*Stems plus grains. †Stems, 32.5 ton/ha; grains, 3.0 ton/ha. ‡Stems, 20.0 ton/ha; grains, 2.0 ton/ha. §Stems, 66 liter/ton; grains, 340 liter/ton. ‖Stems only.

Sweet sorghum. This crop is not yet cultivated in Brazil; the assumptions and data we used allow us only to present a crude estimate of the energy balance; nevertheless the importance of this calculation justifies the approach.

Agricultural yield was taken as 32.5 tons per hectare for stem and 3.0 tons per hectare for grain. Both products can be used for alcohol fabrication with a total yield of 3165 liters per hectare (*7*). Since this crop requires only 4 months for growth, we also considered the possibility of one ratoon crop, estimating for it a yield of 20 tons of stem per hectare and 2.0 tons of grain per hectare. Total biomass production for each crop would be 45 tons and 30 tons per hectare, respectively, which is the same as for the sorghum variety 'Sart' used for cattle feed (*18*); these figures were used for the evaluation of energy expended in raw material harvesting and transportation.

Table 3 lists the coefficients and materials used for the sweet sorghum and ratoon crop. The amount of energy produced from the bagasse is the same as that produced from sugarcane with 50 percent moisture. Each ton of sweet sorghum produces 280 kg of bagasse with a heat value of 1300 kcal per kilogram of bagasse. Energy consumed in the industrial stage is 5.5 and 6.5 kg of steam per liter of alcohol produced from stems and grain, respectively.

Table 2 shows all the energy requirements for the agricultural stages of the three crops. These data show that the fuels (combustibles) used in agricultural machinery account for the highest consumption of energy, approximately 45 percent. Nitrogen used as a fertilizer (ammonium sulfate) requires the second highest energy input (about 20 percent); machinery fabrication and equipment maintenance required about 10 percent of the total energy.

Fertilizers (sodium, phosphorus, and potassium) are responsible for 25 percent of the energy expenditure in sugarcane and cassava production, and 30 percent in sweet sorghum; these numbers suggest the importance of using distillery effluent and sugar factory residues as fertilizers. Herbicides and pesticides use approximately 2 percent of the total energy.

As far as the agricultural phase is concerned, sugarcane uses the highest amount of energy (7946 Mcal/ha for the plant cane; an average of 4303 Mcal/ha for both ratoon crops). Cassava requires 5145 Mcal per kilogram. Since cassava uses twice as much labor as sugarcane and sweet sorghum, this figure is surprisingly high. Sweet sorghum requires an expenditure of 4671 Mcal/ha and 3350 Mcal/ha for the plant and ratoon crop, respectively; on average this means a requirement of 4011 Mcal/ha.

Table 5. The ratio of energy produced from ethyl alcohol to the energy consumed in the agricultural stage, and the net energy gain.

Crop	Produced/ consumed	Net gain
Sugarcane	4.53	2.43
Cassava	1.71	1.16
Sweet sorghum		
Grain plus stems	3.39	1.89
Stems only	2.27	2.01

Since different crops have different cycles it is necessary to transform all results to a common base—that is, megacalories per hectare per year—in order to make a proper comparison. This yields the following data on energy consumption for sugarcane, cassava, and sweet sorghum, respectively: 4138, 2573, and 4011 Mcal ha^{-1} $year^{-1}$. Cassava shows the lowest energy consumption and the largest requirement of manpower. However, for future large plantation areas, mechanical harvesting may be required; this will increase the energy expenditure for cassava.

Table 4 displays the energy balance for all three crops, showing the total cultural energy (industrial and agricultural stages), the energy produced, and the net energy gain. The energy utilized in industrial processing ranges from 2.5 to 3.5 times the energy expended in the agricultural stage; industrial processing is responsible for 70 percent or more of the total amount of energy consumed.

Sugarcane shows a large net gain per year of 21,345 Mcal/ha, that is, 1.43 times the total energy consumed. Cassava has a net gain of only 1815 Mcal ha^{-1} $year^{-1}$, which is 0.16 times the total energy consumed. Sweet sorghum has a net gain of 21,757 Mcal ha^{-1} $year^{-1}$ or 0.89 times the total energy consumed. If one assumes that only stems are used, sweet sorghum has a net gain of 18,802 Mcal ha^{-1} $year^{-1}$, or 1.01 times its total cultural energy.

It is possible to furnish the total industrial energy requirements from the byproducts of some of the crops. Thus it is also informative to consider a simplified energy balance in which only the agricultural energy is taken as input and only ethyl alcohol is considered as output, the bagasse supplying the energy for the industrial stage. Although currently some schemes for utilization of excess sugarcane bagasse (5 Mcal ha^{-1} $year^{-1}$) for paper production or supplementary alcohol production are being considered, here we will assume that the low energy content of the bagasse (1.3 Mcal per kilogram) in general precludes its commercialization, and thus we will not include it in this simplified energy balance as a source of output energy.

The ratio between energy produced from ethyl alcohol and energy consumed in the agricultural stage is shown in Table 5 for the three crops with all possibilities of utilization already discussed. Sugarcane gives the highest return (4.53) and cassava the lowest (1.71). In the latter case energy expenditure in industrial processing is supplied from the ethyl alcohol produced. Sweet sorghum and sugarcane present a very similar net energy gain if stems and grain are used; they have, respectively, 2.0 and 2.5 times higher energy gain than cassava.

For plant cane in Hawaii [see Heichel (*1*)] the energy requirement in the agricultural stage is 6425 Mcal ha^{-1} $year^{-1}$, which is approximately 50 percent higher than the figure we calculated (3973 Mcal ha^{-1} $year^{-1}$). The difference is explained by the larger quantity of chemicals used and the higher yields, which leads to higher transport costs, for example.

Our results emphasize the importance of energy balance evaluation for crops and the need to obtain more information on agriculture practices in Brazil.

Cultural energy balance for the production of ethyl alcohol from different biomass origins must be properly estimated, and such estimates must include all agricultural and industrial processing, if we are to find a satisfactory oil substitute.

Our data indicate that sugarcane and sweet sorghum have very favorable energy balances. Thus, at the current technological level of Brazil's agriculture, utilization of sugarcane as a raw material for fuel production is compatible with PNA's general policy of reducing the amount of energy that is imported.

Sweet sorghum also has a good energy balance. It also has several advantages over sugarcane in the agricultural process: it has a shorter growing season; a higher level of mechanization can be used for its cultivation; it should be possible to grow it on land not suitable for sugarcane. The last advantage is related to the short growing season of sweet sorghum in that the crop can be grown in the warmer seasons in areas that have unfavorable winter climates. Thus it is also a possible candidate for the PNA program.

Cassava could be used only in special

situations, mainly in pioneer areas where large quantities of wood and other biomass residues are available which could provide energy for its industrialization. On the other hand, cassava grows in poor-quality soil and is also convenient for the employment of nonqualified manpower, that is, people in the lowest income groups. It may also be possible to increase the yield of cassava by undertaking a minimal amount of research. A new field study is being conducted in order to obtain more realistic figures for the cultural energy of a number of crops in Brazil.

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Carbon Isotopic Evidence for Different Feeding Patterns in Two Hyrax Species Occupying the Same Habitat

Abstract. *The carbon-13/carbon-12 ratios of the carbonate and collagen fractions of bone of the sympatric hyrax species* Procavia johnstoni *and* Heterohyrax brucei *indicate that the former obtains most of its diet by grazing while the latter is primarily a browser. The carbon-13/carbon-12 ratios of these fractions in fossil bone will record information about diet if they have not been altered during diagenesis.*

Closely related animal species living in an environment with restricted resources can coexist if there are differences in their feeding habits. Hoeck (*1*) has shown, from visual observations, that such an ecological separation occurs for sympatric *Procavia johnstoni* and *Heterohyrax brucei*. These herbivorous species of hyrax differ significantly in the amount of feeding time devoted to grazing and browsing on plants in and around the rock outcrops on which they live together in the Serengeti National Park of Tanzania. During the wet season, which extends from November through May, *P. johnstoni* spends 78 percent of its feeding time grazing, whereas grazing accounts for 43 percent of its feeding time during the dry season, when the nutritional quality of the grasses declines. The remainder of the feeding time during both seasons is spent browsing. In contrast, *H. brucei* is predominantly a browser. Grazing accounts for 19 percent of its feeding time during the wet season and 9 percent during the dry season. We have found that the difference in the grazing and browsing habits of these two species is reflected in the $^{13}C/^{12}C$ ratios of the carbonate and collagen fractions of their bones.

Laboratory experiments (*2*) in which animals were raised on diets of known and constant carbon isotopic composition have demonstrated that the isotopic composition of carbon incorporated into an animal is a function of the carbon isotopic composition of its diet. The $^{13}C/^{12}C$ ratio of the diet can be determined from the $^{13}C/^{12}C$ ratio of some component of the animal by taking into account the specific isotopic fractionation which occurs during the assimilation of dietary carbon into that component. The $^{13}C/^{12}C$ ratios of the plants which comprise the diets of herbivores in turn depend on the photosynthetic pathways—C_3, C_4, or crassulacean acid metabolism (CAM) (*3*)—by which they fix carbon dioxide. Plants with C_4 metabolism have characteristically higher $^{13}C/^{12}C$ ratios than C_3 plants; CAM species can, depending on environmental conditions, fix carbon dioxide by either the C_3 or the C_4 pathway, or both, and consequently can have C_3-like, C_4-like, or intermediate $^{13}C/^{12}C$ ratios (*4*). Many tropical grasses are C_4 plants, possessing a collection of biochemical and physiological adaptations for growth in warm environments with high light intensities (*3*). On the other hand, most plants which are classified as browse materials (*1*) are C_3 plants.

Although the photosynthetic types of the plants which are available to *P. johnstoni* and *H. brucei* (*1*) have not been determined directly, most of them can be classified as C_3 or C_4 based on their taxonomic affinities. Of the 27 grass species, 22 either belong to families or genera which have been found to contain only C_4 types or have been identified as C_4 types at the species level; of the 64 species which make up the browse materials, 54 belong to families in which C_4 or CAM photosynthesis have not been found and hence are assumed to contain only C_3 types (*4-6*). Thus it should be possible to measure differences in the relative amounts of grazing and browsing by *P. johnstoni* and *H. brucei* based on differences in the $^{13}C/^{12}C$ ratios of their carbon. The carbon contained in the carbonate and collagen fractions of bone was analyzed for this purpose. These fractions were chosen since applications of this method of dietary analysis to fossil situations would be of considerable interest, and these fractions are generally the only well-preserved animal carbon available in fossil vertebrate material.

Bones were dissected from recently killed hyrax specimens and air-dried (*7*). Jawbones were used exclusively in this study. They were freed of surface contaminants by sonication, then ground in a diamond mortar to pass through a 0.71-mm mesh sieve. The lipid fraction was extracted (*8*) from the bone powder and discarded. The $^{13}C/^{12}C$ ratios of the carbonate and collagen fractions of the defatted bone powder were determined by methods which have been described previously (*2*). The results are reported as $\delta^{13}C$ values (*9*).

The $\delta^{13}C$ values of the bone carbonate and collagen fractions of each of four *P. johnstoni* and *H. brucei* specimens

