9

Biomass Plantation Energy Systems and Sustainable Development

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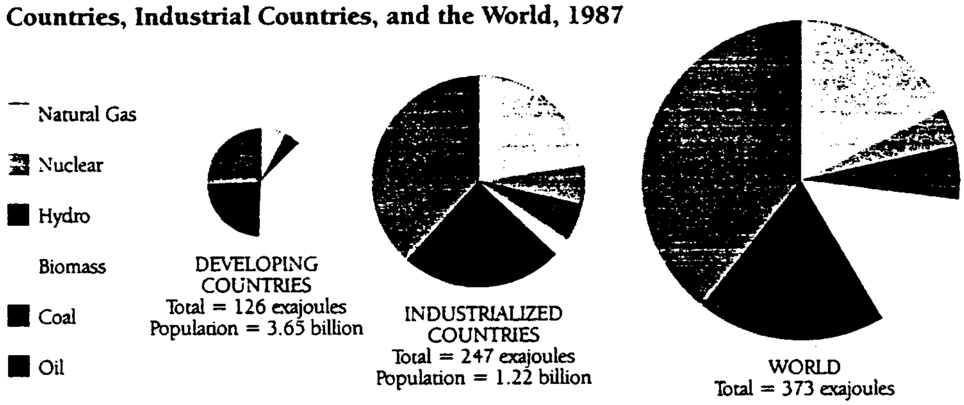
FIGURE 9.1

Estimated Energy Use Distribution in Developing Countries, Industrial Countries, and the World, 1987



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Biomass today accounts for over one third of all energy used in developing countries (see Figure 9.1). It has been called "the poor man's oil" because its direct use by combustion for domestic cooking and heating ranks it at the bottom of the ladder of preferred energy carriers.[2] Existing biomass-using technologies are relatively inefficient; thus, biomass provides less energy service than the proportion of total energy it represents, and women and children in rural areas spend considerable time collecting daily fuelwood needs. Biomass energy use today also contributes to indoor air pollution and associated negative health impacts. *(Editor's Note: see chapters 2 and 5 in this volume.)* Furthermore, most biomass energy today comes from natural forests, contributing to deforestation in some countries.

Biomass has the potential to provide a much higher level of energy services in developing countries, in environmentally friendly ways, if the production and conversion of biomass is modernized.[3] A recent assessment of the potential for renewable energy, prepared as input for the U.N. Conference on Environment and Development (UNCED), found that sustainable biomass energy systems could be the largest single contributor to global energy supply; the study found that under a "Renewables-Intensive Global Energy Scenario" (RIGES), biomass could provide as much as 35 per cent of the total demand for primary energy in 2050 (see Figure 9.2a).[4] A "sustained growth scenario" developed by the Shell International Petroleum Company's Group Planning Division found biomass' potential contribution to total energy supplies in 2050 to be similar (about 210 EJ—one Exajoule is 10^{18} joules) (see Figure 9.2b).[5]

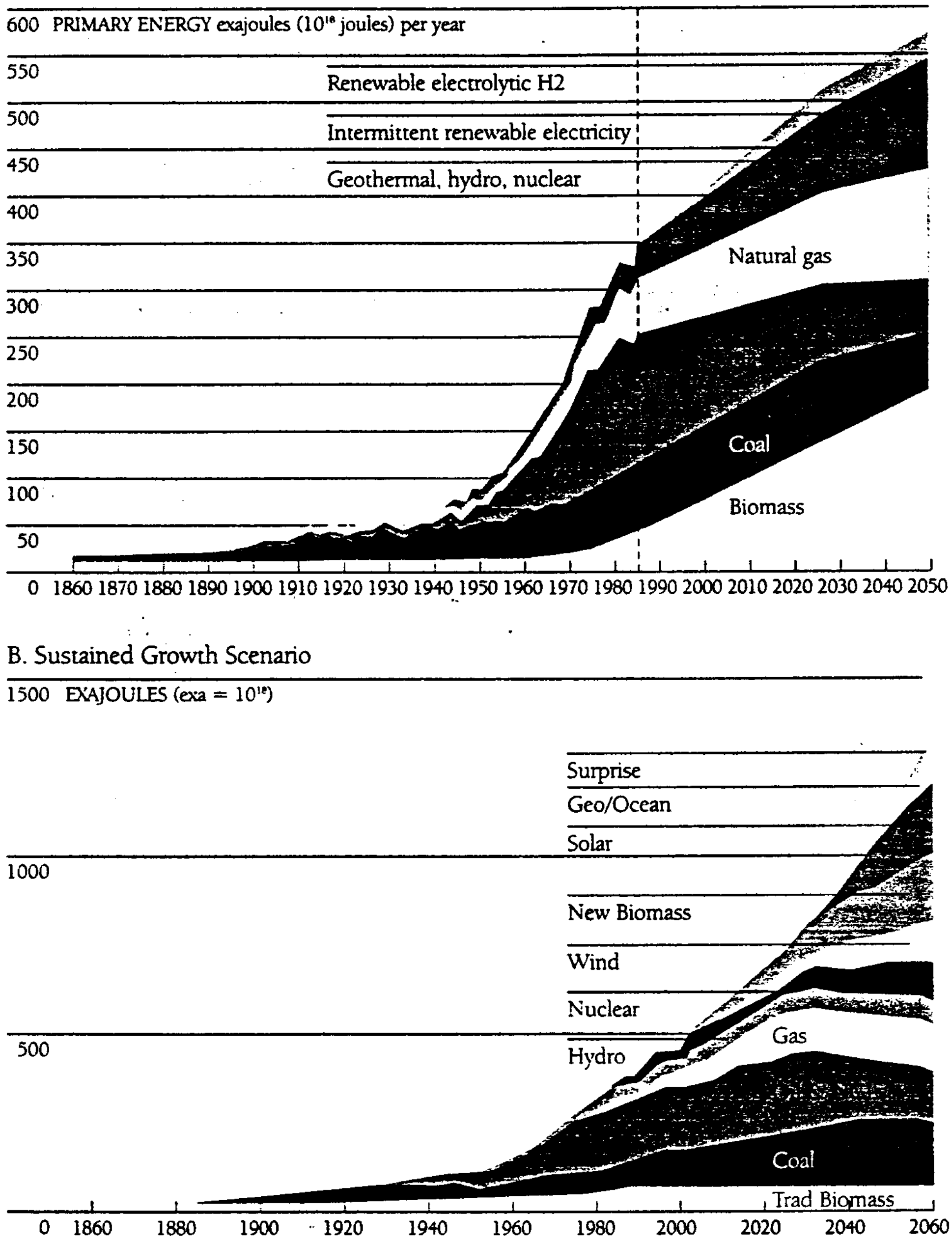
Such visions of large contributions by biomass to global energy supply are plausible because ongoing technological advances offer the promise of being able to turn biomass into more desirable forms of energy (such as electricity and liquid and gaseous fuels) in ways that are both environmentally friendly and economically competitive with fossil fuel alternatives.[6] These technological advances are of comparable significance to the fundamental technological developments (steam turbines and internal combustion engines) that were largely responsible for the expansive growth in global fossil fuel use that began late in the nineteenth century.

In the RIGES, the majority of biomass energy supplies come from high-yielding energy plantations covering some 430 million hectares worldwide, or an area equivalent to roughly one fourth the area currently used for agriculture worldwide. Africa

FIGURE 9.2

Two Biomass-Intensive Future Global Energy Scenarios

A. Renewables-Intensive Global Energy Scenario (RIGES)



Sources: Part A is the renewables-intensive global energy scenario (RIGES) of T.B. Johansson, H. Kelly, A.K.N. Reddy, and R.H. Williams, "Renewable Fuels and Electricity for a Growing World Economy: Defining and Achieving the Potential," Chapter 1, pp. 1-71, and "A Renewables-Intensive Global Energy Scenario," Appendix to Chapter 1, pp. 1071-1142, in T.B. Johansson et al. (eds.), *Renewable Energy: Sources for Fuels and Electricity* (Washington: Island Press, 1993).; the historical data are from J. Davis, "Energy for Planet Earth," *Scientific American* (September 1990). Part B is the "Sustained Growth Scenario" developed by the Shell International Petroleum Company's Group Planning Division in P. Kassler, *Energy for Development*, Selected Paper (London: Shell International Petroleum Company, Shell Centre, August 1994).

Note that in both scenarios, the total contribution of biomass in 2050 is approximately 210 EJ.

and Latin America would be the two largest biomass producing regions (Table 9.1).

The RIGES envisions that initial major markets for commercial (monetized) biomass would be primarily for electric power generation since advanced technologies for power generation from biomass at scales of 20 to 150 MW_e (gasifier/gas turbine systems) will be commercially available by the year 2000; these can be expected to be competitive with new and much larger coal-fired power plants and, in some cases, with hydroelectricity.[7]

The RIGES further envisions that as oil and natural gas prices rise, domestic and export markets for transportation fuels (e.g., methanol and hydrogen) will provide further opportunities for continued rapid growth of biomass energy industries. Under this scenario, developing countries (especially in Latin America and Africa), thus, have rural-based domestic sources of commercial fuels, and thereby, new opportunities for rural development. Moreover, energy markets for biomass would provide economic incentives for afforestation of degraded and marginal lands and, in the longer term, foreign exchange earnings.

This paper examines potential land availability for a biomass-intensive energy future, some of the economic and social implications of such a

TABLE 9.1

Total Biomass Supplies for Energy (EJ/year) for the Renewables-Intensive Global Energy Supply Scenario (RIGES)

	YEAR 2025				YEAR 2050			
REGION	Forests	Residues	Energy Crops	TOTAL	Forests	Residues	Energy Crops	TOTAL
Africa	2.43	6.81	18.94	28.18	2.43	9.38	31.81	43.62
Latin America	1.59	10.92	32.30	44.81	1.59	13.59	49.60	64.78
S&E Asia	3.13	13.61	—	16.74	3.13	20.42	—	23.55
CP Asia	1.21	3.85	5.00	10.06	1.21	4.16	15.00	20.37
Japan	—	0.89	—	0.89	—	0.95	—	0.95
Australia/NZ	0.02	1.14	—	1.16	0.02	1.39	—	1.41
USA	0.61	5.86	9.60	16.07	0.61	5.68	9.60	15.89
Canada	0.04	1.43	1.20	2.67	0.04	1.42	1.20	2.66
OECD Europe	0.31	4.85	9.00	14.16	0.31	4.86	9.00	14.17
Former CP Europe	0.58	5.28	4.00	9.86	0.58	5.68	12.00	18.26
Middle East	0.02	0.18	—	0.20	0.02	0.23	—	0.25
TOTAL	9.94	54.82	80.04	144.80	9.94	67.76	128.21	205.91

Source: T.B. Johansson, H. Kelly, A.K.N. Reddy, and R.H. Williams, "Renewable Fuels and Electricity for a Growing World Economy: Defining and Achieving the Potential," Chapter 1, pp. 1-71, and "A Renewables-Intensive Global Energy Scenario," Appendix to Chapter 1, pp. 1071-1142, in T.B. Johansson et al. (eds.), *Renewable Energy: Sources for Fuels and Electricity* (Washington: Island Press, 1993).

future for rural development of developing countries, and some key environmental issues associated with extensive biomass energy production.

Potential Land Availability for Biomass Energy

Because populations are growing, an important question is whether there are sufficient land resources to both feed future populations and sustain the magnitude of biomass energy development implied in the RIGES and the Shell scenario.

USING DEGRADED LANDS FOR BIOMASS ENERGY

To help insure a minimum of competition between agriculture and energy production, a number of analysts have proposed that developing countries target degraded lands for energy production.[8] Grainger and Oldeman et al. have estimated that developing countries have over 2,000 million hectares of degraded lands, and Grainger estimates that some 621 million of these are suitable for reforestation.[9] This is consistent with estimates that previously forested area suitable for reforestation amounts to 500 million hectares, with an additional 365 million hectares available from land in the fallow phase of shifting cultivation.[10]

Worldwide interest in restoring tropical degraded lands is growing, as indicated by the ambitious goal of a global net afforestation rate of 12 million hectares per year by 2000, set in 1989 at the Ministerial Conference on Atmospheric Pollution and Climate Change.[11] This is comparable to the rate at which biomass energy plantations would have to be established in the first quarter of the twenty-first century for Africa, Latin America, and centrally planned Asia to meet the goals envisaged in the RIGES.

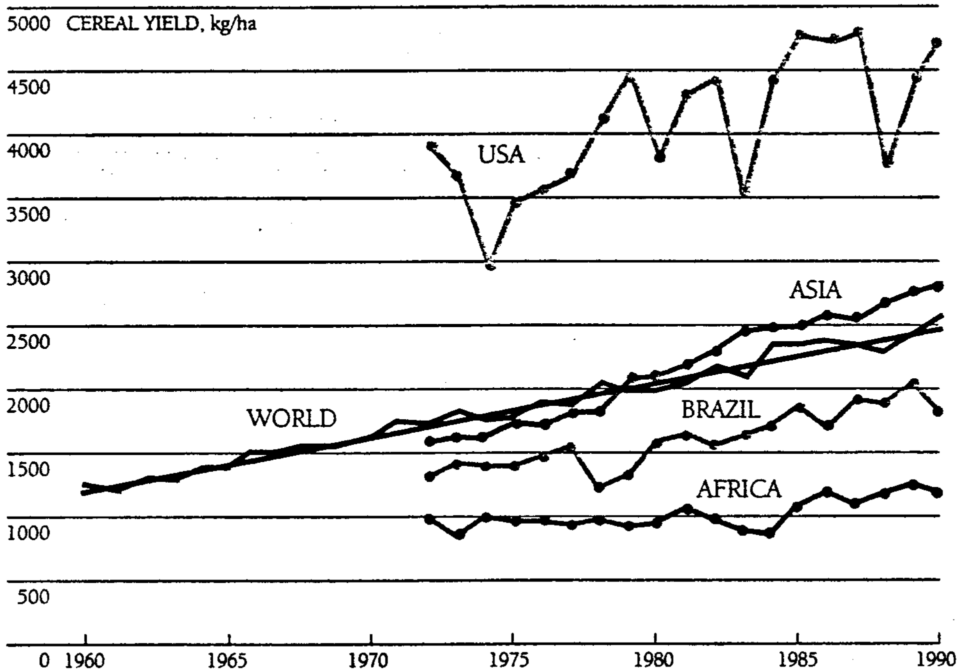
Energy industries might provide the capital needed to finance land restoration activities since advanced biomass conversion technologies like gasifier/gas turbine systems are expected to be highly economically attractive. In principle, energy industries would have an incentive to restore lands in sustainable ways because they would require secure supplies of biomass feedstocks throughout the lifetimes (twenty years or more) of their capital-intensive investments in energy conversion facilities. Such supply security could be assured only if the plantations were managed sustainably.

The main technical challenge is to find a sequence of plantings that can restore ground temperatures, organic and nutrient content, moisture levels, and other soil conditions to a point where crop yields are high and sustainable. It appears feasible to overcome this challenge.[12] Other difficulties that must be surmounted reflect general conditions in many developing regions, for example, complex or disputed land ownership, lack of roads or other means to transport biomass to processing facilities and biofuels to markets, and the fact that growers in poor areas cannot wait the three to eight years that is typically required for cash returns on short-rotation tree crops. Despite these technical, socio-economic, political, and other difficulties, however, proof of the potential for growing energy crops on degraded lands can be found in the many successful energy plantations that already exist in developing countries.[13]

Nevertheless, intensive research, development, and implementation programmes are needed to accelerate the rate of plantation development. Such programmes should lead to the development of region-specific restoration plans that take into account local bioclimatic and socio-economic conditions. Restoration activities involving both outside experts and local farmers should be investigated. Also, restoration plans that can lead to commercial energy crops should be demonstrated. Such demonstrations might be conducted as joint ventures among local agricultural producers and equipment supply firms, local and multinational energy companies, and local and international organizations interested in land restoration.

FIGURE 9.3

Average Cereal Yields for the World, the United States, Brazil, Asia, and Africa, 1960-1990



Note: Over the period 1972 to 1990, yields increased a total of 28% in Africa, 77% in Asia, 49% in Brazil, and 33% in the United States.

Sources: Country and regional data are Food and Agriculture Organization data cited in C.I. Marrison and E.D. Larson, "A Preliminary Estimate of the Biomass Energy Production Potential in Africa for 2025," Center for Energy and Environmental Studies, Princeton University, Princeton, New Jersey, March 23, 1995. World data are from U.S. Department of Agriculture (USDA), "Production, Supply, and Distribution Database" (diskette), Economic Research Service, USDA, Washington (September 1994).

FOOD VERSUS FUEL

The use of degraded lands offers an important opportunity for growing biomass energy crops, but other possibilities should be examined as well. This, in turn, requires careful examination of the potential land requirements for agriculture.

Waggoner argues that a world with twice the present population could be fed with no increase in cropland, largely because of expected continuing increases in yields.[14] A cursory examination of historical trends in grain yields suggests this may be reasonable. Worldwide average grain yields have been increasing at an average linear rate of 40 kilograms per hectare per year since 1960 (see Figure 9.3). To provide constant per capita levels of grain using the same amount of land as at present, as suggested by Waggoner, would require an average global increase in yields from 2.6 metric tonnes per hectare per year in 1993[15] to 4.5 tonnes per hectare per year in 2050 and 5.2 in 2100.[16] The implied linear growth rate is 33 kg/ha/yr from 1993 to 2050, and 14 kg/ha/yr from 2050 to 2100, both slower than the average growth rate of 40 kg/ha/yr from 1960 to the early 1990s. The target yield of 5.2 tonnes per hectare in 2100 is about 94 per cent of the 1993 U.S. yield, 30 per cent higher than China's 1993 average, and 18 per cent above the 1993 South Korean yield.

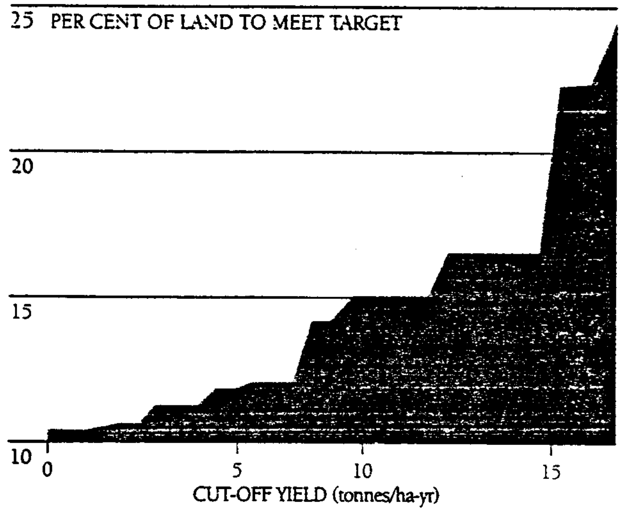
While such a global analysis is encouraging, it may prove difficult in practice to maintain agricultural land use at present levels on a regional or sub-regional basis. In a more detailed analysis aimed at a preliminary country-level quantification of potential biomass energy production, Marrison and Larson estimate the land availability and associated bioenergy production potential for fifty African countries in the year 2025.[17] Their analysis assumes that food crop yields in Africa grow at the same linear rate between 1990 and 2025 as average cereal-crop yields grew there from 1972 to 1990 (13.8 kg/ha/year). Average crop yields in 2025 would then still be below Brazil's 1990 level, and far below the 1990 U.S. level (see Figure 9.3).

Marrison and Larson use U.N. baseline population projections, which suggest that Africa's population in 2025 will be 2.5 times the 1990 level. They assume that food imports do not increase beyond the absolute 1990 levels, and that per capita calorie supplies grow to correct current undernourishment. With these assumptions, the cropland requirements for Africa in 2025 will be 451 million hectares, or 2.4 times the present cropland area. Marrison and Larson assume that new cropland would be established on land that is presently not cropland, not natural forest, and not wilderness (including desert areas). After meeting cropland needs, any remaining land that is not cropland, forest, or wilderness is assumed to be available for other uses, including biomass energy production. There will be a variety of competing uses for this available area that must be examined on a region-by-region basis when considering the establishment of biomass plantations.

Marrison and Larson project biomass energy crop yields on the potentially available land on the basis of annual nationally averaged precipitation and a yield-precipitation correlation for modern commercial eucalyptus plantations in Brazil. Figure 9.4 shows the percentage of non-crop, non-forest, non-wilderness area in 2025 that would be needed in Africa to produce 18.9 EJ of biomass energy in 2025—the amount specified by the RIGES for Africa in Table 9.1. The percentage of available land required in each country producing biomass is shown as a function of the bioenergy plantation yield below which, biomass production is assumed to be uneconomic, i.e. the cut-off yield. Only 15 per cent (or 38.7 million hectares) of non-crop, non-forest, non-wilderness land in the producing countries (i.e., those with average yield higher than the cut-off level) would be needed to meet the RIGES target, if a cut-off yield of 10 dry tonnes per hectare per year is assumed.

FIGURE 9.4

Land Area Required for Biomass Production in Africa as a Function of Cut-off Yield



Note: The cut-off yield is the yield below which it is assumed that biomass production would not be economically viable. This figure shows the percentage of non-crop, non-wilderness, non-forest land that would be needed in Africa in 2025 to produce a continent total of 18.9 EJ of biomass energy. The percentage of land required in each country that produces biomass goes up with increased "cut-off" yield because the total number of countries in Africa with yields above the cut-off yield drops with increasing cut-off yield.

Source: C.I. Marrison and E.D. Larson, "A Preliminary Estimate of the Biomass Energy Production Potential in Africa for 2025," Center for Energy and Environmental Studies, Princeton University, Princeton, New Jersey, March 23, 1995.

Marrison and Larson's analysis suggests that land resources are sufficient to support a biomass-intensive energy future in Africa without compromising food production needs. Subsequent analysis suggests similar conclusions for Latin America and Asia.[18] That Asia could become a major bioenergy producer without compromising food production needs is surprising. It results form the high rate of growth in crop yields between 1972 and 1990 (see Figure 9.3). Marrison and Larson assume that yields continue increasing at the same linear rate (65 kg/ha/year for grains) from 1990 to 2025. With this assumption, crop yields in 2025 in Asia (5.4 t/ha/yr for cereals) are about the same as in the United States in 1993 (5.5 t/ha/yr). Thus, despite growing populations, increased crop yields mean that the land needed for agriculture in Asia in 2025 is the same as in 1990, which leaves some 1,300 million hectares of available land for other uses. An independent and more detailed analysis focusing on India (see next section) appears to support

Marrison and Larson's conclusion. Nevertheless, because it is contrary to conventional thinking about land use constraints in Asia, more detailed country-level assessments are warranted.

FEASIBILITY OF PLANTATION BIOENERGY PRODUCTION: NORTHEAST BRAZIL AND INDIA

The preceding section suggests that land resources are sufficient to support a significant biomass energy industry globally. However, detailed country and sub-country assessments are needed to determine the feasibility of implementing biomass plantation energy systems on an extensive basis. Two studies are reviewed here: one for northeast Brazil, a region with high per capita land availability, and one for India, a country with low per capita land availability.

Brazil. The nine states comprising the northeast region of Brazil account for 18 per cent of Brazil's land area, or nearly 10 per cent of South America. The northeast region has the lowest population density among the three most populated regions in Brazil. The only significant conventional energy resource in the region is hydroelectric power, the full economic potential of which will have been tapped by the end of the decade.

Given the high per capita land availability and the looming shortage of conventional energy sources, the utility responsible for electricity in northeast Brazil (Companhia Hidroelctrica do Sao Francisco—CHESF) began to examine the region's potential for biomass energy production over a decade ago.[19] The CHESF studies mapped key physical aspects of the region (soil type and quality, rainfall, topography, elevation, etc.) to define five bioclimatic regions. For each of these, CHESF estimated the potential yields and costs of producing biomass based on experience with industrial eucalyptus plantations in other regions of Brazil. The CHESF studies took account of potential competition for land, and considered for biomass energy production only land that was judged suboptimal for most other uses, including agriculture.

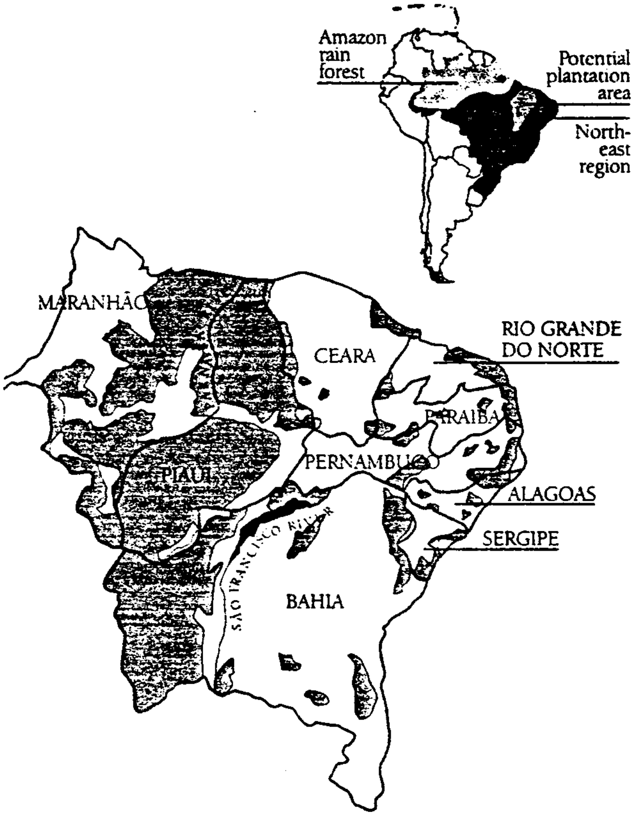
The CHESF study estimated the land area potentially available for biomass plantations to be some 50 million hectares, or one third of the region (see Figure 9.5). Biomass yields were estimated to range from less than 3 dry tonnes per hectare per year on the worst lands to over 20 t/ha/yr on the best sites, with 12.5 t/ha/yr the average yield. The total potential biomass production on 50 million hectares in the northeast region is estimated to be some 12.6 EJ per year.[20] By comparison, total primary energy use in the northeast in 1990 was only about 1.1 EJ.

That the biomass energy production potential of the region is so large is surprising because a large part of the region is considered semi-arid. Furthermore, roughly half the area identified by CHESF as suitable for plantations is characterized as having soil that is being degraded to some extent by wind erosion, water erosion, or chemical deterioration.[21] A smaller percentage of area has also been characterized as susceptible to desertification, based on physical characteristics (soils, water resources, etc.), social conditions (e.g., land ownership structure), economic criteria (e.g., present use of land), and other indicators.[22]

Given the encouraging analysis of the biomass energy production potential in northeast Brazil, CHESF is now developing plans for implementing a biomass-electricity generating programme. Some potential social implications of such a programme are discussed below.

FIGURE 9.5

Land Potentially Available for Growing Biomass in Northeast Brazil



Note: The shaded areas on the large map are identified by CHESF as available and suitable for establishing biomass energy plantations in Northeast Brazil; they amount to approximately 50 million hectares. The inset positions the northeast region of Brazil within South America.

Source: A.E. Carpentieri, E.D. Larson, and J. Woods, "Future Biomass-Based Electricity Supply in Northeast Brazil," *Biomass and Bioenergy* 4(3) (1993), pp. 149-73.

India. Recent analysis suggests that India, a country with a population density sixteen times greater than that for Brazil, may also have substantial potential for establishing biomass-plantation energy industries.

Ravindranath and Hall observe that total area under crops in India was roughly the same in 1990 (around 125 million hectares) as it was twenty years earlier, despite population growth averaging about 2.4 per cent per year during these two decades.[23] (Cultivable non-cropland has also remained stable at about 40 million hectares.) In looking to future land requirements for agriculture, Ravindranath and Hall note that the average yield of India's most important crop, rice, is 1.7 tonnes per hectare per year, or about one half the Asian average, one third the yield in China and Japan, and one fifth the yield in South Korea. On the other hand, in some states in India (Tamil Nadu and Punjab), the rice yield is double the Indian average.

From these data and an analysis of the barriers to increasing crop yields and intensities (i.e., cultivation of at least two crops per year through irrigation), Ravindranath and Hall conclude that the prospects for doubling or tripling average annual yields in India are good. Thus, food production might be doubled or tripled without increasing cropped area, leaving substantial amounts of land for other uses.

Ravindranath and Hall propose using degraded lands in India for biomass energy production. They cite three estimates of degraded land area in India that range from 66 to 106 million hectares. (Total land area is about 300 million hectares.) Excluding degraded land presently under cultivation reduces these estimates to a range of 61 to 71 million hectares.

This land area can be put in perspective by considering its biomass energy production potential relative to present energy use in India. Assuming an average biomass yield of 10 dry tonnes per hectare per year (and a biomass energy content of 20 GJ/dry tonne—one GJ is 10^9 joules), 65 million hectares would produce 13 EJ of energy. India's total primary energy consumption in 1991 was under 11 EJ (26 per cent of which was in the form of biomass).[24]

Potential Role of Biomass Plantation Energy Systems in Promoting Sustainable Development

What roles could large-scale biomass plantation energy systems play in promoting sustainable development? The case of biomass electric power generation, the likely initial major market for new biomass energy supplies, is considered here as a concrete example.

LOWER ENERGY COSTS

In order to succeed, biomass power systems must be economically competitive with conventional fossil fuel alternatives. Since plantation-grown biomass is more costly than traditional residue biomass sources, the technologies used to convert the biomass into electricity must be more efficient and/or lower in capital cost than traditional biomass-electric technologies, which today typically use residues as fuel. (Traditional biomass-electric technologies would not be competitive with conventional energy sources when more costly plantation biomass is the fuel.) At a scale of 20 to 150 MW_e, biomass-gasifier/gas turbine (BIG/GT) systems that will be commercialized by the turn of the century promise efficiencies that are roughly double those for traditional (steam-turbine) biomass power systems; moreover, they would substantially lower capital costs.[25] BIG/GT technology should make it possible to deliver electricity to consumers from biomass-plantation energy systems at costs that are competitive with electricity from new coal-fired steam-electric plants. BIG/GT electricity is also likely to be able to compete with hydroelectric power in some situations.[26]

MAGNET FOR RURAL ECONOMIC ACTIVITY AND EMPLOYMENT GENERATION

In part, because of the availability of low-cost electricity, rural industrial-scale biomass energy systems might act as magnets for a variety of income-generating activities, leading to the creation of employment that could help stem urban migration.

The most direct income-generating activity would be managing the plantations. In regions where climate is especially suitable for biomass growth and labour costs are relatively low, such as in parts of Brazil, biomass production costs from plantations are less than US$2/GJ.[27] If biomass is sold at $2/GJ, and yields are 10 to 15 dry tonnes per hectare per year, a plantation could generate gross revenues of $400 to $600 per hectare. This is comparable to the revenues generated from soybean production in Brazil today.[28] Yet the cost of inputs (such as fertilizer and herbicides) for biomass energy production (especially for woody crops with 3 to 8 year rotations) are likely to be substantially lower than those for an annual crop like soybeans (see Table 9.2). Moreover, unlike Brazilian soybeans, which are largely exported, biomass would be used locally to generate electricity, which, in turn, could be consumed by additional income-generating industries within the region.[29]

Carpentieri et al. estimate that large-area (contiguous tens of thousands of hectares) commercial plantations in Brazil generate 1.9 to 3.6 direct jobs per square kilometre. While this

TABLE 9.2

Typical Fertilizer and Herbicide Application Rates and Soil Erosion Rates for Selected Food and Energy Crop Production Systems in the United States

Cropping System	N-P-K Application Rates *(kg/ha/year)*	Herbicide Application Rates *(kg/ha/year)*	Soil Erosion Rates *(tonnes/ha/yr)*
Annual Crops			
Corn	135-60-80	3.06	21.8[1]
Soybeans	20[b]-45-70	1.83	40.9[a]
Perennial Energy Crops			
Herbaceous	50[a]-60-60	0.25	0.2
Short-rotation woody	60[c]-15-15	0.39	2.0

[a] Based on data collected in the early 1980s. New tillage practices used today may lower these values.
[b] The nitrogen input is inherently low for soybeans, a nitrogen-fixing crop.
[c] Not including nitrogen-fixing species.

Source: W.G. Hohenstein and L.L. Wright, "Biomass Energy Production in the United States: An Overview," *Biomass and Bioenergy* (1994), pp. 161-73.

level of employment is relatively modest, it could be important locally. Furthermore, the availability of low-cost biopower could attract other employment-generating activities to the area. Energy-intensive industries, with their well paying jobs, might be especially attracted.

One concern with such a rural industrialization strategy is that it may first require a sufficient amount of already existing electricity-consuming industrial activity to justify building any power plant. While this may be desirable, it is not essential. Initially, if there is insufficient local demand to utilize all the electricity being generated, the excess could be transported by wire to urban centers (as hydroelectricity is transported from remote sites in many countries today). Although this electricity would not be as cheap as that made available near the plant site, the extra electric transmission costs should not be prohibitive: transmission lines would tend be operated at high capacity factors, thus, reducing unit costs. (This is in contrast to the opposite situation in which centralized power generation near urban centers provides electricity for rural consumers: in this case, the lines are often poorly utilized because of sporadic demand patterns of rural electricity consumers.)

SMALL-SCALE BIOMASS PRODUCTION: THE FARM FORESTRY ALTERNATIVE

It is often assumed that contiguous, large-area plantations are required: a) to take advantage of economies of scale that can make biopower competitive, and b) to make a large contribution to global energy supply, such as those envisaged in the RIGES. However, large plantations may not be necessary for biomass to play major roles in the energy economy. An alternative small-scale biomass supply system—farm forestry—shows great promise and is increasingly being implemented in Brazil.[36] Similar activities have been reported elsewhere.

In a typical farm-forestry programme in Brazil, a forestry company provides the material inputs and technical know-how for establishing trees on a farmer's land (1 to 50 hectares of trees per farm) and contracts with the farmer to buy some or all of the first harvest for an agreed upon price that incorporates repayment for the initial inputs and services. The inputs include saplings (usually some species of eucalyptus), fertilizers (applied at planting), herbicides (applied at some point after planting), and pesticides. The company samples the farmer's soil and provides fertilizers and species "tuned" to that soil.

Because of the sophisticated material inputs and the careful tending provided by the farmer, the biomass yields reported from small-farm plantings are not much below those reported for large-scale plantations owned and operated by forestry companies, and yields can be expected to increase as both farmers and their contracting companies learn improved methods and approaches (most programmes in Brazil started less than a decade ago). Moreover, any yield reductions are often offset by substantially lower costs to companies for establishing farm forests. Limited survey data indicate that the per hectare cost for farmer-contracted land ranges from 2 per cent to 42 per cent of the cost for company-owned land (see Table 9.3). The limited data suggest that delivered costs for biomass do not differ much between farm-forests and large-scale plantations.

Farm forestry is growing rapidly in Brazil, with encouragement from the private sector; from federal, state and local governments; and from farmers. Several hundred thousand hectares have been established without fanfare in less than a decade. This compares favourably with the estimated 6 to 7 million hectares of large-scale plantations established in Brazil since

TABLE 9.3

Some Corporate Farmer Forestry Programmes in Brazil *(based on information provided by individual companies)*

Company	Aracruz	Champion	Cenibra	Riocell	Pains	Ripasa	Inpacel	Bahia Sul
Location (state)	EspiritoSanto	SaoPaulo	Minas Gerais	R. Grande do Sul	Minas Gerais	Sao Paulo	Parana	Bahia, E. Santo
Company-Owned Land								
Total area (hectares)	200,000	n.a.	156,194	71,751	85,073	69,942	47,874	115,138
Area planted (hectares)	131,000	n.a.	87,935	52,487	51,467	50,365	25,768	66,902
Average establishment cost for new plantings[2] ($/ha)	1,250	n.a.	1,670	960	n.a.	917	712	427
Average productivity of planted area (dry tonnes/ha/year)[3]	22.3[4]	n.a.	17.8[d]	19.2[d]	n.a.	17.3[d]	19.8[5]	21.8[d]
Average delivered cost of wood ($/dry tonne)[6]	39	n.a.	48	30	n.a.	n.a.	22	16
Farmer-Forestry Program								
Year programme was started	1989	1960	1985	1989	1988	1991	1991	1992
Total number of farmers	2000	328	500	3098	314	85	110	16
Average total farm size (ha)	n.a.	n.a.	100	16	63	90	n.a.	300
Primary activity of farm	n.a.	cattle, corn, coffee, citrus	cattle	n.a.	n.a.	cattle	cattle, crops	cattle
Total area contracted for trees (ha)	30,000	13,000	8,500	4,985	2,431[7]	2,425	1,575	850
Average per-farm area planted with trees (ha)	15	40	17	1.6	7.7	29	14	53
Average productivity of planted area (dry tonnes/ha/year)	n.a.	15[d]	12.7[d]	15[d]	n.a.	15.8[d]	n.a.	n.a.
Average establishment cost to company ($/ha)	n.a.	430	240	23	n.a.	130	266	180
Average delivered cost of wood to company ($/dry tonne)[c]	n.a.	16	42	n.a.	n.a.	n.a.	n.a.	n.a.
Per cent of farms intending to commit total area to trees	n.a.	8	27	0	n.a.	6	2	0

[1] Based on data collected in the early 1980s. New tillage practices used today may lower these values.

[2] Includes land rent, sapling production, land preparation, planting, fertilizers, herbicides.

[3] Yield data were originally provided in solid cubic meters. Typical species of eucalyptus in Brazil have a density of about 0.5 dry tonnes per solid cubic meter.

[4] Includes only stem wood with diameter 7 cm or larger.

[5] Starting from the total yield at harvest (in solid m^3/ha) provided by the company, this has been calculated assuming a 6-year rotation and a wood density of 0.5 dry tonnes/m^3.

[6] Calculated from costs in $/solid m^3, assuming a wood density of 0.5 dry tonnes per cubic meter.

[7] Pains has a goal of contracting over 56,000 hectares under their farmer forestry programme, which would involve some 4,000 farmers.

Source: E.D. Larson, L.C.E. Rodriguez, and T.R. de Azevedo, "Farm Forestry in Brazil," presented at BioResources '94: Biomass Resources, A Means to Sustainable Development, Bangalore, India, 3-7 October, 1994.

the 1960s. Farmer-owned plantations account for as much as 20 per cent of some forestry companies' total planted area (Table 9.3), and some companies have a goal of raising this fraction to 50 per cent or more.

Three recent developments are spurring the growth in farm forestry: 1) the federal tax incentives introduced in 1966 in Brazil to encourage tree planting were eliminated in 1988, making it much less attractive for forestry companies to expand their own plantation areas; 2) in regions where natural forests were being cut for wood (especially the states of Minas Gerais and Sao Paulo), natural forests within reasonable transportation distances have essentially been completely cut, with insufficient replanting to meet local needs; and 3) objections of environmentalists and others (largely on aesthetic grounds) to "overplanting" of trees have discouraged expansion of large tracts of company-owned plantations. (In the state of Espirito Santo, for example, Aracruz Florestal, a private company, is now prohibited by law from purchasing additional land for eucalyptus planting.)

The overall result of the small-farm forestry programmes has been minimal changes in land ownership and use patterns, while local wood supplies at reasonable costs have increased, and farmers (including formerly subsistence farmers) have gained a revenue source.

TAX BASE TO HELP FINANCE RURAL INFRASTRUCTURE DEVELOPMENT

Private biopower systems in rural areas could provide a substantial tax base for supporting rural infrastructure development, *if the tax is structured to use at least most of the revenues this way*, rather than diverting them to the urban sector.[11] Tax revenues could help finance a wide range of infrastructure, including that needed to attract energy-using industries and to provide such public services as schools, hospitals, etc. As biopower plants attract power-consuming firms to rural areas, these firms would further add to the rural tax base.

In many developing countries, privatizing power generation would lead to higher electricity prices. At present, most elec-

BOX 9.1

Taxing Rural Industries: An Illustration of the Potential

There are a variety of approaches that could be considered for taxing rural industries to pay for infrastructure development. Without passing judgement on the relative merits of one taxation instrument over another, consider the following illustration of the potential revenue base that might be generated from a taxation strategy.

In the United States, property taxes on businesses and homes are levied to support much local infrastructure building. A property tax levied on a rapidly-growing, capital-intensive industry, such as the electric power industry, could provide an enormous tax revenue base. To illustrate this, suppose that a 1.5 per cent property tax were levied on biopower production facilities. (A 1.5 per cent per year tax on the installed capital cost is a typical rate for investor-owned power plants in the United States.) Such a tax applied to a first-generation 26 MW_e BIG/GT power plant would account for only 6 per cent of the busbar cost (see Table 9.4), but the tax revenues would mount to \$0.5 million per year or \$15 million over the 30-year life of the plant.

Consider the implications of this calculation for a particular developing country, say India. In the mid-1980s, only about one sixth of electricity generated was provided to rural areas of India, even though nearly three-fourths of the population is rural. Suppose that a concentrated effort were made on the part of policy-makers to accelerate rural industrialization and that:

- for the country as a whole, installed electrical generating capacity grows 5 per cent per year;
- one-third of all new electrical generating capacity is sited in rural areas;
- the average installed cost for new generating capacity is \$1300/kW_e (the estimated cost for first-generation, mass-produced BIG/GT systems—see Table 9.4); and
- all rural power is provided by private power producers, who pay annual property taxes equal to 1.5 per cent of the installed capital cost.

Assuming an estimated installed generating capacity in India of 100 GW in 1994, then over the 30-year lives of all the power plants installed in a single year at the time this new policy is adopted, property tax revenues would amount to about \$1 billion per year:

$$(30\text{-year plant life}) \times (0.015/\text{year}) \times (\$1300/kW_e) \times (1/3) \times (0.05/\text{year}) \times (100{,}000{,}000\ kW_e) \approx \$10^9/\text{year}.$$

tric utilities are publicly owned, and electricity prices are often kept below economically efficient long-run marginal cost levels on the assumption that low electricity prices are needed to stimulate development. As a result, revenues typically are insufficient to provide the capital needed for financing new power plant construction.[32] Privatizing power generation and opening it up to independent power producers would overcome this problem, and the resulting competition would keep electricity prices in line with long-run marginal costs.

Electricity so produced could be a powerful instrument for rural development if taxation instruments are used creatively. The methods of taxation should reflect cultural preferences, as well as considerations of economic and administrative efficiency. Taxes on capital, for example, might be especially effective with a capital-intensive industry like power generation (see Box 9.1).

Tax revenues could be used to promote several kinds of infrastructure development, including that which will attract employment-generating industries to rural areas, and that which can contribute to meeting basic human needs in communities that remain outside of monetized economies.

TECHNOLOGY TRANSFER

A strategy to develop bioenergy at industrial scales in rural regions could be launched immediately using commercially available technologies (e.g., steam turbines) in markets with large under-utilized biomass residues available at low cost (e.g., in the cane sugar industry[33]). But biopower production cannot expand substantially unless such initial markets are supplemented by much larger markets based on the use of more costly, but much more widely producible feedstocks grown on dedicated plantations—markets that require high-efficiency technologies that have low per unit capital costs (e.g., BIG/GT).

Such advanced technologies can be either developed indigenously or transferred from abroad, or some mixture of both. If technology is transferred, it should be accompanied by local technological capacity-building; moreover, there should be safeguards to ensure that the technology itself, and the way it is transferred, are compatible with sustainable development goals.[34] Multinational corporations (MNCs), in particular, might be considered instruments for technology transfer; for example, BIG/GT technology might be transferred via independent power companies that are joint ventures between local companies and MNCs.[35]

One frequently voiced criticism of MNCs is that the technologies transferred often do not serve the best interests of the host countries. While this undoubtedly has been true, it is not

TABLE 9.4

Busbar Electric Generation Cost in India for First-Generation BIG/GT Technology[1]

Cost Component	*Cents per kWh*
Capital[2]	2.10
Insurance[3]	0.10
Property Tax[4]	0.30
Labour for Plant Operation[5]	0.18
Maintenance[6]	0.40
Administration[7]	0.10
Fuel[8]	1.59
Total	4.77

[1] The first-generation BIG/CC system is assumed to be a 34.0% efficient (HHV), 25.9 MWe directly-heated, atmospheric-pressure biomass gasifier (TPS) coupled directly to a gas turbine/steam turbine combined cycle based on an aeroderivative gas turbine (GE LM-2500) [Larson and Consonni, 1994], for which the installed capital cost in mass production is estimated to be $1300/kWe [Elliott and Booth, 1993].

[2] Assuming a 10% real discount rate and a 30-year plant life the capital recovery factor is 10.61% per year. Baseload operation @ 75% capacity factor is assumed.

[3] The annual cost of insurance is assumed to be 0.5% of the installed capital cost.

[4] As is typical for the US, the annual property tax is assumed to be 1.5% of the installed capital cost.

[5] It is assumed that 7 operators are needed to run the power plant, as in a US situation (see note f, Table 3, in Williams and Larson [1993]). However, unlike the US, where the cost of labour is assumed to be $22.55/hour, the cost of labour is assumed here to be $5/hour.

[6] The annual maintenance cost is assumed to be 2% of the installed capital cost (see note g, Table 3, in Williams and Larson [1993]), with 40% accounted for by labour and 60% by materials.

[7] The annual administrative cost is assumed to be 30% of labour costs for operation and maintenance (see note h, Table 3, in Williams and Larson [1993]).

[8] For a fuel price of $1.5/GJ (HHV basis) (930 Rs/t for wood with a HHV of 20 GJ/t and an exchange rate of 31 Rs/$). That this is a reasonable cost comes from the assessment by Carpentieri, et al. [1993], who estimate that eucalyptus could be grown on 4 x 10[6] ha of available relatively good lands in the Northeast of Brazil at an average annual yield of 20.7 t/ha/year at a cost (including 85 km of transport) of $1.23/GJ (1991 $). To this should be added a chipping cost of $5.13/t ($0.26/GJ) (cost estimate for the US [Perlack and Wright, 1995]), bringing the total cost to $1.5/GJ for wood chips delivered to the conversion facility.

an intrinsic problem. Developing countries may need MNCs, but MNCs need developing-country markets even more. MNCs must "grow or die." Since many industrialized-country energy markets are growing only slowly or not at all, most prospective markets for multinational energy companies are in the developing countries. If developing countries make known their preferences and dislikes about alternative technologies and put into place appropriate institutional safeguards to prevent abuses, MNCs will have to orient their business activities accordingly. At the same time, however, MNCs will generally have to be convinced that potential bioenergy markets are large and worth pursuing.[36]

If MNCs are convinced that bioenergy technologies have large potential markets and are competitive alternatives to fossil and nuclear energy technologies, they will inevitably become agents of development through technology transfer. And, via the rural industrialization promoted by the deployment of bioenergy systems and the tax base these systems would provide, they will contribute to rural infrastructure-building.

Environmental Issues

Many people consider large-scale cultivation of biomass for energy a massive assault on nature. Environmentalists are critical of the intensive agricultural management practices that biomass energy plantations require; they are concerned about chemical contamination of groundwater, loss of soil quality, aesthetic degradation of landscapes, and loss of biological diversity. Unless such concerns can be effectively addressed so that there is wide public support for biomass energy production, it will be difficult for large-scale biomass energy systems to play a major role in the world's energy future.

Biomass can, of course, be grown for energy in ways that are environmentally undesirable. However, production of biomass for energy can also improve the land environmentally relative to present use. The environmental outcome depends on how the biomass is produced, an issue that is beginning to receive attention in a variety of fora.[37]

Consider first the challenge of sustaining the productivity of the land. Since harvesting biomass removes nutrients from the area planted, care must be taken to ensure that these nutrients are restored. With thermochemical processes for biomass conversion (such as BIG/GT power production), it is feasible to recover all mineral nutrients as ash at the biomass conversion facility and to return the ash to the plantation as a fertilizer. However, nitrogen lost to the atmosphere at the conversion facility must be replenished.

This can be done in a number of environmentally acceptable ways. First, when trees are the harvested crop, the leaves, twigs, and small branches in which nutrients are concentrated can be left at the site to reduce nitrogen loss; this also helps maintain soil quality and reduce erosion. Second, biomass species that fix nitrogen in the soil can be selected for the plantation or for interplanting with the primary plantation species to eliminate or reduce to low levels the need for artificial fertilizers. Biomass production for energy allows much more flexibility than agriculture in meeting fixed nitrogen requirements this way. In agriculture, the market dictates the choice of feedstocks within a narrow range of characteristics. Thermochemical energy conversion technology, on the other hand, puts few restrictions on the choice of biomass feedstock, aside from the requirement of high yield, which is needed to keep costs at acceptable levels.

Energy crops also offer flexibility in dealing with erosion and chemical pollution from herbicide use—problems that occur mainly at the time the energy crop is planted. If the energy crop is an annual crop (e.g., sorghum), the erosion and herbicide pollution problems would be similar to those for annual row-crop agriculture; cultivating such crops — for energy or for agriculture — should be avoided on erodible lands. However, potential biomass energy crops also include: a) fast-growing trees that are harvested only every three to eight years and replanted perhaps every fifteen to twenty-four years, and b) perennial grasses that are harvested annually, but replanted only once in a decade or so. Both of these alternatives tend to sharply reduce erosion as well as the need for herbicides (see Table 9.2).

Another concern is chemical pollution from the use of pesticides. Experience with plantations in tropical regions shows that careful selection of species and good plantation design and management can be helpful in controlling pests and diseases, thereby minimizing or even eliminating the use of chemical pesticides. A good plantation design will typically include areas set aside for native flora and fauna to harbour natural predators for plantation pest control, and subsections of the plantation planted with different clones and/or species. If a pest attack breaks out in one such subsection, a now common practice in well-managed plantations is to let the attack run its course and to let predators from the set-aside areas help halt the outbreak.

Biomass plantations are sometimes criticized because the range of biological species they support is much narrower than for natural forests. While this is generally true, the criticism is not always relevant. It is true if a biomass plantation replaces virgin forest. However, if a plantation is established on degraded lands, it generally can support a more diverse ecology than was possible before restoration. Similarly, if biomass energy crops replace monoculture food crops, the effect on the local ecology depends on the plantation crop species chosen, but in many cases the shift will be to a more ecologically varied landscape.

As already noted, establishing and maintaining natural reserves at plantations can be helpful in controlling pests while providing ecological benefits. However, preserving biodiversity on a regional basis will require, *inter alia*, land-use planning in which patches of natural vegetation are connected via a network of undisturbed corridors (e.g., riparian buffer zones, shelterbelts, and hedgerows between fields), thus, enabling species to migrate from one habitat to another. Regional-level land-use planning and landscape design can also help address aesthetic concerns sometimes expressed about extensive, contiguous monocultures.

Summary

Biomass plantation energy systems could make important contributions toward sustainable development in developing countries. Land resources appear to be sufficient to support significant biomass energy production. Restoring degraded lands (of which there are several hundred million hectares in developing countries) by converting them to biomass energy plantations is one promising approach to establishing plantations on a large scale. But other land resources might also be exploited without compromising future agricultural production requirements.

Coupled with advanced conversion technologies, such as biomass-gasifier/gas turbines for electricity production, large-scale biomass-energy plantations could contribute to sustainable development in a variety of ways. In addition to the direct employment provided by plantations, the economically competitive electricity that could be produced by such systems would act as a magnet to draw other employment- and income-generating activities into rural areas, especially energy-intensive industries that offer well-paying jobs. Privatized biomass-power generation and the industrial activities it attracts could provide a tax base to help finance rural infrastructure building that would serve to attract additional economic activities. Such tax revenues could also be used to subsidize the provision of basic human needs to communities that are currently outside of the monetized economy.

The establishment of contiguous, large-area plantations have been criticized in some regions for socio-economic disruptions, including displacing small-scale farmers from their land. Such plantations may not be essential, however, for modernized biomass production and conversion systems to play an important role in the energy economy. Small-scale farm forestry is a promising alternative approach that is growing rapidly in Brazil. In this approach, forestry companies would loan their know-how and some capital to local farmers to help them establish tree crops. Farmers are, thus, able to grow trees on some or all of their land with high yields, while reducing costs for the forestry companies. Farmers thereby maintain control over their land and gain a revenue source, while forestry companies benefit from the increased local supply of wood.

Environmental concerns must be addressed if biomass energy systems are to make important contributions to sustainable development. Such concerns include the potential impacts of intensive plantation management practices, such as chemical contamination of groundwater and loss of soil quality. The characteristics of plantations required to insure environmental sustainability will vary with local bioclimatic and socio-economic factors, but biomass energy crops—especially those that would be converted into other energy carriers via thermochemical processes (like gasification)—would have some inherent advantages relative to conventional annual agricultural crops in dealing with environmental concerns. These include the flexibility to mix species within stands (e.g., nitrogen-fixing varieties might be included), reduced rates of soil erosion and herbicide application due to multi-year implanting of root systems, and reduced pesticide application through use of natural predators inhabiting non-harvested natural vegetation areas adjacent to harvested stands.

NOTES

[1] Eric D. Larson is Research Engineer, and Robert H. Williams is Senior Research Scientist, at the Center for Energy and Environmental Studies, Princeton University.

[2] J. Goldemberg, T.B. Johansson, A.K.N. Reddy, and R.H. Williams, *Energy for a Sustainable World* (Delhi: Wiley-Eastern, 1988).

[3] R.H. Williams, "Roles for Biomass Energy in Sustainable Development," *Industrial Ecology and Global Change* (Cambridge University Press, 1994), pp. 199-225.

[4] The assessment was prepared as input to the United Nations Conference on Environment and Development (UNCED). The study was commissioned by the U.N. Solar Energy Group for Environment and Development (UNSEGED), a high-level group of experts convened by the United Nations under the mandate of General Assembly Resolution A/45/208, December 21, 1990. That resolution requested that UNSEGED prepare a comprehensive and analytical study on new and renewable sources of energy aimed at providing a significant input to UNCED. The study was published in 1993 as a book of 1160 pages, with 23 chapters reviewing the state-of-the-art and future of renewable energy sources and technologies: Thomas B. Johansson, Henry Kelly, Amulya K.N. Reddy, and Robert H. Williams (eds.), *Renewable Energy: Sources for Fuels and Electricity* (Washington: Island Press, 1993). The energy supply projections in Figure 9.2a are for the Renewables-Intensive Global Energy Scenario (RIGES) described in the Appendix to Chapter 1 in that volume. For the RIGES, the demands for electricity and for solid, liquid, and gaseous fuels were assumed fixed at the levels of demand in the "high economic growth, high energy efficiency" scenario of the Response Strategies Working Group of the Intergovernmental Panel on Climate Change, *Climate Change: The IPCC Response Strategies* (Washington: Island Press, 1991).

[5] Analyses of Shell's Group Planning Division are used as input for long-term decision-making in the worldwide Royal Dutch/Shell group of companies.

[6] E.D. Larson, "Technology for Electricity and Fuels from Biomass," *Annual Review of Energy and the Environment*, Vol. 18 (1993), pp. 567-630; R.H. Williams and E.D. Larson, "Advanced Gasification-Based Biomass Power Generation," in Thomas B. Johannson et al., *Renewable Energy*, pp. 729-85; and T.P. Elliott and R. Booth, *Brazilian Biomass Power Demonstration Project*, Special Project Brief (London: Shell International Petroleum Company, Shell Centre, 1993).

[7] E.D. Larson and S. Consonni, "Biomass-Gasifier/Aeroderivative Gas Turbine Combined Cycle Power Generation," presented at **BioResources '94**, Bangalore, India, October 3-7, 1994; R.H. Williams, "Roles for Biomass Energy in Sustainable Development;" and A.E. Carpentieri, E.D. Larson, and J. Woods, "Future Biomass-Based Electricity Supply in Northeast Brazil," *Biomass and Bioenergy* 4(3) (1993), pp. 149-73.

[8] T.B. Johansson, H. Kelly, A.K.N. Reddy, and R.H. Williams, "Renewable Fuels and Electricity for a Growing World Economy: Defining and Achieving the Potential," Chapter 1, pp. 1-71, and "A Renewables-Intensive Global Energy Scenario," Appendix to Chapter 1, pp. 1071-1142, in T.B. Johansson et al. (eds.), *Renewable Energy*; D.O. Hall, F. Rosillo-Calle, R.H. Williams, and J. Woods, "Biomass for Energy: Supply Prospects," in T.B. Johannson et al. (eds.), *Renewable Energy*, pp. 593-652; R.H. Williams, "Roles for Biomass Energy in Sustainable Development;" N.H. Ravindranath and D.O. Hall, *Biomass, Energy and Environment: A Developing Country Perspective from India*, manuscript submitted to Oxford University Press, September 1994.

[9] A. Grainger, "Estimating Areas of Degraded Tropical Lands Requiring Replenishment of Forest Cover," *International Tree Crops Journal*, Vol. 5 (1988), pp. 31-61; A. Grainger, "Modeling the Impact of Alternative Afforestation Strategies to Reduce Carbon Emissions," *Proceedings of the Intergovernmental Panel on Climate Change Conference on Tropical Forestry Response Options to Climate Change*, Report No. 20P-2003 (Washington: Environmental Protection Agency, Office of Policy Analysis, 1990); and L.R. Oldeman et al., *World Map of the Status of Human Induced Soil Degradation*, International Soil Reference and Information Center and United Nations Environment Programme (April 1991).

[10] R.A. Houghton, "The Future Role of Tropical Forests in Affecting the Carbon Dioxide Concentration of the Atmosphere," *Ambio* 19(4) (1990), pp. 204-09.

[11] Ministerial Conference on Atmospheric Pollution and Climate Change, "The Noordwijk Declaration on Atmospheric Pollution and Climate Change," Noordwijk, The Netherlands (November 1989).

[12] Office of Technology Assessment (OTA) of the U.S. Congress, *Technologies to Sustain Tropical Forest Resources and Biological Diversity*, OTA-F-515 (Washington: Government Printing Office, 1992); W.E. Parham, P.J. Durana, and A.L. Hess (eds.), "Improving Degraded Lands: Promising Experiences from South China," *Bishop Museum Bulletin in Botany*, Vol. 3, The Bishop Museum, Honolulu, Hawaii (1993).

[13] D.O. Hall et al., "Biomass for Energy."

[14] P.E. Waggoner, *How Much Land Can Ten Billion People Spare for Nature?* (Ames, Iowa: Council for Agricultural Science and Technology, February 1994).

[15] U.S. Department of Agriculture (USDA), "Production, Supply, and Distribution Database" (diskette), Economic Research Service, USDA, Washington (September 1994).

[16] These figures assume the most recent published World Bank population projections, which show population growing from 5.52 billion in 1993, to 9.58 billion in 2050, to 11.0 billion in 2100. See E. Bos, M.T. Vu, E. Massiah, and R.A. Bulatao, *World Population Projections, 1994-95 Edition* (Baltimore: Johns Hopkins University Press, 1994).

[17] C.I. Marrison and E.D. Larson, "A Preliminary Estimate of the Biomass Energy Production Potential in Africa for 2025," (submitted to *Biomass and Bioenergy*), Center for Energy and Environmental Studies, Princeton University, March 23, 1995.

[18] E.D. Larson, C.I. Marrison, and R.H. Williams, "CO_2 Mitigation Potential of Biomass Energy Plantations in Developing Regions," forthcoming report (Princeton: Center for Energy and Environmental Studies, Princeton University, May 1995).

[19] Divisao de Projetos de Fontes Alternativas, *Estudos de Florestament no Semiarido Nordestino*, Companhia Hidroeletrica do Sao Francisco, Recife, Brazil, (November 1985); and A.E. Carpentieri et al., "Future Biomass-Based Electricity Supply in Northeast Brazil."

[20] A.E. Carpentieri et al., Future Biomass-Based Electricity Supply in Northeast Brazil."

[21] L.R. Oldeman et al., *World Map of the Status of Human Induced Soil Degradation*, International Soil Reference and Information Center and United Nations Environment Programme (April 1991).

[22] D.G. Fereira, H.P. Melo, F.R. Rodrigues Neto, P.J.S. do Nascimento, and V. Rodrigues, *A Desertificacao do Nordeste do Brasil: Diagnostico e Perspectiva*, Nucleo de Pesquisa e Controle da Desertificacao do Nordeste, Universidade Federal do Piaui, Teresina, Piaui, Brazil (1994).

[23] N.H. Ravindranath and D.O. Hall, *Biomass, Energy and Environment*.

[24] World Resources Institute, *World Resources, 1994-95* (New York: Oxford University Press, 1994).

[25] T.P. Elliott and R. Booth, *Brazilian Biomass Power Demonstration Project*; and R.H. Williams and E.D. Larson, "Advanced Gasification-Based Biomass Power Generation."

[26] E.D. Larson and S. Consonni, "Biomass-Gasifier/Aeroderivative Gas Turbine Combined Cycle Power Generation."

[27] A.E. Carpentieri et al., "Future Biomass-Based Electricity Supply in Northeast Brazil."

[28] According to the U.S. Census Bureau, the average revenue per hectare for soybean production in the United States between 1990 and 1992 was $486/ha (*Statistical Abstract of the United States: 1993*, 113th edition, Washington 1993). The revenue might be similar in Brazil, since state-of-the-art yields for soybean production in Brazil are probably comparable to U.S. yields.

[29] The comparison of soybeans with biomass production does not imply that the two would compete for the same land. In fact, as discussed elsewhere, it might be desirable to target degraded areas for multi-year rotation biomass energy production. Such areas may not be suitable for an annual crop like soybeans.

[30] E.D. Larson, L.C.E. Rodriguez, and T.R. de Azevedo, "Farm Forestry in Brazil," presented at **BioResources '94**, Bangalore, India, October 3-7, 1994.

[31] Establishing rural biopower systems would require at least the minimum level of infrastructure development associated with biomass plantations. Where industrial plantations have been successful today, the concomitant development of some infrastructure serving all locals is cited as one of the most important reasons for their success. See C. Sargent and S. Bass (eds.), *Plantation Politics: Forest Plantations in Development* (London: Earthscan Publications, 1992). However, such development would be relatively minor compared to the infrastructure development that could be supported through tax revenues, as discussed here.

[32] The demand for new generating capacity in developing countries from 1989 to 1999 was expected to grow at an average rate of 6.1 per cent per year, with new capacity in this period added at an average rate of 38 GW_e per year. See E.A. Moore and Smith, "Capital Expenditures for Electric Power in the Developing Countries in the 1990s," Energy Series Paper No. 21, Industry and Energy Department (Washington: World Bank, February 1990), with an associated present value capital requirement of over $0.2 trillion (assuming $1000/kW installed cost and 10 per cent discount rate).

[33] High-pressure steam-turbine-based cogeneration systems have already been installed in some cane sugar factories worldwide. See E.D. Larson, R.H. Williams, J.M. Ogden, and M.G. Hylton, "Biomass-Gasifier Steam-Injected Gas Turbine Cogeneration for the Cane Sugar Industry," in D.L. Klass (ed.), *Energy from Biomass and Wastes XIV* (Chicago: Institute of Gas Technology, 1991).

[34] T.B. Johansson et al., "Renewable Fuels and Electricity for a Growing World Economy," and "A Renewables-Intensive Global Energy Scenario," Appendix.

[35] Alternatively, MNCs might be involved only as vendors selling technology to locally-based power companies, but this model may be a less effective instrument for technology transfer. The alternative proposed here, of involving MNCs as partners in independent power companies, gives the MNCs "cradle-to-grave" responsibility for helping manage the technologies being transferred and would facilitate access to internationally based maintenance services, if and as needed.

[36] Despite the advances being made with modernized bioenergy technologies, the notion that biomass can come to play major roles in the overall energy economy flies in the face of conventional wisdom in the fossil energy circles where most MNCs move. In these circles, it is generally believed that because of (*i*) the low efficiency of photosynthesis and (*ii*) the low energy density of biomass compared to conventional fossil fuels, biomass will always remain a minor energy source.

[37] J. Beyea, J. Cook, D.O. Hall, R.H. Socolow, and R.H. Williams, *Toward Ecological Guidelines for Large-Scale Biomass Energy Development*. Report of a Workshop for Engineers, Ecologists, and Policymakers Convened by the National Audubon Society and Princeton University, May 6, 1991; J. Davidson, *Bioenergy Tree Plantations in the Tropics: Ecological Implications and Impacts*, IUCN (International Union for the Conservation of Nature), Gland, Switzerland and Cambridge, UK, 1987; L. Gustafsson (ed.), "Environmental Aspects of Energy Forest Cultivation," special issue of *Biomass and Bioenergy*, 6(1/2) (1994); OTA, *Technologies to Sustain Tropical Forest Resources*; J. Sawyer, *Plantations in the Tropics: Environmental Concerns*, IUCN, Gland, Switzerland and Cambridge, UK (1993); Shell and WWF, *Shell/WWF Tree Plantation Review*, Shell International Petroleum Company, Shell Centre, London, and World Wildlife Fund for Nature, Surrey, UK (June 1993); World Energy Council, *New and Renewable Energy Sources: A Guide to the Future* (London: Kogan Page, 1993).