20 Biomass: Food versus Fuel

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Biomass resources (fuelwood, dung, crop residues, ethanol) constitute a major fuel source in the world (Hall et al., 1985; Pimentel et al., 1986a; Hall and de Groot, 1987). Biomass is a prime energy source in developing nations, where it meets about 90% of the energy needs of the poor (Chatterji, 1981). Each year 2.5 billion tons of forest resources are harvested for a variety of uses, including fuel, lumber, and pulp (FAO, 1983a). About 60% of these resources are harvested in developing nations; of this amount, about 85% is burned as fuel (Montalembert and Clement, 1983). Fuelwood makes up about half (1.3 billion tons) of the 2.8 billion tons of biomass consumed annually worldwide; the remaining half consists of crop residues (33%) and dung (17%) (Pimentel et al., 1986b).

High fossil fuel prices and rapid population growth in developing countries have made it necessary for the people there to rely more on biomass in the form of fuelwood, crop residues, and dung for energy (Dunkerley and Ramsay, 1983; OTA, 1984; Sanchez-Sierra and Umana-Quesada, 1984). Estimates are that the poor in developing nations spend 15%–40% of their income for fuel and devote considerable time and energy to collecting biomass for fuel (CSE, 1982; Hall, 1985).

BIOMASS RESOURCES

The use of biomass for food and energy in the United States, Brazil, India, and Kenya is compared here. These countries were selected because they represent different economic, social, and environmental conditions.

UNITED STATES

The United States, with 917 million ha of land and a human population of 256 million (Table 20.1), is the largest of the four countries in land area and the second largest in total population. It has the lowest rate of population growth but the largest per capita GNP (gross national product) (Table 20.1).

Nearly half of the land area in the United States is used for crop production and pastures (Table 20.2). The extensive forested area of 290 million ha provides only about 4% of the total energy used in the United States (Tables 20.2 and 20.3). Fossil fuel resources are the major sources of U.S. energy. In per capita use of biomass for fuel, the United States ranks third—just ahead of India (Table 20.2).

TABLE 20.1
Population, Area, and per Capita Gross National Product (GNP)

Country	Estimated Population (10^6)[a]	Annual Rate of Increase (%)	Surface Area (10^6 km^2)[a]	Density (Habitants/km^2)	GNP ($ per Capita)
United States	256	1.1[b]	9.17	28	22,560
Brazil	152	1.5[c]	8.51	18	2920
India	897	2.1[c]	3.28	273	330
Kenya	28	3.7[c]	0.58	48	340

[a] UN (1976).
[b] USBC (1992).
[c] PRB (1993).

TABLE 20.2
Land Distribution by Uses and Population Engaged in Agriculture[a]

Country	Total Area (10^6 ha)	Cropland (10^6 ha)	Pasture (10^6 ha)	Forests and Woods (10^6 ha)	Other land (10^6 ha)	Percentage of Laborers in Agriculture
United States[a,b]	917	192	300	290	135	4
Brazil[a,c]	845	60	184	493	108	31
India[a,c]	298	170	12	67	49	70
Kenya[a,c]	57	2.4	38	2.3	14	81

[a] WRI (1992).
[b] USDA (1991a).
[c] WRI (1984).

TABLE 20.3
Consumption of Commercial Energy (10^{12} kcal)

Country	Solid Fuels[a]	Liquid Fuels[a]	Natural Gas[a]	Hydroelectric and Nuclear[a]	Total	Per Capita (10^6 kcal)
United States[a]	4300	7775	4475	1825	18,375	76.6
Brazil[b]	57	383	19	132	591	4.1
India[b]	439	295	18	104	856	1.1
Kenya	0.8	9.9	0	1.6	12.3	0.6

[a] DOE (1983).
[b] UN (1986).

TABLE 20.4
Tons (10^6 Dry) of Biomass Energy Currently Used[a]

Country	Firewood	Animal Wastes	Bagasse and Crop Residues	Food Grains, Sugars, etc.	Total Biomass	Metric Tons per Capita of Biomass
United States[b]	166 (747)	1 (5)	4[c] (18)	1 (5)	172 (774)	0.72
Brazil	102[d] (459)	Negligible	46[e] (207)	10[e] (45)	158 (711)	1.1
India	124[f] (558)	38[g] (118)	64[g] (126)	>0	226[f] (855)	0.29
Kenya	20.4[e] (92)	11[e] (50)	1.5[e] (7)	>0	32.9[e] (148)	1.57

[a] Values in parentheses indicate energy equivalent if dry biomass were incinerated (10^{12} kcal).
[b] ERAB (1981).
[c] Mostly sugarcane bagasse.
[d] UN (1982).
[e] Meade and Chen (1977); FAO (1984).
[f] UN (1982).
[g] Derived from Gl (1979).

Wood accounts for about 97% of the biomass used as fuel (Tables 20.3 through 20.7). The second largest quantity of biomass energy comes from bagasse, the by-product of sugar production. About 172 million tons of biomass are converted for energy use each year, and this quantity could more than double, to about 440 million tons (ERAB, 1981; Pimentel et al., 1994). An increase of this magnitude would conflict with agricultural land needs and probably be detrimental to the environment.

Brazil

Brazil is the fifth largest country in the world, with 851 million ha of land. Its population of 152 million is increasing at a rate of 1.5% per year (Table 20.1), and its per capita GNP is $2920. At present, 45% of its total energy supply comes from fossil fuel and 55% from biomass fuel (Tables 20.3 and 20.4). Brazil's total annual biomass production is slightly less than that of the United States and more than that of India and Kenya (Table 20.5). Approximately 23% of the biomass produced in Brazil is used for food and fiber (Table 20.6).

Although forests still cover 67% of the country (Table 20.2), rapid deforestation is taking place, primarily caused by slash and burn agriculture rather than by commercial logging or cattle production (Myers, 1986a). Much of the tropical rainforest has limited potential as fuel resource because it is located in remote areas and far from consumers. Firewood provides 22% of the country's total energy needs (Tables 20.3 and 20.4). Forests not only are important to Brazil as an energy source but also, as in all areas, protect land from soil erosion, reduce flooding, and minimize the silting of river streams, and human-made reservoirs.

TABLE 20.5
Annual Biomass Production in the United States, Brazil, India, and Kenya[a]

	United States		Brazil		India		Kenya	
	Land Area (10^6 ha)	Biomass Production	Land Area (10^6 ha)	Biomass Production	Land Area (10^6 ha)	Biomass Production	Land Area (10^6 ha)	Biomass Production
Arable land and production crops	192	1083	75	450	143	858	2.3	13.8
Pasture and grazing land	300	900	164	492	12	36	6.2	18.6
Forests	290	580	568	1136	46	92	2.4	94.8
Other	135	68	39	20	127	64	46.1	50.7[b]
Total area	917	—	851	—	328	—	57	—
Total biomass	—	2631	—	2098	—	1050	—	84.2
Total energy fixed (10^{15} kcal)	11.8		9.4		4.7		0.38	
Solar fixed energy per capita (10^6 kcal)	59.2		104		6.0		18.1	
Biomass production (t/ha)	2.9		2.5		3.2		1.5	

[a] The average biomass yields per hectare were crops, 6 t; pastures, 3 t; forests, 2 t; and other, 0.5 t.

[b] Calculated using figures for woody biomass production given by O'Keefe et al. (1984) and assuming an annual nonwoody biomass production of 1 t/ha in arid grasslands.

TABLE 20.6
Total Annual Amount of Solar Energy Harvested in the Form of Agricultural Crops and Forestry Products (Dry)

	United States		Brazil		India		Kenya	
	10^6 metric tons[a]	10^{12} kcal	10^6 metric tons[a]	10^{12} kcal	10^6 metric tons[a]	10^{12} kcal	10^6 metric tons[a]	10^{12} kcal
Corn	194	873	21	95	7.8	35	1.3	6
Wheat	71	320	1.8	8	45	203	0.1	0.5
Rice	6	27	9	41	91	410	0.03	0.1
Soybeans	51	230	16	72	8	4	—	—
Sorghum	22	99	0.3	14	12	54	0.15	0.7
Potatoes	16	72	0.4	18	2.4	11	0.1	0.5
Cassava	—	—	4.2	19	1.2	5	0.15	0.7
Vegetables	6	27	1.8	8	8.8	40	0.02	0.5
Fruits	5	23	4.9	22	3.9	18	0.15	0.7
Nuts	0.8	4	0.1	0.5	0.2	0.9	0.02	0.1
Oil seeds	9	41	2.0	9	18	365	0.13	0.6
Sugarcane	2.5	—	24.1	105	18	81	0.4	1.8
Sugar beets	2	27	—	—	—	—	—	—
Pulses	1	5	2.7	24	13	59	0.25	1.1
Oats	7	32	0.1	0.5	—	—	0.01	0.05
Rye	1	5	<0.1	<0.5	—	—	—	—
Barley	13	59	0.1	0.5	—	—	0.09	0.4
Subtotal	407.3	1833	88.6	399	229.3	1032	2.9	13.1
Pasture and others	900[b]	4050	492[b]	2214	36[b]	162	19[b]	85
Forest industrial products	100[c]	450	40[d]	180	14[d]	63	0.8[e]	2.3
Total	1407	6332	7590	2655	274	1235	22.4	101
Total per capita (tons)	5.8		4.1		0.3		1.1	
Total per capita (10^6 kcal)	26.3		18.6		1.6		4.8	

[a] From data presented by the Food and Agriculture Organization (FAO, 1984).
[b] From Table 20.5.
[c] USDA (1985).
[d] FAO (1983b).
[e] O'Keefe and Raskin (1985).

After the 1973 oil crisis, Brazil embarked on an ambitious plan to produce ethanol from sugarcane in an effort to reduce its dependence on foreign oil. Currently, Brazil has the largest ethanol system in the world, producing 12 billion L annually, primarily from sugarcane (Boddey, 1995). The United States produces only 2.4 billion L of ethanol annually, primarily from corn grain (DOE, personal communication, Information Office, Alcohol Fuels Program, Department of Energy, Washington, D.C., 1986). Ethanol supplies approximately 19% of Brazil's current biomass energy. However, expansion of the sugarcane crop for ethanol production

TABLE 20.7
Forest Utilization (10^6 t)

	Potential Sustainable Production[a]	Actual Use		
		Industry	Firewood	Total
United States	580	191[b]	166[c]	357
Brazil	1136	40[d]	102[e]	142
India	92	14[d]	124[f]	138
Kenya	2.5	0.8[g]	19.6[g]	20.4[c]

[a] Assuming a net productivity of 2 t/ha.
[b] USDA (1985).
[c] ERAB (1981).
[d] FAO (1983b).
[e] Bogach (1985).
[f] See Table 20.4.
[g] O'Keefe and Raskin (1985).

is associated with a decrease in the per capita production of domestic food crops. From 1974 to 1984 food production decreased 1.9% per year, whereas sugarcane production increased 7.8% per year (de Melo, 1986). The increasing demand for firewood, construction lumber, and sugarcane, combined with the effects of slash-and-burn agriculture, seem likely to continue to exacerbate problems in agricultural production and the quality of the environment.

India

India's surface area is 36% that of the United States, but its population, at 897 million, is more than three times greater (Table 20.1). Of the four countries, India has the highest population density and the lowest GNP (Table 20.1). India's population growth rate remains at 1.7%, and country has more than 1.1 billion (PRB, 2006). A majority of the people live in rural areas and engage in agriculture.

Although India will have to increase food production to keep pace with population growth, it can expand its cropland only by removing forests (Mishra, 1986; Sharma, 1987). The present Indian forest area of about 67 million ha makes up only 23% of the country's total land area (Table 20.2). India is losing about 3.4 million ha of forestland each year (World Development Report, 1995), and there is virtually no forest growth left below 2000 m (Myers, 1986b). The principal factor responsible for this deforestation is population pressure imposed by both humans and livestock (Sharma, 1987). Most of India's large livestock population must graze on fallow agricultural land, uncultivated lands, and forest areas because little fodder is produced.

In addition to using biomass resources for food production, India relies heavily on biomass for energy. Biomass resources supply about half of the energy consumed, fossil energy the other half. The Indian household sector utilizes nearly all of the biomass energy consumed (Tables 20.3 and 20.4), primarily for cooking and lighting (Government of India, 1979). The sugar industry uses bagasse to provide heat and steam energy for the manufacture of sugar.

Wood is the primary source of biomass energy, making up 55% of all biomass energy consumed, followed by bagasse and crop residues at 28% and animal dung at 17% (Table 20.4). This pattern of biomass energy use in India resembles the world pattern, which averages about 50% wood, 35% crop residues, and 15% dung. However, India's heavy reliance on firewood is alarming because 45% more firewood is being used than its forest area can sustainably provide (Tables 20.5–20.7). It should be noted, however, that not all firewood in India is obtained from forests. Although in total forests are the greatest source of fuelwood (Government of India, 1979), about 22% of fuelwood is collected from nonforest land, such as privately owned plantations and woodlots, other private property, riverbanks, canals, and roadsides (Government of India, 1979). To meet future food and fuel needs, India will have to utilize more of its biomass resources; however, it is dubious if the land resources can sustain such use. Of the total annual biomass currently produced, India already harvests 25% in the form of fuel (Tables 20.4 and 20.5).

Kenya

Kenya occupies 570,000 km^2 of arid East Africa and has a population of 28 million people that is expanding at a rate of about 3.7% per annum (Table 20.1). The per capita GNP in Kenya is $340 (Table 20.1). Of the total land area, 4% is in forests and woodland, 4% is used for growing crops, and 7% is pastureland (Table 20.2). Parks and reserves occupy 4%–5%, and villages and cities occupy 1%. The remaining 80% of the land comprises semiarid savanna and rangeland.

Although 75% of the population lives on 20% of the land resulting in densities of 500–1000 people per km^2 (World Development Report, 1995), only 15% live in urban areas. In rural areas, 75% of the labor force is engaged in agriculture (Table 20.1). Per capita food production and caloric intake decreased during the 1970s. Thus, the daily per capita food supply was only 90% of the minimum requirement of 2340 kcal/person/day necessary for the maintenance of health (Yeager and Miller, 1986). In 1992–1993, Kenya imported 569,000 t of cereals and received another 287,000 t in aid.

Biomass provides the bulk of Kenya's energy needs (Tables 20.3 and 20.4), with firewood supplying 80% of the total annual energy requirements (F. Mugo, Nairobi, Kenya, personal communication, 1995). Most of the wood consumed (about 20 million tons) was removed from arable cropland, grazing land, and urbanlands. Only 27% came from forests, yet this amount still exceeded the sustainable yield of the forests by more than 50% (O'Keefe and Raskin, 1985). Consumption exceeded yields by 9 million tons, causing depletion of the standing stocks. The yearly rate of deforestation is 1.6%, primarily because of expanding agriculture but also because of increased needs for firewood (Molofsky et al., 1986).

In addition to wood, crop residues and dung are used to produce biomass energy. Crop residues, including bagasse, total about 4.2 million tons per year (Table 20.4). All bagasse is used in the sugar-refining process. Of the other crop residues, about 30%

of the total harvested biomass, including the woody residue from coffee and tea plantations, is used for energy (O'Keefe, 1983).

Of the 12 million tons of dung produced annually in Kenya, an estimated 0.6 million tons are burned. A survey by Hosier (1985) found that rural people burn animal dung when firewood supplies are insufficient, and then only for heating, not for cooking.

Ethanol production using molasses was started at Muhoroni, Kenya (Stuckey and Juma, 1985). (Another plant near Kisumu was discontinued after cost overruns had nearly tripled its initial \$60 million cost.) The Muhoroni plant, which has a capacity to produce 64,000 L of ethanol per day, can produce 1 L of ethanol for \$0.57, including the cost of molasses, running costs, capital costs, and transportation.

Of the total annual biomass production of 91.3 million tons in Kenya, only 35.2 million tons are produced on arable land, pastureland, and forests, where 80% of the population lives (Tables 20.4 and 20.5). Of these 35.2 t, about 54% is used for fuel and 8.2% for food (Banwell and Harriss, 1992). Further expansion of Kenyan agriculture and increased consumption of firewood will be necessary through 2000 and thereafter to support Kenya's rapidly growing population.

BIOMASS ENERGY USE

Forest and other biomass are produced from solar energy if temperature, soil, water, and biological resources are sufficient for plant growth. In the United States, 14.2×10^{15} kcal of solar energy is collected as plant biomass each year (Tables 20.5 through 20.7). This amounts to 3.0 t/ha/year (Table 20.5). The average yields for Brazil are 2.5 t/ha, for India 3.2 t/ha, and for Kenya 1.25 t/ha. The low yield for Kenya is due to low rainfall (Tables 20.5–20.7).

How does the amount of solar energy collected annually in biomass compare with fossil energy consumed? The United States uses about 40% more fossil energy than all the plant biomass in the United States captures in solar energy. In India, the fossil energy consumed represents about 18.2% of the total solar energy captured by plant biomass; in Brazil this percentage is 6.3%, and in Kenya only 3.5% (derived from Tables 20.3 and 20.5).

CONVERSION OF BIOMASS TO ETHANOL, BIOGAS, AND HEAT

The utilization of some forms of biomass for fuel requires conversion, which frequently requires significant inputs of energy and may cause environmental as well as social problems. In the following discussion, energy inputs, environmental impacts, and social costs are assessed for ethanol, biogas, and heat energy.

ETHANOL

The conversion of sugars to ethanol by fermentation is a well-established technology. Yeast carry out the fermentation in an 8- to 12-h batch process that produces 8%–10% ethanol by volume. The ethanol is then recovered by continuous distillation. Theoretically, each 1 g of sugar or starch should produce 0.51–0.57 g of ethanol. In practice, about 90% of the theoretical yields are achieved (the yeast population consumes

TABLE 20.8
Inputs per 1000 L of Ethanol from U.S. Sugarcane[a]

Inputs	kg	kcal × 10^3	Dollars
Sugarcane	14,000	1938[b]	167[b]
Transport of sugarcane	14,000	400[c]	42
Water	125,000[d]	70	20
Stainless steel	3[d]	45	10
Steel	4[d]	46	10
Cement	8[d]	15	5
Bagasse	1900	7600	—
Pollution costs	—	—	60
Total		10,114	314

[a] Outputs: 1000 L of ethanol = 5,130,000 kcal.
[b] Table 20.9.
[c] Estimated.
[d] Slesser and Lewis (1979).

some of the sugar and starch for its maintenance and growth). The yield of ethanol is about 1 L per 2.7 kg of corn or 14 kg of sugarcane (2.5 kg of sugar) (Table 20.8).

Sugarcane production in the United States requires significant dollar and fossil energy inputs (Table 20.9), which represent the major costs in ethanol production. (For details for producing ethanol from U.S. corn, see Chapter 19.) A hectare of U.S. sugarcane yields an average of 88,000 kg and requires 12.2 million kcal of fossil energy and $1059 to produce (Table 20.9).

Once the sugarcane is harvested, three additional energy costs are involved in its conversion to ethanol: transport to the plant, the conversion process, and pollution control. These costs in both energy and dollar terms are large for a modern chemical plant with an output of 200 million L per year (Pimentel, 1991).

Although the costs of producing ethanol are slightly lower for sugarcane than for corn ($0.31/L, see Chapter 19), the energetics are similar (Table 20.8). The total energy input to produce 1000 L of ethanol using sugarcane is 10.1 million kcal, or about double the energy value of the ethanol itself (5.1 million kcal). However, the fermentation/distillation process for ethanol produced from sugarcane has no energy cost because all the required energy is supplied by conversion of the bagasse by-product. However, in this assessment the fuel energy from the bagasse is charged as a cost (Table 20.8) because the bagasse could be used as an organic fertilizer or a fuel source for other processes. For the sugarcane system, sugarcane feedstock represents 53% of the cost of producing ethanol; thus, the price of the end product depends on the agricultural production costs.

Production of ethanol in the chemical plant also has major pollution costs (Table 20.8), which add 10%–15% to the overall cost of production. For each 1000 L of ethanol produced using sugarcane, 160,000 L of wastewater are produced. This wastewater has a biological oxygen demand (BOD) of 18,000–37,000 mg/L

TABLE 20.9
Average Energy Input and Output per Hectare per Year for Sugarcane in Louisiana[a,b]

	Quantity/ha	10^3 kcal/ha	Dollars/ha
Inputs			
Labor	30 h	21	150
Machinery	72 kg	1944	119
Gasoline	54 L	546	15
Diesel	284 L	3242	75
Nitrogen (ammonia)	158 kg	3318	84
Phosphorus (triple)	97 kg	611	49
Potassium (muriate)	149 kg	373	40
Lime	1120 kg	353	168
Seed	215 kg	802	215
Insecticide	2.5 kg	250	25
Herbicide	6.2 kg	620	62
Transportation	568.9 kg	146	57
Total		12,226	1059
Outputs			
Sugarcane	88,000 kg	24,618,000	
Sugar yield	6600 kg		

[a] Ricaud (1980).
[b] kcal input/kcal sugar = 2.01.

depending on the type of plant (Kuby et al., 1984). (The third supplemental energy input, transportation, is not included in this analysis.)

The foregoing data were based on U.S. sugarcane. Overall costs are slightly lower in Brazil than in the United States (Tables 20.8 and 20.10). The energy inputs for sugarcane production in Brazil are similar to those in the United States (Tables 20.9 and 20.11).

About 1.9 million kcal is required to produce 14,000 kg of sugarcane feedstock, which in turn produces 1000 L of Brazilian ethanol. These figures are similar to the energy inputs required in the United States (Tables 20.8 and 20.10). The total input to produce 1000 L of ethanol is about 9.9 million kcal, nearly double the yield in ethanol of 5.1 million kcal. About half a liter of imported fossil petroleum equivalent is needed to produce 1 L of ethanol (Table 20.10). Others have reported that it takes about 1 L of imported petroleum to produce 1 L of ethanol (Chapman, 1983; Chapman and Barker, 1987).

Brazilian ethanol costs \$0.30/L to produce (Table 20.10). This figure includes pollution costs of \$0.06/L. With the pollution costs removed, the cost is lowered to \$0.24/L, well within the range of \$0.23–\$0.27 reported by others (MME, 1987; Goldemberg, J. personal communication, Institute of Physics, University of São Paulo, Brazil, 1987). This \$0.30/L estimate does not factor in the crop subsidy; doing

TABLE 20.10
Inputs per 1000 L of Ethanol from Brazilian Sugarcane[a]

Inputs	kg	10^3 kcal	Dollars
Sugarcane	14,000	1946[b]	172[b]
Transport of sugarcane	14,000	195	24
Water	125,000	70[c]	20
Stainless steel	3	45[c]	10
Steel	4	46[c]	10
Concrete	8	15[c]	5
Bagasse	1,900	7600	—
Pollution costs	—	—	60
Total		9917	301

[a] Outputs: 1000 L of ethanol = 5,130,000 kcal.
[b] Table 20.11.
[c] Slesser and Lewis (1979).

TABLE 20.11
Average Energy Input and Output per Hectare per Year for Sugarcane in Brazil[a]

	Quantity/ha	10^3 kcal/ha	Dollars/ha[b]
Inputs			
Labor	210 h[c]	157[d]	120
Machinery	72 kg[e]	1944	119
Fuel	262 L[f]	2635	131
Nitrogen (ammonia)	65 kg[f]	1364	42
Phosphorus (triple)	52 kg[f]	336	27
Potassium (muriate)	100 kg[f]	250	27
Lime	616 kg[f]	192	92
Seed	215 kg[e]	271[d]	70
Insecticide	0.5 kg[f]	50	5
Herbicide	3 kg[f]	300	30
Total		7499	663
Output			
Sugarcane	54,000 kg[f]	15,120,000	
Sugar yield	3672 kg		

[a] kcal input/kcal sugar = 2.02.
[b] Calculated based on quantity of inputs.
[c] Calculated from footnote b.
[d] Ghirardi (1983).
[e] Similar to Louisiana (Table 20.9).
[f] da Silva et al. (1978).

so would add 20% to the cost (Nastari, 1983). Sugarcane feedstock accounts for 56% of the total production costs. Further, inputs include the costs for controlling pollution. The BOD of wastewater from Brazilian sugarcane-based alcohol plants has an environmental impact equal to about two-thirds of the wastes produced by the total human population in Brazil (Desai et al., 1980).

In the Brazilian ethanol production system, 2.6 ha per year of land is needed to fuel one automobile (Tables 20.10 and 20.11). Therefore, if all the automobiles in Brazil were fueled using sugarcane-produced ethanol, a total of 26 million ha of cropland would be needed. This amounts to more than one-third of the total cropland now in production (Table 20.2).

Fuelwood and Other Solid Biomass Fuels

The oldest and simplest use for biomass fuel is cooking and heating. Firewood is the most common form of biomass used. In many environments, wood is readily available and can be easily cut and transported to people's homes. It is easily stored and burns slowly.

Firewood supplies have declined in many parts of the world, creating a need on the part of farmers, governments, development agencies, and many others to promote reforestation to improve the firewood supply (Allen, 1986) Generally, these efforts have been categorized under the titles "social forestry" and "agroforestry" and help increase farmer access to wood supplies outside traditional forest systems.

Social forestry, or community forestry, has received much publicity and has been favored by large donor organizations because they feel large forests have a greater visible impact than numerous scattered, small farm woodlots (Khoshoo, T.N., personal communication, New Delhi: Tata Energy Research Institute, 1987). However, social forest projects have not been successful for many reasons (Allen, 1986; Khoshoo, 1987). First, the people planting and caring for the trees do not have the same interest in these plantings as they usually have in their own trees. They tolerate grazing and other activities, and as a result large portions of these forests have been destroyed. Second, harvesting in such a large area is difficult to control and regulate; people who live close to the forest typically harvest a large share of the wood. Third, many people who depend on the social forests must travel long distances to cut; transport their wood. Together these factors have made social forests much less effective than farm woodlots (Allen, 1986).

Agroforestry is the deliberate management of trees on a given piece of land in association with crops, livestock, or a combination of the two (Teel, 1984). In many situations it has been demonstrated that, although the productivity of a given component may decrease in an agroforestry system, the overall productivity of the entire system increases (Kidd and Pimentel, 1992). Agroforestry should not be regarded as the only strategy for providing energy resources for all the rural poor. It is not appropriate for certain areas, such as the rice-growing regions of India, where population densities of people and animals make the survival of trees nearly impossible. There people have had to use locally available biomass, such as crop residues and dung, as fuel. But dung has value as a fertilizer and in protecting the soil from erosion. The manure and urine of milk cows contains

19.5% nitrogen by dry weight (Jewell et al., 1977) and 3.6 million kcal/ton of heat energy (Bailie, 1976). About 195 kg of nitrogen fertilizer is lost for every ton of dry dung burned. Replacing this nitrogen fertilizer, which has an energy value of 2.87 million kcal/ton, costs $0.53/kg, or $103/ton. These values do not include the replacement costs for phosphorus, potassium, and calcium, because these are assumed to be recovered from the ash or as loss to the soil of the organic material in the manure.

Burning crop residues for energy has been proposed. However, many environmental problems are associated with this practice, which involves removing the vegetative covering, a protective layer that significantly decreases soil erosion and water runoff. For example, soil erosion rates may increase 90% when crop residues on soil surfaces are reduced from about 6 t/ha to 0.5 t/ha (Mannering, 1984). Water runoff rates increase 10–100 times when vegetative cover is removed from the land (USDA-ARS and EPA-ORD, 1976). In certain localized land areas that can tolerate some loss of organics without an increase in erosion, crop residues could be an energy source. However, under current agricultural practices in the United States and elsewhere, little or no crop residue should be burned for fuel (ERAB, 1981; Pimentel et al., 1981, 1987).

Burning crop residues is more complicated and costly than burning coal. More work hours are required to tend and stoke the furnace to prevent clogging, control air flow to the chamber, clean the ash, and add small, constant amounts of fuel (Bailie, 1976). Although about 12.5 kg of crops residues equals 1 kg of fuel oil in energy terms, about double the amount of energy is used to obtain the same heat value because of the energy-intensive burning process (OECD, 1984).

Biogas

Biomass material that contains large quantities of water can be effectively converted into usable energy using naturally occurring microbes in an anaerobic digestion system. These systems are presently used with dung and certain plants, such as water hyacinth (though production and harvesting problems are greater with the latter). The system is comparatively simple, utilizing mesophilic bacteria, with an overall construction cost of around $600 (Teel, W., personal communication, Department of Natural Resources, Cornell University, Ithaca, NY, 1987), or complex systems for 320-cow operations costing $120,000 or more for construction (SF, 1983). The basic principles for both are similar.

On a small dairy or cattle operation, manure is loaded or pumped into a sealed, corrosion-resistant digestion tank and held there for 14–28 days at temperatures around 30°C–38°C. In some systems, the manure in the tank is constantly stirred to distribute heat and speed the digestion process. During this period the mesophilic bacteria present in the manure break down volatile solids, converting them into methane gas (65%) and carbon dioxide (35%). Small amounts of hydrogen sulfide may also be produced. These gases are then drawn off through pipes and either burned directly, in the same way as natural gas, or scrubbed to eliminate the H_2S and used to generate electricity. The cost breakdown for one system is listed in Table 20.12.

TABLE 20.12
Energy Inputs Using Anaerobic Digestion for Biogas Production from 100 t Wet (13 t Dry) Cattle Manure[a]

	Quantity	10^3 kcal
Inputs		
Human hours[b]	20 h	—
Electricity	2234 kWh[c]	5822[d]
Cement foundation[e] (30-year life)	0.9 kg[c]	2[f]
Steel (gas collector[e] and other equipment with 30-year life)	35 kg[c]	725[g]
Pumps and motors[h]	0.05 kg[c]	1[g]
Steel truck/tractor[b] for transportation (10-year life)	10 kg[c]	200[g]
Petroleum for transport[b] (10 km radius)	34 L[c]	340[i]
Total		7090
Total output		10,200[j]

[a] The retention time in the digester is 20 days. The unit has the capacity to process 1825 t (wet) per year. The yield in biogas from 100 t of manure (wet) is estimated at 10.2 million kcal. Thus, the net yield is 3.1 million kcal (Pimentel et al., 1978). The energy for heating the digester is cogenerated, coming from the cooling system of the electric generator.

[b] Estimated.

[c] Vergara et al. (unpublished data).

[d] 1 kWh = 860 kcal. Based on an energy conversion of fuel to electricity of 33%; thus, 1 kWh is equivalent to 2606 kcal.

[e] The digester was placed underground. Materials used for its construction were concrete and steel. Materials also included a gas storage tank.

[f] 1 kg of cement = 2000 kcal for production and transport (Lewis, 1976).

[g] 1 kg of steel = 20,700 kcal for mining, production, and transport (Pimentel et al., 1973).

[h] The design included three electrical devices: a motor to drive the agitator in the digester, a compressor to store gas, and a pump to supply hot water.

[i] A liter of fuel is assumed to contain 10,000 kcal. Included in this figure are mining, refining, and transportation costs.

[j] It was assumed that anaerobic digestion of manure takes place at 35°C, with a solids retention time of 20 days. The temperature of the fresh manure is taken as 18°C and the average ambient temperature as 13°C. The manure is assumed to have the following characteristics: production per cow per day, 23.6 kg total; solids, 3.36 kg; biological oxygen demand (BOD), 0.68 kg. The digestion is assumed to transform 83% of the biodegradable material into gas. Gas produced is said to be 65% methane, and its heat of combustion is 5720 kcal/m^3 at standard conditions.

The amount of biogas produced is determined by the temperature of the system, the manure's volatile solids content, and the efficiency of converting them to biogas. This efficiency varies from 18% (Jewell and Morris, 1974) to 95% (Jewell et al., 1977). Dairy cows daily produce 85 kg of manure per 1000 kg live weight. The total solids in this manure are 10.6 kg and of these 8.6 kg are volatile solids. Theoretically, a 100% efficient digester would produce 625 L of biogas from every 1 kg of volatile solids added (calculated from Stafford, 1983). The digester utilized for the data in Table 20.12 was 28.3% efficient, producing 177 L of biogas/kg of volatile solids added. With this digester 1520 L of biogas per 1000 kg live weight will be produced each day. If the total heat value of the manure were used in calculating efficiency, then the efficiency rate would be only 5%.

Biogas has an energy content of about 5720 kcal/m^3, less than the 8380 kcal/m^3 for pure methane because of the carbon dioxide present. When processed into biogas, 100 t of manure (wet weight) yields a total of 10.2 million kcal; the process itself requires 7.1 million kcal energy, so the net energy yield is 3.1 million kcal (Table 20.12). Much of the energy cost comes from the production of electricity to run the pumps and the stirring system used to reduce the retention time in the digester. The volume of the digester is determined by the amount of manure produced by the animals during the usual retention time. In this example, with a retention time of 14 days, the volume would be slightly more than 75 m^3. It is assumed that this added electric energy will be generated from the biogas itself and that the conversion efficiency of this operation is 33%. The energy needed to heat the digester is cogenerated by the electric generator via the use of the generator's cooling system. The net energy produced by the digester can be used either to generate electricity for the farm or as a heat source.

When the biogas is not used to produce electricity, the energy data listed in Table 20.12 will change considerably, and other costs will be associated with the changes. The heat requirements were calculated by including the heat losses to the surroundings, the heat associated with the feed and the effluents, and the heat generated by the biological reaction. Processing biogas for use in engines involves significant amounts of added energy for compression and for removal of hydrogen sulfide and water.

Although material costs are lowered if there is no generator or stirring mechanism on the digester, the size of the digester must be increased because the retention time increases. Also, more of the biogas will have to be used to heat during the extended retention time, as much as 610,000 kcal for every 100 t of wet manure digested (Vergara et al., 1977). In the tropics the overall efficiency of biogas systems is enhanced because the system does not have to be heated.

Dairy cattle are not the only source of manure for biogas systems. They are used as a model because they are more likely to be located in a centralized system, making the process of collecting the manure less time-consuming and energy-intensive than for range-fed steers or even for draft animals. Efficiencies of conversion vary not only from system to system but also from animal to animal (Stafford, 1983). Swine and beef cattle manure appear to yield more gas per kilogram of volatile solids than dairy cattle manure. Poultry manure is also a good source, but sand and other forms of heavy grit in their dung cause pump maintenance problems.

Manure that exits the digester retains its fertilizer value and has less odor than undigested manure. It can be spread on fields in the usual way and may be easier to pump if a cutter pump is used to break up stray bits of straw or long undigested fibers. Biogas systems can easily be adapted in size according to the scale of the farm operation. However, the pollution problem associated with manure produced in centralized dairy production systems remains.

Biogas for Small Landholders

The costs and benefits of biogas production in a rural area of a developing nation such as Kenya or India are mixed. The capital costs of constructing a simple biogas

TABLE 20.13
Energy Inputs for an Anaerobic Digester for Biogas Production Using 8 t Wet (1 t Dry) Cow Manure[a,b]

	Quantity	kcal
Output from 1 t biomass (dry) methane gas	143 m^3	820,000[c]
Inputs for 1 t biomass		7140
Cement foundation (30-year life)	0.07 kg[d]	140[e]
Steel (30-year life)	0.33 kg	7000[f]
Net return/ton dry biomass		812,860

[a] The retention time is 20 days without a means of storing the methane gas (Pimentel, unpublished data).
[b] Efficiency = (812,840 kcal output)/(4.7×10^6 kcal input) $\times$ 100 = 17.3%. The input is the energy content of manure if burned.
[c] It was assumed that anaerobic digestion of biomass takes place at 35°C with a solids retention time of 20 days. The temperature of the fresh biomass and the average ambient temperature are taken as 21°C. The efficiency of the digester is 25%. Gas produced is said to be 65% methane, and its heat of combustion is 5720 kcal/m^3.
[d] Vergara et al. (unpublished data).
[e] 1 kg of cement = 2000 kcal for production and transport (Lewis, 1976).
[f] 1 kg of steel = 21,000 kcal for mining, production, and transport (Pimentel et al., 1973).

digester with a capacity to process 8 t (wet) of manure per 20-day retention period, or 400 kg per day (Table 20.13), are estimated to be \$2000–\$2500. Because the unit would have a life of 30 years, the capital cost would be about \$80 per year. If rural workers were to construct the generator themselves, material costs might range from \$300–\$600. If we assume \$400, the capital investment would be only \$14 per year for the life of the digester.

A digester this size in India, where the cows are much smaller and produce only 225–330 kg manure each per 20 days, would require access to 20 cows. With a conversion rate of 25% (Table 20.13) this amount of manure would produce an estimated 2277 m^3 of biogas per year with an energy value of 13.0 million kcal. Assuming \$8.38/million kcal, the value of this much energy would be \$109. If no charge is incurred for labor and dung, and the capital cost is only \$14/year, the annual net saving is \$95.

Although the labor requirement for running the generator described is only 5–10 min per day, the labor input for collecting and transporting biomass for the generator may be significant. For instance, if the required 400 kg of manure had to be transported an average of 3 km, it would take two laborers a full 8-h day to collect it, feed it into the digester, and return it to the fields where it could be utilized as a fertilizer. The laborers would have to work for about \$0.03/h to keep labor costs equal to the value of the gas produced. However, in densely populated areas or with centralized systems, the amount of transport would be minimal.

Although the profitability of small-scale biogas production may be low even without labor costs, digesters have advantages, especially in rural areas. Manure biomass can be processed and fuel energy can be obtained without loss of the valuable nutrients (nitrogen, phosphorus, potassium, and sulfur). Nitrogen and phosphorus are major limiting nutrients in tropical agriculture. The only change in the manure is the breakdown of its fibrous material, making it less effective in controlling soil erosion (Pimentel, 1980). By contrast, when manure is burned directly as a fuel, nitrogen and other valuable nutrients are lost to the atmosphere. The biogas slurry from the U.S. cattle example (146 t/year) contains approximately 3.7 t of nitrogen. This has an energy value of 77 million kcal and, as chemical fertilizer, a market value of $1960 ($0.53/kg) (USDA, 1991b). Therefore, producing biogas is more cost effective than burning manure. When the value of the retained nitrogen and the gas output are combined, the return of the system is about $6.42/h of work.

Another consideration in assessing the use of biogas production is the possibility of replacing firewood with biogas as an energy resource. The production of 2277 m^3 of biogas (13.0 million kcal) would replace 3 t of firewood, which has an average energy value of 4500 kcal/kg (NAS, 1980). Because gas is more efficient than wood for cooking (heating), the amount of wood replaced could double. In areas where wood is scarce, biogas could diminish reliance on wood and slow deforestation.

SOCIOECONOMIC FACTORS

Promoters of biomass energy emphasize its benefits to society, the economy, and the environment (Hall et al., 1985; Sourie and Killen, 1986). These include the creation of jobs, increased economic development, reduction in energy cost, debt reduction, and the use of indigenous technology. In this section we attempt to make a detailed analysis of the socioeconomic benefits and costs of the Brazilian alcohol fuels program, which is frequently cited as demonstrating the benefits of biomass energy. In addition, some data are presented on the socioeconomic impact of biomass energy use in the United States.

BRAZIL

The Brazilian alcohol program, PROALCOOL, is held up as a model of how developing countries can meet their fuel oil needs using renewable biomass resources such as sugarcane. Alcohol production appeared to be an elegant solution to many problems faced by developing countries in the early 1970s. Substituting a homegrown energy resource for costly imported fuel made sense. Sugarcane had been cropped in Brazil since the earliest days of colonization, and Brazilians had conducted research on alcohol production from sugar. Because the concept sounded so sensible and the press coverage was so good, PROALCOOL moved ahead rapidly with little or no criticism.

Analyzing the socioeconomics of Brazilian alcohol production is complicated. Not only must the relationship between the price and elasticity of demand for sugar, alcohol, and gasoline be carefully examined, but this must be done within the context of often rapid inflation and with the limited data provided by the Brazilian government. Although a total analysis is needed, this assessment focuses on the costs of alcohol production in Brazil and the known effects of alcohol production on food prices, food availability, and employment.

By all accounts appearing in the literature, the costs of alcohol production are higher than the price Petrobras charges retailers for alcohol (Ortmaier, 1981). Thus, the Brazilian government must subsidize to make up the difference. Of course, pricing depends on the world prices for sugar and gasoline at any given time. The Ministry of Industry and Commerce published the statement that 56% of the cost of alcohol production was assigned to the purchase of sugarcane, resulting in a production cost of \$0.33/L (Pimentel et al., 1988).

The high cost of production necessitated government subsidies for alcohol producers. According to Nastari (1983), from 1976 to 1980 subsidies reached 61 billion cruzeiros, or about \$490 million per year. Alcohol producers increased their gross income by more than 200% in this same time period (Nastari, 1983). Although the large subsidies contribute significantly to the Brazilian debt, ethanol production helps the government reduce the amount of foreign exchange expended to import oil. Brazil imports about 39 million L, or \$9 billion worth, of oil annually and has to pay an interest rate of about 4.7% per annum on all borrowed money (World Development Report, 1995). Thus, the production of 9.1 L of ethanol helps reduce the amount of oil imported and, in turn, the level of costly borrowing. However, 1 L of ethanol does not equate to 1 L of imported oil. About 0.5 L of oil equivalent has to be imported to produce 1 L of ethanol.

A fundamental economic issue generated by the PROALCOOL program is the relationship among alcohol production, the price, and the availability of food. This matter is usually discussed only in terms of the relative proportion of land devoted to energy crops and food crops. The question is particularly complicated in a country such as Brazil, which has abundant cropland and the capacity to provide far more food than its population can consume. Despite the availability of this cropland, 25% of Brazil's population is malnourished (Calle and Hall, 1987).

Many factors determine the price and availability of foods, but supply and demand are the primary ones. From 1971 to 1980 an increasing percentage of land was planted to sugarcane and export crops, including soybeans, whereas the percentage of land with food crops remained constant from 1976 to 1980 (Table 20.14).

TABLE 20.14
Trends in Areas under Sugarcane and Other Crops in Brazil from 1971 to 1980[a]

	1971–1973	1975	1976	1977	1978	1979	1980
Alcohol production (10^6 L)[b]	654	556	664	1,470	2,491	3,396	3,786
Area under sugarcane (10^3 ha)	1,830	1,969	2,093	2,270	2,391	2,537	2,607
Soybeans (10^3 ha)	2,507	5,824	6,417	7,070	7,782	8,256	8,766
Food crops (10^3 ha)[c]	24,659	25,837	28,036	28,270	26,922	27,542	28,030
Export crops (10^3 ha)[d]	12,951	15,566	14,526	16,730	17,789	18,408	18,949
Total cultivated area (10^6 ha)	37.3	42.0	43.3	45.7	45.5	46.8	47.9

[a] OECD (1984).
[b] Production from May of the year concerned until April of the following year.
[c] Rice, potatoes, beans, manioc, maize, wheat, bananas, onions.
[d] Cotton, groundnuts, cocao, sissal, coffee.

Between 1973 and 1980 black bean production declined by 16% and sweet potato production declined 56% (OECD, 1984). From 1976 to 1981, the total area planted for three basic staple crops—maize, rice, and black beans—remained stable at about 1.9 million ha (Pluijm, 1982). During this period the Brazilian population increased by about 15 million people (PRB, 1977), increasing food demand by about 12%.

In São Paulo state, where 70% of the alcohol is produced, significant changes have taken place in agriculture since the start of the PROALCOOL program. Sugarcane production increased by 1.1 million ha from 1968/1969 to 1982/1983, whereas acreage planted in food crops declined by 0.4 million ha during the same period (excluding soybeans that are exported) (Calle and Hall, 1987). About 60% of the expansion in sugarcane acreage came from reclaimed pastureland, adversely affecting milk and meat supplies. In this same period, export crop acreage increased by 0.2 million ha, further diminishing acreage used for domestic food crop and milk/meat production (Calle and Hall, 1987).

The stagnant levels of food production in Brazil overall and growing food demand have led to reduced availability and high prices of food (La Rovere, 1985). In 1976 riots broke out in Rio de Janeiro over a shortage of the local staple, black beans, coupled with general political and economic unrest (Goldemberg, 1987). The decline in black bean availability led to the importation of black beans from Chile. The cycle continued, with increases in alcohol production and export crops, accompanied by a decline in per capita output of major staple food crops. At the same time, food prices increased more than the general inflation rate, an occurrence without precedent in Brazil's economic history (La Rovere, 1985).

An additional incentive to produce sugarcane and alcohol was provided by the rapidly escalating value of land located near distilleries. Land prices in Brazil for producing sugarcane rose to about $1500/ha (Ghirardi, 1983). With the income of the Brazilian laborer estimated to be about $1000/year, it would take a laborer many years to save sufficient money to purchase even 1 ha of land. Increased land values also encouraged smallholders, who usually grow food crops for domestic consumption, to sell their land to large sugarcane growers, thereby expanding the land area devoted to sugarcane (Pluijm, 1982). Because most distilleries are located close to towns and urban centers, basic food production has moved farther away from food consumers, increasing the energy costs of transport and contributing to higher food prices.

The workplace and wages were also affected by the PROALCOOL program. Landless agricultural workers who live on the periphery of cities accept almost any job they can find, often being trucked to rural areas each day to work in the fields (Desai et al., 1980). Thousands of small farmers were transformed into landless laborers during a period in which food production for the domestic market was stable. Small farmers provide the bulk of their own subsistence. The displacement of small subsistence farmers meant food production for domestic consumption would have to increase to enable these workers to eat as they once did. This did not occur. Instead, about 40% of the Brazilian labor force now earns a minimum wage of about $100/month, or about $0.63/h. Basic foods per month for a family cost three times this wage (World Tables, 1995).

Another aspect of the food-versus-fuel question is employment. According to Ortmaier (1981), 51% of the land converted to sugarcane in 1975 previously had been planted to food crops. Whenever sugarcane production replaced a more labor-intensive crop or a crop providing year-round employment, a net loss of jobs resulted.

Typically, sugarcane/alcohol production work is highly seasonal, resulting in at least 50% unemployment among sugar and alcohol workers during the 4-month off-season (OECD, 1984). Only when sugarcane production is accompanied by diversified agricultural production can people find steady work. This is not the usual practice.

Projections concerning the creation of jobs because of the ethanol program were encouraging. The World Bank (1980) reported that 1 new job would be created for each 20,000 L of alcohol produced and that 172,000 new jobs would be created if alcohol production was increased by about 7 billion L. A similar trend was suggested by Pereira (1983). OECD (1984) projected that 27,700 jobs would be created if the increased production was from large alcohol plants (production of up to 120,000 L of alcohol per day). However, other analysts reported that the overall increase in employment was not as great as anticipated, with far fewer jobs created than either the World Bank or the Brazilian government projected (OECD, 1984).

Obviously, the 25% of the people who are malnourished (Calle and Hall, 1987) and the 40% who are unemployed have not benefited from the Brazilian alcohol program. Their plight contrasts sharply with the 10% of the people who own cars and have benefited from low fuel costs of the subsidized ethanol program (Kurian, 1995).

United States

Although biomass production in the United States has certain problems (Pimentel, 1991), it will provide at least one advantage—some increased employment. For example, the direct labor inputs for wood biomass resources are 2–30 times greater per million kcal energy produced than for coal (Pimentel et al., 1983a); thus, wages would be lower for workers in biomass production. A wood-fired steam plant requires two to five times more construction workers and three to seven times more workers per plant. Total employment overall would be expected to increase from 5% to 20% depending on the quantities of biomass used and general economy of the nation.

However, a shift to more biomass energy production can be expected to increase occupational hazards in the industry (Morris, 1981). Significantly more occupational injuries and illnesses are associated with biomass production in agriculture and forestry than with either coal (underground mining), oil, or gas recovery operations (OTA, 1980). Agriculture has the highest rate of injuries—25% more injuries per day of work than any other private industry (OTA, 1980). The total injury rate in logging and other forest industries annually averages about 25 per 100 full-time workers, whereas it is about 11 for bituminous coal miners, who work mostly underground (BLS, 1978, 1979, 1980, 1981). Per kilocalorie output, forest biomass production has 14 times more occupational injuries and illnesses than underground coal mining and 28 times more than oil and gas extraction (BLS, 1978).

Food and lumber products have a higher economic value per kilocalorie in their original form than when converted into either heat, liquid, or gaseous energy (ERAB, 1980, 1981; OTA, 1980). For example, 1 million kcal of corn grain has a market value of $40, but when converted to heat energy it has a value of only $5. Producing liquid fuels (e.g., ethanol) is also expensive. A liter of ethanol now costs about \$0.40 to produce; nearly 65% of the cost of production is for the grain itself (Pimentel et al., 1991).

Subsidies help make gasohol competitive with gasoline. Federal and state subsidies may range as high as \$0.36/L for U.S. ethanol (OTA, 1980). As a result, when production and subsidies are included, a liter of ethanol costs \$0.83, compared with the \$0.15 cost of a liter of gasoline at the refinery (Pimentel, 1991). For the equivalent of 1 L of gasoline (8000 kcal), 1.5 L of ethanol (5310 kcal/L) would be needed, with a total value of \$1.25.

The real cost to the consumer is greater than the \$0.83 needed to produce a liter of ethanol because 50% of all grain consumed in the United States is fed to livestock (WRI, 1994). Therefore, shunting corn grain into ethanol will increase the demand for grains, resulting in higher grain prices. Higher grain prices will in turn raise the consumer prices of meat, milk, and eggs (ERAB, 1980).

ENVIRONMENTAL IMPACTS

The removal of biomass from land for energy production increases the effects of wind and water on soil degradation. Erosion and increased water pollution and flooding disrupt many wildlife communities and may adversely affect the health of some human populations.

Soil Erosion Problems in Biomass Systems

It is difficult to derive biomass for energy use from crops such as corn, sugarcane, wheat, and rape grown on sloping land that is unsatisfactory for agriculture (Figure 20.1). High

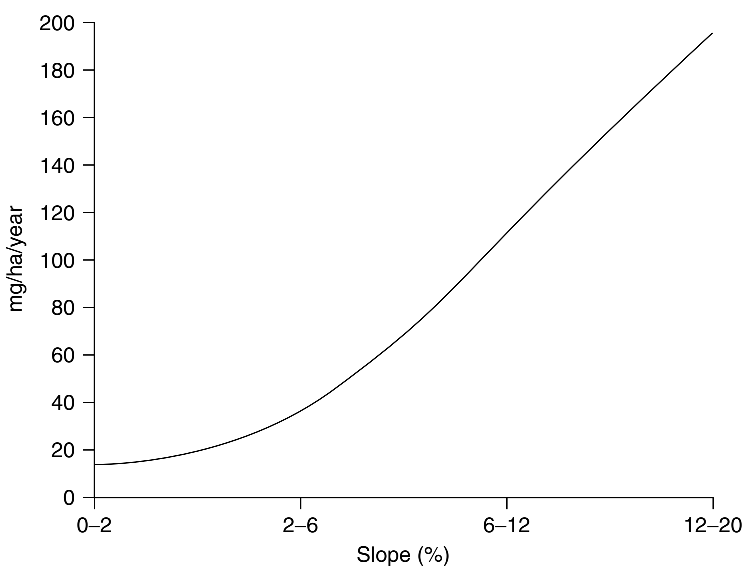

FIGURE 20.1 Increased soil erosion rates (mg/ha/year) associated with rising land slope percentages.

erosion rates for these crops occur even when biomass residues are left on the land (Table 20.15). If these crop residues are harvested for fuel, the erosion rates increase (Pimentel et al., 1981). For example, leaving 6.7 t/ha of corn residues on land will keep erosion rates at 1–1.6 t/ha when no-till planting is employed. However, if 4–5 t/ha of residues are removed, soil loss increases about eight times (Table 20.16). This latter erosion rate is about 14 times greater than the soil re-formation rate (Pimentel et al., 1987). The production of forage and hay crops for energy is possible on land with slopes of up to 12%, provided that care is taken to maintain a dense stand of vegetation cover and that good management practices are employed in the harvesting of biomass (ERAB, 1981). Unless steps are taken to protect soil, the removal of crop residues from slopes of 2% or greater would seriously degrade soil resources.

Soil erosion rates of undisturbed forests, with their dense soil cover of leaves, twigs, and other organic material, typically range from less than 0.1 to 0.2 t/ha/year (Megahan, 1972, 1975; Dissmeyer, 1976; Patric, 1976; USFS, 1977; Yoho, 1980; Patric et al., 1984). These conditions make most natural forest soils, even those on steep slopes of 70%, fairly resistant to erosion and rapid water runoff.

Forests lose significant quantities of water, soil, and nutrients when the trees are cut and harvested. For instance, the surface runoff after a storm from a forested watershed averages 2.7% of the precipitation; after forest cutting and farming, water runoff rises to 4.5% (Dils, 1953). Clear-cutting of trees without harvest and without soil disturbance causes flood damage from high stream flow to occur 10% more often than with the normal forest stand (Hewlett, 1979). Replacing natural forest growth with coppice forest regrowth increases annual stream flow about 10 cm above normal (Swank and Douglass, 1977). Nitrogen leached after forest removal may be six to nine times greater than in forests with normal cover (Hornbeck et al., 1973; Patric, 1980).

In any area, harvesting timber and pulpwood greatly increases erosion, because covered land becomes exposed and the clearing process disturbs the soil. Typically, tractor roads and skid trails severely disturb 20%–30% of the soil surface (Megahan, 1975; Froelich, 1978). Harvesting techniques such as highland and skyline disturb 10%–20%, whereas balloon harvesting disturbs only about 6% of the land area (Rice et al., 1972; Swanston and Dyrness, 1973). Further, the heavy equipment used compacts the soil, causing increased water runoff.

For example, compaction by tractor skidders harvesting ponderosa pine reduce growth in pine seedlings from 6% to 12% over a 16-year period (Froelich, 1979). Water percolation in wheel-rutted soils is significantly reduced for as long as 12 years and in log-skid trails for 8 years (Dickerson, 1976). This creates a long-range problem, because lack of water is the major limiting factor in forest biomass production. Growth of slash pine in Florida over a 5-year period with irrigated treatment is 80% greater than in the untreated acreage (Baker, 1973). Depending on slope, soil type, and climate, the effects of soil compaction on tree growth may last from 8 to 16 years (Dickerson, 1976; Froelich, 1979).

Though erosion rates can be as high as 215 t/ha/year on severely disturbed slopes, average soil erosion in harvested forests ranges from 2 to 17 t/ha/year, with long-term averages between 2 and 4 t/ha/year (USFS, 1977; Yoho, 1980; Patric, 1976). Erosion from conventional logging can last for 20 years, but the most serious erosion ceases in about 5 years, when vegetation cover becomes established (Patric,

TABLE 20.15
Selected Erosion Rates in Certain Geographical Regions

Country	Erosion Rate (t/ha/year)	Comments	Sources
United States	13[a]	Average, all cropland	USDA (1994)
Midwest, deep loess hills (Iowa and Missouri)	35.6[a]	MLRA[b] # 107, 2.2 million ha	Lee (1984)
Southern high plains (Kansas, New Mexico, Oklahoma, and Texas)	51.5[a]	Lee (1984) MLRA[b] # 77, 6.2 million ha	
Brazil	150	Beans grown up and down slope	Silva et al. (1985)
	12	Beans grown with agroforestry	
India	25–30	Cultivated land[c]	DST (1980)
	28–31	Cultivated land	Narayana and Babu (1983), CSE (1982)
Deccan black soil region	40–100		
China	43	Average, all cultivated land middle reaches, cultivated rolling loess	Brown and Wolf (1984)
Yellow River basin	100	Brantas River basin	AAC (1980)
Java	43.4		Brabben (1981)
Belgium	10–25	Central Belgium, agricultural loess soils	Bollinne (1982; in Richter, 1983)
East Germany	13	1000-year average, cultivated loess soils in one region	Hempel (1951, 1954; in Zachar, 1982)
Ethiopia	20	Simien Mountains, Gondor region	Lamb and Milas (1983)
Madagascar	25–40	Nationwide average	Randrianarijaona (1983); Finn (1983)
Nigeria	14.4	Imo region, includes uncultivated land	Osuji (1984)
El Salvador	19–190	Acelhuate basin, land under basic grains production	Wiggins (1981)
Guatemala	200–3600	Corn production in mountain region	Arledge (1980)
Thailand	21	Chao River basin	El-Swaify et al. (1982)
Burma	139	Irrawaddy River basin	El-Swaify et al. (1982)
Venezuela and Colombia	18	Orinoco River basin	El-Swaify et al. (1982)

[a] Indicates combined wind and water erosion, all others are water erosion only.
[b] MLRA: major land resource area.
[c] Assumes that 60%–70% of the 6 million tons of topsoil lost is from cultivated land.

TABLE 20.16
Percentage of Soil Loss from Several Conservation Tillage Systems Compared with Conventional Tillage on Land with Continuous Corn Culture[a]

	Surface Residue after Planting (%)				
Tillage System	**1.1–2.2 t/ha**	**2.2–3.4 t/ha**	**3.4–4.5 t/ha**	**4.5–6.7 t/ha**	**Over 6.7 t/ha**
Till planting (chisel, disk)	89	61	48	33	20
No till	71	48	33	18	8

[a] Continuous corn with conventional tillage on land with a slope of 2% or more will suffer about 20 t/ha/year soil erosion.

Source: Mannering, J.V., Agronomy Guide (Tillage) AY–222, Cooperative Extension Service, Purdue University, West Lafayette, IN, 1984.

1976). Although erosion caused by forest harvesting is not great compared to that associated with row crop production, its effects can be long-lasting because of the extremely slow rate of soil formation in forest ecosystems. The nutrients lost when topsoil is eroded also affect forest growth. Losing 3 cm of soil surface reduces biomass production in ponderosa pine, Douglas fir, and lodgepole pine seedlings as much as fivefold (Klock, 1982).

As the need to produce more biomass for energy becomes critical in countries such as Brazil, more land will have to be placed under cultivation to supply it. If this additional land is taken from food crop acreage, farmers may be forced to clear forests or use poor-quality cropland in an effort to maintain or augment the level of food production to feed the expanding human population. Utilization of poor-quality land for crops only will further intensify soil erosion rates. Often these marginal lands are on slopes, making them highly susceptible to erosion when planted to crops.

Nutrient Losses and Water Pollution Associated with Biomass Energy and Erosion

Rapid water runoff and soil nutrient losses occur when crop residues are harvested and subsequent rainfall erodes soils. Water quickly runs off unprotected soil because raindrops free small soil particles, which in turn clog holes in the soil and further reduce water infiltration (Scott, T.W., personal communication, Department of Agronomy, Cornell University, Ithaca, NY, 1985). For example, conventional corn production causes an average of about 5 cm/ha/year more water runoff than production employing conservation practices (Pimentel and Krummel, 1987). Harrold et al. (1967) reported that under conventional corn production, erosion reduced soil moisture volume by about 50% compared with no-till corn culture. Rapid water runoff not only diminishes the amount of water reaching plant roots, it also carries valuable nutrients, organic matter, and sediments with it. Soil nutrient losses have a major negative effect on soil quality. One ton of fertile agricultural soil contains about 4 kg of nitrogen, 1 kg of phosphorus, and 20 kg of potassium (Buttler, I., personal communication, Department of Agronomy, Cornell University, Ithaca, NY, 1986). Based on these soil nutrient values

TABLE 20.17
Nitrogen, Phosphorus, and Potassium Content of Crop Residues and Firewood

	Nutrient Content (%)		
	Nitrogen	Phosphorus	Potassium
Corn[a]	1.1	0.2	1.3
Rice[a]	0.6	0.1	1.2
Wheat[a]	0.7	0.1	1.0
Soybean[a]	2.3	0.2	1.0
Sugarcane[a]	1.0	0.3	1.4
Firewood[b]	0.12	0.01	0.06

[a] Power and Papendick (1985).
[b] Pimentel et al. (1983b).

and average U.S. erosion rate of 18 t/ha/year, erosion causes an average yearly loss of about 72 kg/ha of nitrogen, 18 kg/ha of phosphorus, and 360 kg/ha of potassium.

When conservation technologies are employed by protecting the soil with residues and vegetation, increased crop yields result because water, nutrients, and soil organic matter are retained. For example, in Texas, yields of cotton grown on the contour and with ample soil protection are 25% greater than from cotton grown with the slope (Burnett and Fisher, 1954). Similar results have been reported for corn (12.5%) in Missouri (Smith, 1946) and for corn (12%), soybeans (13%), and wheat (17%) in experiments in Illinois (Sauer and Case, 1954). On land with a 7% slope, yields from cotton grown in rotation increase 30%, and erosion is cut nearly in half (Hendrickson et al., 1963). In Nigeria, yields from no-till corn grown under favorable soil and climatic conditions are 61% greater than from corn grown with conventional tillage (Wijewardene and Waidyanatha, 1984). In an experiment comparing tillage practices used on 22 consecutive maize crops grown on highly erodible Nigerian soils, the average grain yields from no-till plots were 20% higher than those from conventional plots because of the accumulated effects of erosion-induced degradation of the unprotected soil (Lal, 1983).

When crop residues are removed and burned, significant quantities of nutrients are lost. On average, residues contain about 1% nitrogen, 0.2% phosphorus, and 1.2% potassium (Table 20.17). When burned, the nitrogen volatilizes into the atmosphere, and 70%–80% of the phosphorus and potassium is lost with the particulate matter during the process (Flaim and Urban, 1980). Thus, a relatively small percentage of the nutrients in crop residues would be conserved, even if the ash residue were returned to the cropland.

Air Pollution

The smoke produced when firewood and crop residues are burned for energy contains nitrogen, particulates, and other chemicals, making it a serious pollution hazard. A recent EPA report (1986) indicated that although burning wood provides only about 2% of U.S. heating energy, it causes about 15% of the air pollution in the United States. Emissions from wood and crop residue burning are a threat to public health, because of the highly respirable nature of some of the 100 chemicals the emissions contain (Pimentel et al., 1983a). Of special concern are the relatively high concentrations of potentially carcinogenic polycyclic organic compounds (POMs, e.g., benzo(a) pyrene) and particulates. Sulfur and nitrogen oxides, carbon monoxide, and aldehydes are also released, but usually in smaller quantities (DOE, 1981; Morris, 1981). According to the Department of Energy (1980), wood smoke contains "up to 14 carcinogens, 4 co-carcinogens, and 6 cilia toxic and mucus coagulating agents." Concern is being expressed for people in developing nations who cook indoors, breathing in the smoke released by burning wood, dung, and crop residues.

The concerns of inhaling wood smoke have been particularly great in India, where people commonly cook in inefficient stoves known as *chullahs* without venting the smoke from the house. Wood smoke, as mentioned, contains many dangerous chemicals, including carbon monoxide, which has been associated with poor fetal development and heart disease in Indian women (Sharma, 1987). Sharma (1987) also reported that women are routinely exposed to chemicals and suspended particulate matter levels as much as 10 times higher than safe public health levels.

Air particulates increase when dung is used in addition to or in place of wood as a fuel (CSE, 1985). However, biogas can be a healthier energy option for cooking than dung. In India, 1000–1050 Mt of wet dung is available from 237 million cattle for recycling into biogas. The 206 Mt/year of manure slurry provides about 1.4 Mt of nitrogen, 1.3 Mt of phosphate, and 0.9 Mt of potash for the soil (Khoshoo, 1986). As of 1992, approximately 1.4 million biogas plants were operational in India; their use predicted to save 1.2 Mt of wood equivalent each year (Sinha, 1992).

Methanol and ethanol are also proposed as cooking-fuel options. These are liquid fuels, made from wood or crops such as sugarcane and cassava, but the short supply of these crops makes the process expensive (CSE, 1985).

Off-Site Environmental Effects from Biomass Harvesting and Erosion

Harvesting biomass and thereby intensifying erosion and water runoff causes several off-site environmental problems. For instance, water runoff in the United States is "delivering approximately 4 billion t/year of sediment to waterways in the 48 contiguous states" (Pimentel, 1995). About 60% of these sediments come from fertile agricultural lands (Highfill and Kimberlin, 1977). These off-site effects cost an estimated $6 billion annually in the United States (Clark, 1985). Dredging several million cubic meters of sediments from U.S. rivers, harbors, and reservoirs is costly. An estimated 10%–25% of new reservoir storage capacity in the United States is built solely to store sediments (Clark, 1985). These problems are universal. For example, in India, the cost associated with low water flows and heavy siltation that have reduced the storage capacity of reservoirs was estimated to be about $427 million per year in 1980 (Myers, 1986b).

Soil sediments, particularly those containing pesticides and fertilizer nutrients, that are carried into rivers, lakes, and reservoirs from agricultural and forest lands adversely affect fish production (USDI, 1982). Sediments interfere with fish spawning, increase predation on fish, and frequently destroy fish food (NAS, 1982).

These destructive effects reach into estuarines, coastal fisheries, and coral reefs (Alexander, 1979; Day and Grindley, 1981). In the United States, the diverse effects of soil erosion on fish and other wildlife, as well as on water-storage facilities and waterway navigation, are estimated to cost $4.1 billion each year (Clark, 1985).

CONCLUSION

Reaching a sound balance between biomass-food and biomass-fuel production would bring additional economic benefits, despite the fact that food is given higher priority by society and has higher price values than biomass fuels. When governments subsidize biomass fuel production—as in Brazil and the United States with ethanol programs based on sugarcane and corn grain, respectively—a few producers may make enormous profits. In Brazil, revenues to sugarcane growers increased 200% with the ethanol program (Nastari, 1983). However, the heavy subsidization of biomass fuel tends to give higher priority to biomass fuel rather than food. The result is often reduced food production and higher food prices. Food shortages and high food prices have many negative effects for society, including poor child nutrition. The poor commonly suffer the most when food costs rise. Without sound soil and water conservation policies, subsidizing biomass fuel can result in poorer management of important soil, water, and biological resources (ERAB, 1981).

Other societal effects from biomass fuels programs include reducing the standard of living of the labor force, as happened in Brazil (Pluijm, 1982; OECD, 1984). In addition, the occupational risks in the labor force increase when biomass fuels are given priority over fossil fuels (Pimentel et al., 1984).

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