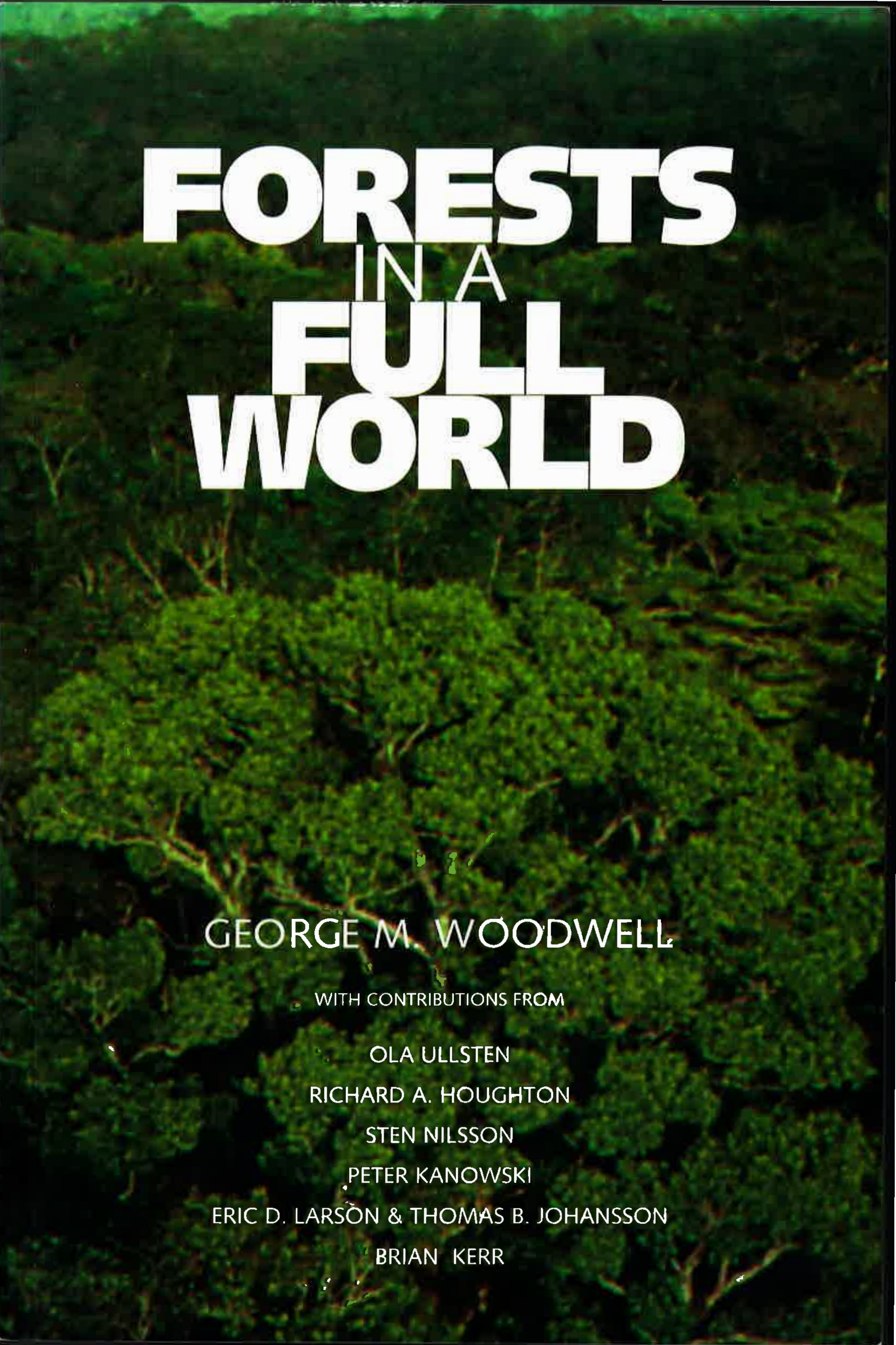

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WITH CONTRIBUTIONS FROM

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CONTENTS

CHAPTER 9

FORESTS AND ENERGY

Most of the energy used in support of human activities is solar energy. It is solar energy that drives the weather, the seasons, the hydrologic cycle, agriculture, forests, the soccer game, the bicycles we ride, and the Americas Cup races. Large supplementary amounts of energy for industrial and other uses are a recent phenomenon extending over a mere two centuries. Before the discovery and exploitation of fossil fuels, virtually all the energy used to support civilization for all of time had been solar energy, used more or less directly. The discovery of oil and coal made great reserves of solar energy stored as hydrocarbons over hundreds of millions of years suddenly available.

The industrial system has been built into a solar-powered biophysical system that is the global environment. One might anticipate that an interest in preserving our own global environment would set limits on the scale and activities of the industrial system. The reality of the limits becomes even more clear and compelling when we realize that the purpose of technology is to enable a better and more comprehensive command of the resources of environment for human use. The free enterprise system that is the basis of democratic capitalism focuses on the profits to be made from applications of technology for industrial development and systematically overlooks the environmental consequences. Limits may not only be ignored but even denied as inappropriately inhibitory to economic growth. Fossil fuels have made wood for fuel nearly obsolete in some parts of the world, yet wood remains a major reliance for heating and cooking among the approximately 4 billion poor of the world.

In this chapter we look into the global budget of industrial energy and the need for, and potential availability of, energy from biotic sources that can be anticipated as the human enterprise continues its expansion. The potential demands are large, especially large as we attempt to replace fossil fuels with enduring sources of energy even as we identify a need to protect the integrity of the biotic functions that are essential to a stable environment.

FUTURE DEMANDS ON FORESTS AS A SOURCE OF ENERGY

ERIC D. LARSON AND THOMAS B. JOHANSSON

The world faces a major challenge in providing in environmentally, socially, and economically sustainable ways the expanded level of energy services needed in a future world with substantially increased population and advanced living standards. New energy strategies will be needed to avoid exacerbating and, indeed, to help solve major problems connected to energy supply and use, such as poverty in developing countries, degradation of local environmental quality, and global warming due to anthropogenic carbon dioxide

The authors thank Robert Williams for the many ideas he contributed to this paper. Eric Larson thanks the W. Alton Jones Foundation, the Geraldine R. Dodge Foundation, and the Energy Foundation for financial support.

emissions. Successful strategies will require major changes in the mix of energy resources and energy-using technologies.

Modernized biomass energy has a potentially important role in providing for future needs. Because plant-derived energy is carbon-neutral when the average rates of use for energy and new plant growth are the same, biomass energy will be a key factor in limiting future energy-related carbon dioxide emissions. Net reductions of carbon emissions from the energy sector could be achieved if the biomass-derived energy displaces existing fossil fuel use. There are also local and regional environmental and socioeconomic benefits to be gained from biomass use for energy. Ecological arguments dictate against using the world's existing natural forests to provide biomass in sufficient quantities to have a significant impact on the world's energy system. However, biomass residues of agricultural production and biomass grown specifically for energy on future plantations could be major sources of energy in the twenty-first century. In this chapter, we review alternative global energy scenarios that envision major roles for biomass. We will discuss technological and land-use changes needed to realize such scenarios, with emphasis on prospects for widespread implementation of energy plantations in developing countries.

Energy for a Sustainable World

Average annual per capita use of energy in developing countries in 1996 was about 36 GJ (36×10^9 Joules), one-fifth the average in industrialized countries. Given the large and growing populations of developing countries and the desires of these people to increase the level of energy services they enjoy, total global demand for energy in the twenty-first century will rise well beyond the 1996 level of about 440 EJ (440×10^{18} Joules), even with aggressive improvements in the efficiency of energy use. Scenarios from a variety of organizations for low energy-growth futures indicate that global commercial energy demand in 2050 will be at least 130%—and perhaps as much as 300%—of 1996 demand (table 9.1). A variety of socioeconomic and environmental problems would be exacerbated by continued or expanded use of conventional energy supplies. For example, expanding the conventional use of fossil fuels to meet increased energy demands will greatly increase the atmospheric carbon dioxide that is causing global warming.

Biomass has the potential to be used for energy in environmentally and socioeconomically sustainable ways, and several recent major assessments of future global energy supply prospects show large potential roles for biomass energy. For example, the Intergovernmental Panel on Climate Change has explored in detail five alternative low-emissions energy supply scenarios (LESS) for satisfying the world's growing demand for energy services in the twenty-first century (figure 9.1) while limiting cumulative CO_2 emissions between 1990 and 2100 to under 500 gigatons of carbon as CO_2. Particularly in the coal-intensive and high-demand variants, "decarbonization" of a substantial amount of the fossil fuels, with long-term subsurface storage (sequestration) of the extracted carbon to prevent it's reaching the atmosphere, is required in the mid-twenty-first century to meet CO_2 emissions targets. In all variants, a substantial contribution from carbon-neutral biomass energy as a fossil fuel substitute is included to help meet CO_2 emissions targets. Biomass energy use is greatest, and the need for fossil-fuel decarbonization and carbon sequestration are smallest, in the biomass-intensive variant. In this scenario, biomass energy would contribute 180 EJ/year to global energy supply by 2050. About two-thirds of this total would be derived from high-yield energy plantations covering nearly 400 million hectares, or an area equivalent to one-fourth of present planted agricultural area.

Most energy analysts are surprised by such visions of large biomass contributions to energy supply for several reasons. First, biomass is often called "the poor man's oil," and the trend has been away from biomass as incomes rise. Second, the economics, energy balances, and CO_2 emissions balances of new biomass energy systems developed to date have often not been favorable. Third, the photosyn-

TABLE 9.1

ALTERNATIVE SCENARIOS FOR GLOBAL ENERGY USE IN 2050 (EJ PER YEAR)

		IPCC 1992, IS92a	World Energy Council/International Institute for Applied Systems Analysis[c]		Shell International Petroleum Company		IPCC 1995
Primary Energy Source	Actual 1996[a]	Reference Scenario[b]	Middle Course	Eco-Driven	Sustained Growth[d]	Dematerialization[e]	Biomass-Intensive[f]
Coal	97.9	356	186	68	184	150	56
Oil	153.7	153	182	120	148	121	75
Natural gas	86.7	143	203	176	140	182	120
Total fossil fuel	338.3	652	571	364	472	453	251
Nuclear	25.4	87	123	23	94	62	11
Traditional biomass	44.4[g]	—	59	50	61	61	—
Renewables	31.7	252	140	203	619	207	312
Total	439.8	991	893	640	1246	783	574

[a]US Energy Information Administration, see http://www.eia.doe.gov. [b]IPCC (1992). [c]Nakicenovic et al. (1998). [d]Kassler (1994). [e]Shell International Petroleum Company (1995). [f]IPCC (1996). [g]Estimated.

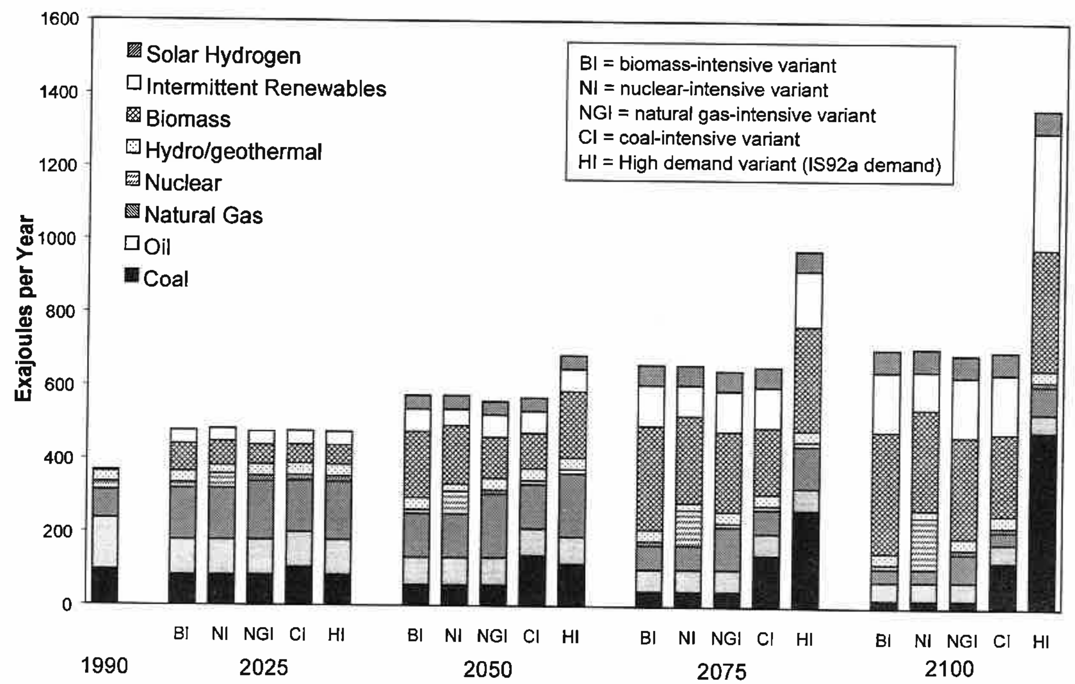


Figure 9.1. Global primary energy use for alternative variants of a low-emissions supply system (LESS) constructed by the IPCC. *Source:* Figure 19–8 in IPCC 1996.

thetic efficiency of biomass is low, making biomass very land-use intensive and giving rise to potential conflicts with other land uses, the most notable of which is food production. Fourth, many are also worried about environmental issues ranging from chemical contamination arising from intensively managed production of biomass energy crops to loss of biodiversity associated with large monoculture bioenergy plantations. Concerns about socioeconomic impacts of large bioenergy plantations have also been raised. In this chapter we address this range of issues in discussing technological and land-use changes that will be required to realize a sustainable global energy system that has significant contributions from biomass.

Alternative Approaches to CO_2 Emission Reductions with Biomass

The distinction between (1) growing and harvesting biomass in "perpetual rotation" for use as a fossil fuel substitute to reduce CO_2 emissions and (2) using planted trees to extract and sequester carbon from the atmosphere is important. Until fairly recently, interest in biomass as a mechanism for coping with greenhouse warming focused on the latter. However, under a wide range of conditions, the growing of biomass on a "perpetual rotation" basis for use as a fossil fuel substitute in modern biomass energy systems would provide substantially greater CO_2 mitigation benefits (Hall et al. 1991a, b; Marland and Marland 1992; Marland and Schlamadinger 1997). With modernization of biomass production and conversion systems, biomass substituted for coal can be as effective in reducing CO_2 emissions as carbon sequestration in planted trees, per ton of biomass; however, fuel substitution can be carried out indefinitely, while carbon storage in trees can be effective only until the planted trees reach maturity. Moreover, there will often be important environmental and socioeconomic benefits other than carbon emissions reductions provided on a continuing basis with a perpetual-rotation strategy (Sathaye et al. 1995), including buildup of soil carbon, jobs created to manage the planted tree system, local revenue generated from sale of biomass, and local biomass availability for nonenergy uses. CO_2 mitigation strategies involving carbon storage in planted trees will be preferred to fossil fuel substitution mainly in regions where biomass yields are too low to be economically interesting for bioenergy production or in remote areas where the costs of transporting the biomass to markets are too high.

Modernizing Biomass Production, Conversion, and End-Use

Photosynthesis produces an amount of new biomass annually with an energy content roughly ten times present global energy use.[1] The amount of biomass presently used for energy—estimated to be 40 to 50 EJ/year (Reddy et al. 1997; WEC 1994; Hall et al. 1993) is less than 1.5% of total photosynthetic production. The actual amount used for energy is uncertain because much of the biomass is used noncommercially for rural household cooking and cottage industries in developing countries. Much of the biomass energy used today is extracted from natural forests, contributing to deforestation, especially where urban residential and industrial fuelwood demands are being supplied (Goldemberg and Reddy 1990).

Traditional direct-use fuelwood markets place a low value on biomass, encouraging sources of low direct-cost (not counting externality costs) biomass such as natural forests (Reddy et al. 1997). Most households that use biomass do so because their fuel choice is limited. As incomes rise, preferences tend to shift away from biomass. For example, in the case of cooking, consumer preferences shift with increasing income from dung to crop residues, fuelwood, coal, charcoal, kerosene, liquefied petroleum gas, natural gas, and electricity (Dutt and Ravindranath 1993).

Although it is true that consumers shift away from biomass energy as incomes rise, the shift is associated with the quality of the energy carrier utilized rather than with the primary energy source itself. If biomass can be converted cost-competitively into more convenient forms such as gases, liquids, or electricity, then wider use is conceivable. In turn, the high value of electricity and fluid fuels that can be made from biomass would enable biomass to be valued more highly, thereby making it possible to provide greater inputs of material and labor into the biomass production process so as to ensure sustainable, environmentally acceptable production. The higher value would also expand the potential economical supplies of biomass.

A key set of assumptions behind the IPCC's LESS constructions (and other similarly biomass-intensive energy scenarios) is that biomass is made widely attractive and competitive in energy markets by dedicated production of suitable feedstocks, efficient conversion into convenient-to-use energy carriers, and use of these carriers in efficient end-use systems. Biomass residues of agriculture also play an important role, for example providing about 35% of biomass energy supply in 2050 in the biomass-intensive LESS variant.

For developing regions the simultaneous modernization of biomass production for energy and biomass production for food may make it possible for biomass to make major contributions to energy supply while minimizing competition with other land uses, food production in particular. These "two modernizations" might be pursued synergistically. The availability of low-cost modern energy carriers and sources, especially for electricity derived from biomass, can help attract industry to rural areas, creating high-paying rural jobs that can generate the rural income needed to pay for the inputs required for modernizing agriculture (Larson and Williams 1995). Higher-yield agriculture can also provide larger quantities of biomass residues that can be used for energy.

Regulatory precautions may be needed to help insure that higher values for bioenergy do not encourage deforestation, but market mechanisms in a modernized bioenergy industry are also likely to discourage deforestation. The firms that invest in modern biomass energy conversion systems will have strong incentives to find ways to provide more secure supplies of biomass feedstocks throughout the lifetime (~30 years) of their capital-intensive investments. Energy plantations (discussed below) will be attractive in this regard and because they can provide the relatively uniform feedstocks preferred for use in advanced conversion technologies.

Plantations will require investments that are typically small compared with the downstream investments in conversion systems. For example, in Brazil, the plantation area required to support an advanced, high-efficiency biomass gasifier/gas turbine power plant with 30 MW_e capacity would be about 6,000 hectares, for which the establishment cost might be about $8 million.[2] In contrast, the total estimated downstream investment is $66 million.[3] Thus, while the plantation establishment cost is only about 10% of the total investment, the entire investment would be jeopardized if there were no secure supply of biomass feedstock. Such supply security could be assured if managed plantations, designed to be ecologically and socioeconomically sustainable, are the feedstock source.

Modernization of Biomass Production

In the production phase, modernization implies the choice of biomass feedstocks that: (1) offer the potential for high yields, low cost, and low adverse environmental impacts and (2) are suitable for use in modern energy systems. Efforts to find optimal combinations of feedstocks, conversion technologies, and end-use systems have not been made in the case of most familiar "new" bioenergy systems, which involve the production of synthetic fuels from grains, sugar cane, sugar beets, or rape seed. These crops were originally optimized for food production (e.g., where tastiness, protein, starch or sugar content are important), so their use as energy crops tends to be suboptimal.

While relatively little biomass is grown today specifically for energy, biomass yields from a variety of activities indicate that very high energy yields are possible compared to yields from conventional agriculture or forestry activities (figure 9.2). Not surprisingly, yields are

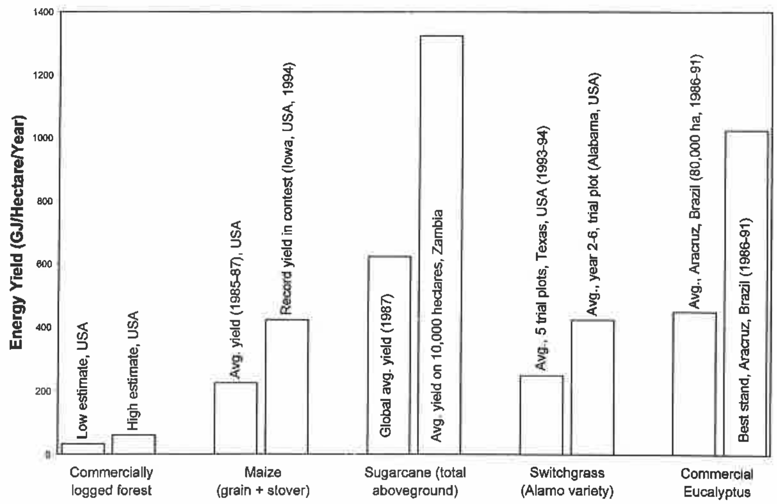


Figure 9.2. Actual biomass yields from various activities. *Source:* Figure 19–3 in IPCC 1996.

highest in tropical regions, where growing seasons are longer. High and sustainable yields are necessary but not sufficient to achieve biomass contributions to global energy supply of the magnitude envisioned in the IPCC's LESS variants and other future energy scenarios. Substantial areas will also need to be dedicated to such high-yield energy plantations.

Modernization of Biomass Conversion

In the conversion phase, modernization implies the use of technologies that offer, at the scales appropriate for biomass energy conversion facilities, low unit capital costs and high thermodynamic efficiencies for making modern energy carriers—mainly electricity and high-quality liquid and gaseous fuels. Since biomass has a low bulk energy density, transporting it long distances can be costly. Thus, conversion facilities must be of relatively modest scale (compared to facilities for coal conversion) if biomass is to be competitive with conventional energy. Technologies that offer high conversion efficiencies at such scales are needed to compete in the conversion of relatively expensive biomass, such as that which might be grown on plantations. A key to attractive economics at modest scales is mass production of equipment in factories, in contrast to the pursuit of economies of scale in field-erected equipment that is characteristic of conventional fossil and nuclear energy conversion systems (Williams and Larson 1988).

A number of technologies that meet the above criteria for modern conversion of biomass can be identified. Processes that begin with thermochemical gasification, which involves the conversion of solid biomass at 800–1,000 degrees C into a fuel gas, look especially promising. Such processes offer enormous flexibility in the choice of feedstock because the only important feedstock properties are high yield, low cost, and low environmental impact.

The gas turbine is one form of technology that is important for conversion of biomass into electricity. This technology, which is widely used with natural gas today and is being commercialized for use with biomass (Waldheim and Carpentieri 1998) offers good thermodynamic performance and low unit capital costs at modest scales (10s to 2 or 3 hundred MW_e), but it requires a clean gaseous or liquid fuel. Integrated with a thermochemical gasifier, the gas turbine has the potential to double the efficiency of electric power generation over conventional (steam turbine) technology and decrease unit capital costs (Williams and Larson 1993). At small scale (under a MW_e), fuel cells and micro gas turbines coupled with biomass gasifiers promise very high efficiencies and competitive economics (Kartha et al. 1997).

The fuel cell vehicle (FCV) is a promising technology for efficiently converting biomass into transport services. Fuel cells were originally developed for space and military applications, but they are now being aggressively developed by most major automobile manufacturers worldwide for commercial introduction in the first decade of the twenty-first century (National Research Council 1997). The low-temperature proton exchange membrane (PEM) fuel cell is the most promising of several fuel cell technologies for vehicle applications (Kalhammer et al. 1998). The PEM fuel cell combines hydrogen electrochemically with oxygen from air to produce electricity at high efficiency (to power the vehicle) and water vapor exhaust. Hydrogen and hydrogen carriers such as methanol can be made from biomass via processes that begin with thermochemical gasification (Williams et al. 1995). The choice of biomass feedstock, transport fuel production technology, and vehicle technology will determine the level of transportation energy services (measured in vehicle-km driven per hectare per year) that can be provided from biomass. In particular, choosing biomass feedstocks with the potential for high yield (e.g., short-rotation tree plantations) would make it possible to deliver far more transportation services than could be realized using more traditional food-crop-based fuels such as ethanol from grain, sugar beets, or sugar cane, or rape methyl ester from rape seed in internal combustion engine vehicles (figure 9.3).

Biomass Energy Resources: Natural Forests, Residues, and Energy Plantations

The annual growth of natural forests globally is substantial. For example, for tropical areas, Hall et al. (1993) estimated the annual growth in natural forests to be equivalent to about 105 EJ/year, or 30% of present global energy use. Ecological concerns, such as loss of biodiversity (Cook et al. 1991), argue against harvesting natural forests for any uses, even for biomass energy production. Some of the biomass-intensive energy scenarios that have been put forward recognize such limitations. For example, the IPCC's biomass-intensive LESS variant includes a fixed contribution of 10 EJ/year from fuelwood harvested from natural forests in the twenty-first century (Williams 1995), a level that is considerably lower than the present level of fuelwood extraction from forests.

The production of biomass residues, including byproducts of food, fiber, and forest production, exceeds 110 EJ/year at present (Hall et al.

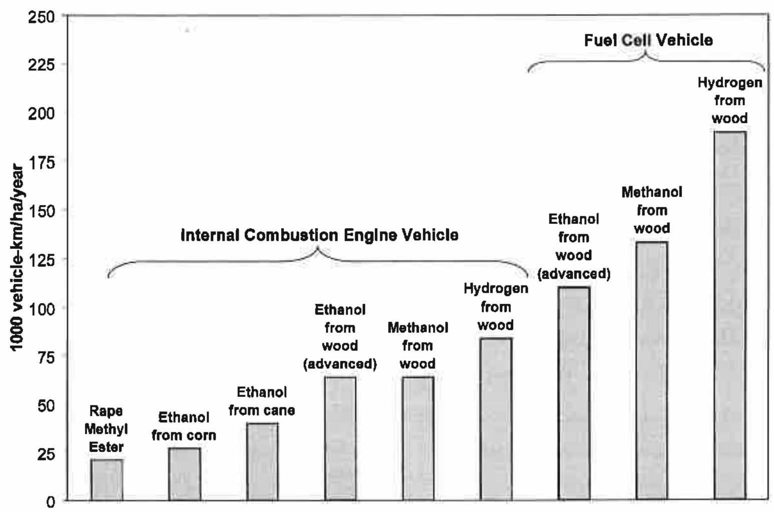


Figure 9.3. Yields of transportation services (vehicle-kilometers) per hectare per year for alternative biomass feedstocks, intermediate fluid fuels, and vehicle end-use technologies. The feedstock "wood" is the product of short-rotation energy plantations with a yield of 15 dry tonnes per hectare per year. "Ethanol from wood (advanced)" refers, speculatively, to an advanced enzymatic hydrolysis conversion process. *Source:* Table 19–4 in IPCC 1996.

1993), perhaps 10% of which is used for energy. Residues concentrated at industrial sites are currently the most common commercially used biomass source. For example, bagasse, the fiber remaining after the juice extraction stage in sugarcane processing, provides energy for processing the juice to sugar or alcohol. Some residues cannot be used for energy: in some cases collection and transport costs are prohibitive; in other cases, agronomic considerations dictate that residues be recycled to the land (Pimentel et al. 1981). In still other cases, there are competing nonenergy uses for residues. Considering such factors, the IPCC's biomass-intensive energy scenario includes a contribution to total global commercial energy supply of 55 EJ/year from biomass residues by 2050 (Williams 1995).

Residues will be especially important biomass energy sources in densely populated regions, where much of the land is used for food production. In fact, biomass residues might play important roles in such regions precisely because the regions produce so much food: crop production can generate large quantities of byproduct residues. Consider China, which in 1996 generated crop residues in the field (mostly corn stover, rice straw, and wheat straw) plus agricultural processing residues (mostly rice husks, corn cobs, and bagasse) totaling about 790 million tons, with a corresponding heating value of 390 million tons of coal equivalent (Gu and Duan 1998). The significance of this resource can be appreciated by a thought experiment. Suppose that half of this resource is potentially available to use for generating electricity and that advanced small-scale biomass power generating technology based on a solid-oxide fuel cell/micro gas turbine combined cycle technology that could be available within a decade were used to do so at an efficiency of ~43% (Kartha et al. 1997). The resulting electricity generation would be nearly equivalent to the total electricity generation from coal in China in 1996.

Potential residue biomass resources alone will be insufficient to provide the world with the levels of biomass energy supply envisioned in the IPCC LESS constructions. This led the IPCC to conclude that a substantial commitment of land to energy plantations will be required to meet the biomass energy supply levels envisioned in their scenarios.

At present, there are an estimated 100 million hectares of commercial tree plantations worldwide (Bazett 1993), most of which are dedicated to industrial products other than energy. For comparison, cropland and forests/woodlands globally occupy approximately 1.5 and 4.1 billion hectares, respectively. Are there sufficient land resources to both feed future populations and to sustainably provide the levels of biomass energy production in the IPCC's biomass-intensive LESS variant? This scenario includes 385 million hectares of biomass energy plantations globally in 2050 (Williams 1995). Three-quarters of the plantation area is in developing countries, where the IPCC foresees much larger potential contributions of biomass to energy supply than in industrialized countries (figure 9.4).

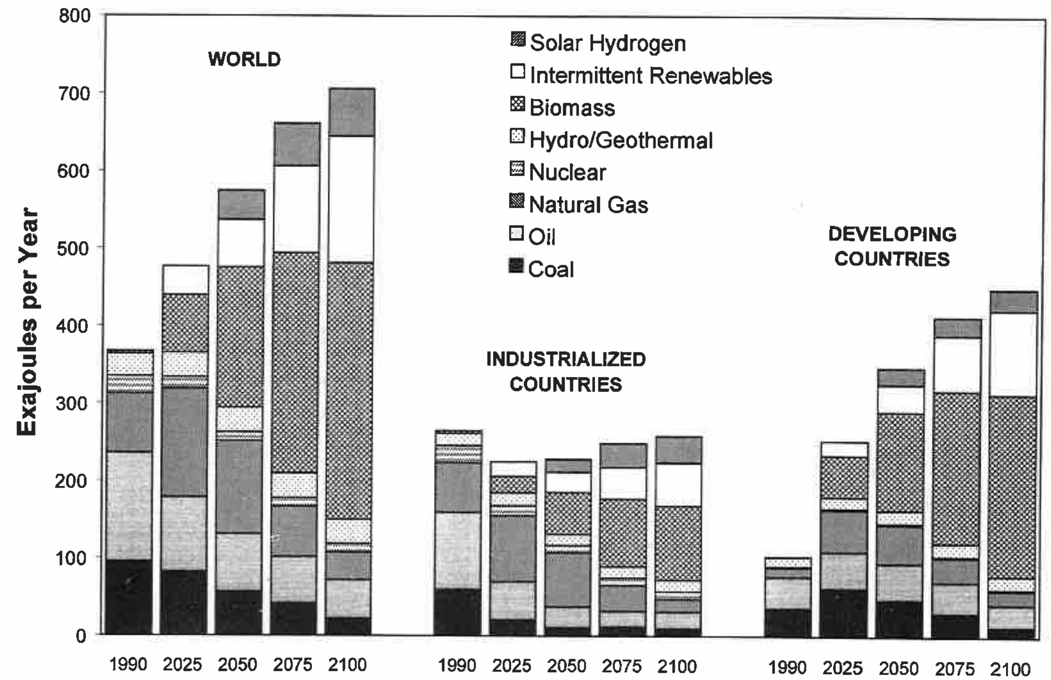


Figure 9.4. Primary commercial energy use by source and region for the biomass-intensive variant of the IPCC LESS constructions. *Source:* Figure 19–13 in IPCC 1996.

Restoring Degraded Lands by Producing Biomass for Energy

Competition between land use for agriculture and for energy production can be minimized by targeting degraded lands for the latter (Johansson et al. 1993; Hall et al. 1993; Williams 1994; Ravindranath and Hall 1994). Grainger (1988 and 1990) and Oldeman et al. (1991) have estimated that there are more than 2 billion hectares of such lands in developing countries. Grainger further estimates that some 621 million hectares of these lands are suitable for reforestation. Houghton (1990) has estimated 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.

Interest in restoring tropical degraded lands is indicated by the ambitious goal of a global net afforestation rate of 12 million hectares per year by 2000 that was set in the 1989 Noordwijk Declaration (Ministerial Conference 1989).[4] The biomass energy plantation establishment rate required in developing countries between 2000 and 2050 to meet the biomass energy goals envisaged in the IPCC's biomass-intensive LESS variant is about 5 million hectares per year. Thus, the joint goals of establishing biomass energy plantations and restoring degraded lands might be served simultaneously by using degraded lands for plantations.

In principle, the capital needed to finance the restoration of degraded lands could be provided by the investors for the energy projects that the resulting plantations would support, because of the prospectively attractive economics of advanced biomass conversion technologies. As discussed earlier, minimizing the risk associated with the large investment in downstream biomass conversion facilities would provide the firms involved with strong incentive to find ways to restore the lands in sustainable ways.

The primary technical challenge in restoring degraded land 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 (OTA 1992; Parham et al. 1993). Other difficulties reflect general conditions in many developing regions, for example, complex or disputed land ownership, lack of roads to transport biomass to processing facilities, lack of the means to move the biofuels to markets, and the problem of growers in poor areas being unable to wait the 3 to 8 years typically required for cash returns on short-rotation tree crops. But the potential for rural industrialization spurred by the prospect of low-cost electricity from biomass would provide strong incentives to tackle such infrastructure-building and other start-up challenges. One indicator suggesting the feasibility of overcoming technical, socioeconomic, political, and other challenges to growing energy crops on degraded lands is provided by the fact that many successful plantations in developing countries have been established on such lands (Hall et al. 1993).

Nevertheless, to help accelerate the rate of plantation development, it is important to initiate intensive research, development, and implementation programs for establishing plantations on degraded lands. Such programs should lead to the development of region-specific restoration plans that take into account local bioclimatic and socioeconomic conditions. Successful restoration activities conducted by both outside experts and local farmers should be investigated. Also, restoration programs involving 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.

Food versus Fuel?

While the use of degraded lands appears to be a potentially major and attractive option for biomass energy crops, concerns about future food supplies have led some to suggest that large land areas will not be available for biomass production for energy purposes in some developing regions. For example, one study concludes that by 2050 no land will remain for large-scale energy plantations in Africa if food crop yields are not substantially increased, although much land will be available in Latin America (Alcamo et al. 1994).

Some analysts have concluded that it will be difficult to expand food production enough in developing countries to keep up with population growth, largely for environmental reasons (Ehrlich et al. 1993; Kendall and Pimentel 1994), calling attention, for example, to the downturn in world cereal production per capita in the early 1990s (Brown 1993). The outlook for future food production may not be so bleak, however. For example, Dyson (1994) points out that the main reason for the early 1990s decline in world cereals production per capita was the reduction in the amount of land committed to cereals production, especially in the United States, Canada, and Latin America, as a result of extremely low world prices for cereals. Moreover, when the demand-supply balance in food markets is restored (so that there is once again incentive to increase yields), there could be substantial increases in crop yields. Waggoner (1994) argued that, with productivity improvements, world food requirements to the middle of the next century could plausibly be met without expanding cropland. Similarly, Smil (1994) concluded that the food requirements of the population in the middle of the next century could be provided with only a small extension of cultivated cropland, even without bioengineering breakthroughs.

A cursory examination of historical trends in grain yields suggests that Waggoner's hypothesis—that a world with twice the present population could be fed with no increase in cropland largely due to an expected continuation of yield increases—may be reasonable. Worldwide average grain yields have been increasing at an average linear rate of 44 kg per hectare per year since 1960 (figure 9.5). 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 yield increase from 2.6 tons per hectare per year in 1993

(USDA 1994) to 4.5 t/ha/yr in 2050 and 5.2 t/ha/yr in 2100.[5] The implied linear growth rates for yields are 33 kg/ha/yr from 1993 to 2050, and 14 kg/ha/yr from 2050 to 2100, both of which are slower than the average growth rate since 1960. Also, the target yield for 2100 is about 91% of the 1999 U.S. yield, 6% higher than the 1999 Chinese average, and 21% below the 1999 South Korean yield.

If continuing improvements in crop yields are to be realized globally, it must be feasible and desirable to carry out agriculture in sustainable ways with relatively high levels of chemical inputs, and income in developing regions must be generated to pay for the inputs. The income could come from rural industrialization that is spurred, at least in part, by the availability of low-cost, high-quality energy from biomass.

There are two levels of concern regarding the chemical inputs to agriculture: (1) chemical contamination of the environment associ-

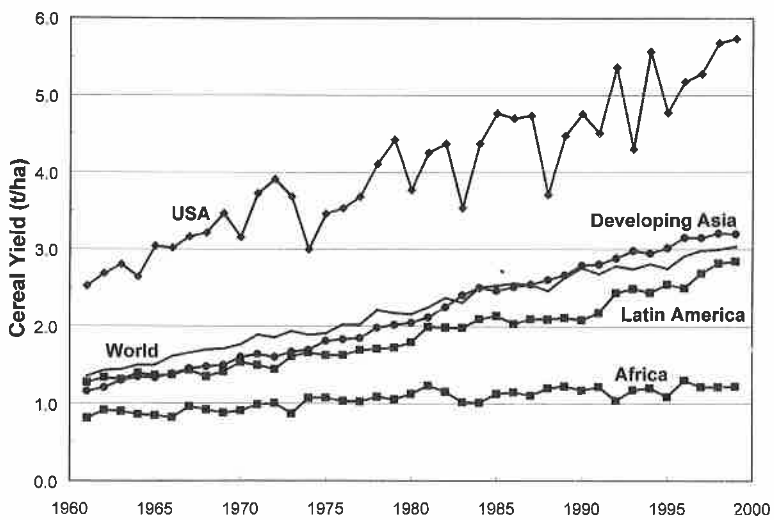


Figure 9.5. Average cereal yields for the world, Africa, Latin America, developing Asia, and the United States from statistics of the Food and Agriculture Organization (FAO 2000).

ated with high specific levels of inputs (e.g., kg fixed N/ha/yr), and (2) a set of issues posed by the overall rate of nitrogen fixation in the world, which is already much higher than the preindustrial rate (Kinzig and Socolow 1994). Crop yields would surely drop if chemical inputs were reduced to zero. But various strategies can be pursued to reduce the intensity of chemical inputs substantially without reducing yields as suggested by Worrell et al. (1995) and Kinzig and Socolow (1994), just as many ways have been found over the last two decades to make more efficient use of energy while increasing the amenities associated with energy use. Also, Waggoner pointed out that a plot of lush foliage generally needs only a little more pesticide to protect it from an insect or disease than does one of sparse foliage and that realizing bumper crops actually requires less herbicides than do sparse crops; the dense shade provided by bumper crops reduces the number of weeds that sprout and limits the growth of the few that do. With regard to applications of chemical fertilizer, Waggoner observed that the use of more fixed nitrogen (say) to increase yields can be minimized if efforts aim to optimize all inputs to crop production simultaneously instead of just applying more nitrogen fertilizer (Waggoner 1994). A Dutch study (NSCGP 1992) exploring four alternative future agricultural scenarios for the European Union (EU) in 2015 (labeled Free Market, Regional Development, Nature and Landscape, and Environmental Protection) projected substantially reduced land requirements for food production and reduced specific levels of chemical inputs relative to today's levels (for both N and chemicals for pest control) in all scenarios, as a result of pursuing alternative agricultural policy objectives (table 9.2). It is noteworthy that for all the scenarios (involving both intensive and extensive agricultural production strategies in the EU), the projected overall levels of chemical N inputs were about the same, even though specific application rates varied by more than a factor of two.

Those who advocate for environmental reasons cutbacks in chemical inputs to levels that would lead to reduced yields even with good chemical management practices might weigh the environmental im-

TABLE 9.2

TOTAL AND SPECIFIC CHEMICAL INPUTS FOR ALTERNATIVE AGRICULTURAL SCENARIOS FOR THE EUROPEAN UNION IN 2015

		Nitrogen Use in Fertilizer		Pesticide Use	
Scenario	Cropland in European Union (10^6ha)	Total Input (10^6 tonnes/yr)	Specific Input (kg-N/ha/yr)	Total Input (10^6 kg a.i./yr)[a]	Specific Input (kg a.i./ha/yr)[a]
Current	127	11	85	400	3.2
Free Market	42	2.1	59	60	1.7
Regional Development	77	2.8	42	89	1.3
Nature and Landscape	26	2.1	80	21	0.8
Environmental Protection	61	2.1	35	33	0.5

Note: These alternative scenarios were generated by the Netherlands Scientific Council for Government Policy (NSCGP 1992). For all the scenarios the demand for agricultural products is exogenously determined by the condition that the diet is unchanged from the present. Each of the alternative scenarios represents optimization for a different set of societal objectives. Under "free market," costs of agriculture are minimized and there is free trade in agricultural products. Under "regional development," the policy is to maintain regional employment in the agricultural sector and to promote self-sufficiency in agricultural production. Under "nature and landscape," the objective is to convert as much agricultural land as possible to natural habitat. Under "environmental protection," the objective is to minimize environmental contamination from the use of agricultural chemicals.

[a]Here, kg a.i. = kilograms of active ingredients.

pacts of carefully managed chemical inputs in intensive agriculture against the environmental risks posed by extensive agricultural expansion brought about either by converting more forests into cropland (e.g., increased loss of biological diversity) or by expanding food production into increasingly marginal lands (e.g., increased erosion). If marginal lands are to be put into crop production, it is far preferable, from an environmental perspective, to plant tree or perennial grass crops for energy than to plant annual row crops for food on these lands.

Preliminary Regional Land Availability Estimates

Although general arguments such as those outlined above are helpful in better understanding the issues involved in estimating the potential for establishing biomass energy plantations in developing regions, detailed analyses are needed at country and subcountry levels. What follows are the results of preliminary country-by-country modeling exercises carried out for Africa, Latin America, and Asia to estimate potential biomass energy production in 2025 (Marrison and Larson 1996; Larson et al. 1995).

Marrison and Larson (1996) have made a preliminary estimate of the land availability and associated bioenergy production potential for fifty African countries in the year 2025. They assume that Africa's population in 2025 is 2.5 times the 1990 level and that food crop yields grow between 1990 and 2025 in Africa at the same linear rate as the average cereal-crop yield grew there from 1972 to 1990 (13.8 kg/ha/year, which is much slower than the global average rate of 40 kg/ha/year [figure 9.5]).[6] Average crop yields in 2025 would be 1.43 times the 1990 average for Africa, but they would still be below the 1990 Brazilian level and far below the 1990 level in the United States. Marrison and Larson further assume that food imports will not increase beyond the absolute 1990 levels, and that per capita calorie supplies will increase to correct current undernourishment. With these assumptions, the cropland requirements for Africa in 2025 are some 451 million hectares, or 2.4 times the 1990 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 as classified by the Food and Agriculture Organization of the United Nations (WRI 1994).[7] After meeting cropland needs, any remaining land that is neither cropland, forest, nor wilderness is assumed to be "potentially available" for other uses, including biomass energy production. For Africa as a whole, Marrison and Larson estimated this potentially available land area to be some 1.1 billion hectares in 2025.[8]

Marrison and Larson projected biomass energy crop yields on potentially available land on the basis of annual nationally averaged precipitation levels and a yield-precipitation correlation for modern commercial eucalyptus plantations in Brazil, where there is significant industrial plantation experience. With this algorithm, the average yield for all Africa is 8.3 t/ha/yr, equivalent to about 170 GJ/ha/yr. This is a relatively modest yield by comparison to actual yields for a variety of biomass systems in place around the world today (figure 9.2).

Marrison and Larson calculated the total potential biomass energy production as a function of an assumed "cutoff" yield—the yield below which biomass energy production is assumed to be uneconomical. In practice, the minimum economically viable yield will depend on local factors such as the costs for land, labor, and competing energy sources. In Brazil, the cost of eucalyptus wood chips from industrial plantations rises sharply with decreasing yield for a yield below 5 to 10 t/ha/yr (figure 9.6).

Marrison and Larson's results are summarized in figure 9.7. In particular, figure 9.7d shows the total biomass energy production for Africa as a function of assumed cutoff yield and for different values for the percentage of potentially available land that is used for plantations. At a cutoff yield of 10 t/ha/yr, less than 5% of the potentially available area would be needed to provide the level of plantation bioenergy supplies (4.9 EJ/yr) envisioned by the IPCC in its biomass-intensive LESS variant for 2025 for Africa. The analysis by Marrison and Larson strongly suggests that land resources are sufficient to sup-

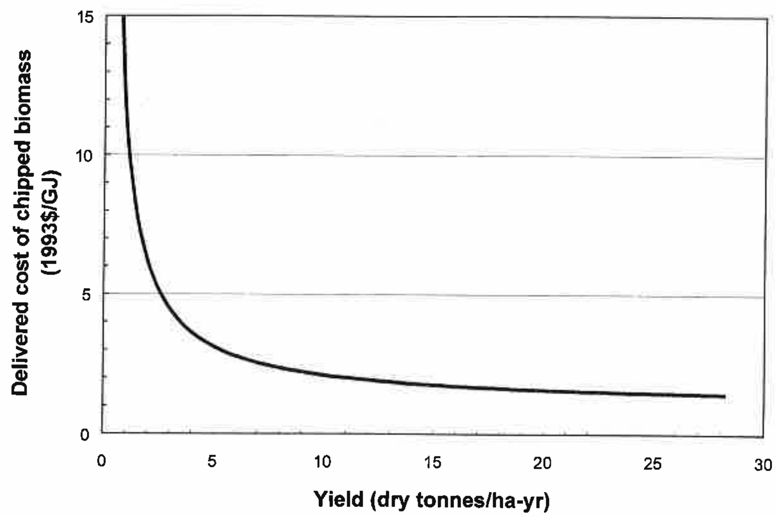


Figure 9.6. Estimated average cost (1993 US$/GJ) of delivered eucalyptus chips in Brazil as a function of yield. The estimated costs include establishment, maintenance, harvesting, and 85 km transport of 7-cm or larger diameter eucalyptus logs with 33% moisture content, based on commercial plantations in primarily central and south-central Brazil (Carpentieri et al. 1993), plus $0.28/GJ for chipping (Perlack and Wright 1994).

port a biomass-intensive energy future in Africa without compromising food production needs.

Larson et al. (1995) apply the same algorithm and biomass yield-precipitation correlation as for the Africa analysis above to estimate the bioenergy potential in 2025 in Latin America and Asia. In Asia and Latin America, crop yields have increased since 1972 at higher rates than in Africa (figure 9.5). A continuation of the historical growth pattern implies an average 2025 cereal yield for Latin America of 4.2 t/ha/yr (51% above the 1990 average for that region) and 5.4 t/ha/yr for Asia (96% above the 1990 yield). The yields in 2025 would be slightly higher in Asia and slightly lower in Latin America than the average 1990 U.S. yield of 4.48 t/ha/yr. The relatively high rates of increase in crop yields lead to calculated cropland requirements in 2025 that are only 1.24 times the 1990 level for Latin America and that are essentially the same in 2025 as in 1990 for Asia. The noncropland, nonforest, nonwilderness area potentially available for biomass energy or other uses in 2025 is 0.71 billion hectares for Latin America and 1.37 billion hectares for Asia.[9]

The calculations of Larson et al. (1995) predicted that both regions can support substantial plantation biomass production. In Latin America (figure 9.8), assuming a cutoff yield of 10 t/ha/yr, about 3% of the potentially available area would be sufficient to deliver the plantation bioenergy level of 6.4 EJ/yr envisioned for Latin America in the IPCC biomass-intensive energy scenario for 2025. In Asia (figure 9.9), less than 1% of potentially available area would be required to deliver the 2.3 EJ/yr envisioned by the IPCC in this region.

An indication of the economics of biomass production on plantations is given in figure 9.10, which shows how much biomass might be produced as a function of marginal production cost in Africa, Asia, and Latin America. In constructing these supply curves, it was assumed that the cost of delivered biomass varies with yield as shown in figure 9.6, so that there is a one-to-one correspondence between a maximum allowable cost and a corresponding cutoff yield. In all regions, a large fraction of the potential biomass production would cost $2/GJ or less.

That Asia might plausibly be a major producer of plantation bioenergy without compromising food production needs is surprising because of the large and growing populations there. This conclusion of Larson et al. is a result of the high rate of growth assumed for crop yields between 1990 and 2025, which corresponds to an assumed continuation of the linear rate (65 kg/ha/yr) observed between 1972 and 1990 for cereals. The assumed crop yields in 2025 for Asia are not implausible, however. For cereals the yield in 2025 is 5.4 t/ha/yr, a level first reached in 1992 in the United States (figure 9.5). Nevertheless, because it is contrary to conventional thinking about land-use constraints in Asia, more detailed country-level and subcountry-level corroboration is needed.

One assessment has been carried out for India by Ravindranath and Hall (1994), who observe that total area under crops in India was

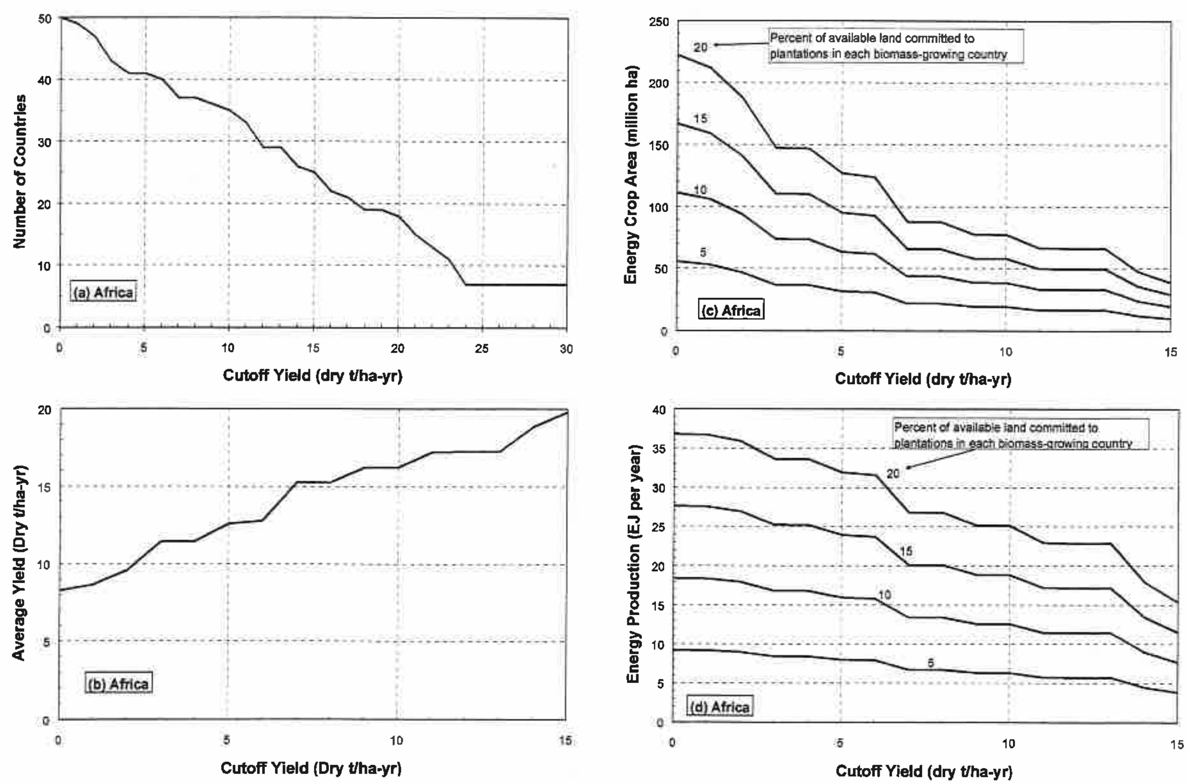

(a) Africa
Number of Countries
Cutoff Yield (dry t/ha-yr)
(b) Africa
Average Yield (Dry t/ha-yr)
Cutoff Yield (Dry t/ha-yr)
(c) Africa
Energy Crop Area (million ha)
Percent of available land committed to plantations in each biomass-growing country
Cutoff Yield (dry t/ha-yr)
(d) Africa
Energy Production (EJ per year)
Percent of available land committed to plantations in each biomass-growing country
Cutoff Yield (dry t/ha-yr)

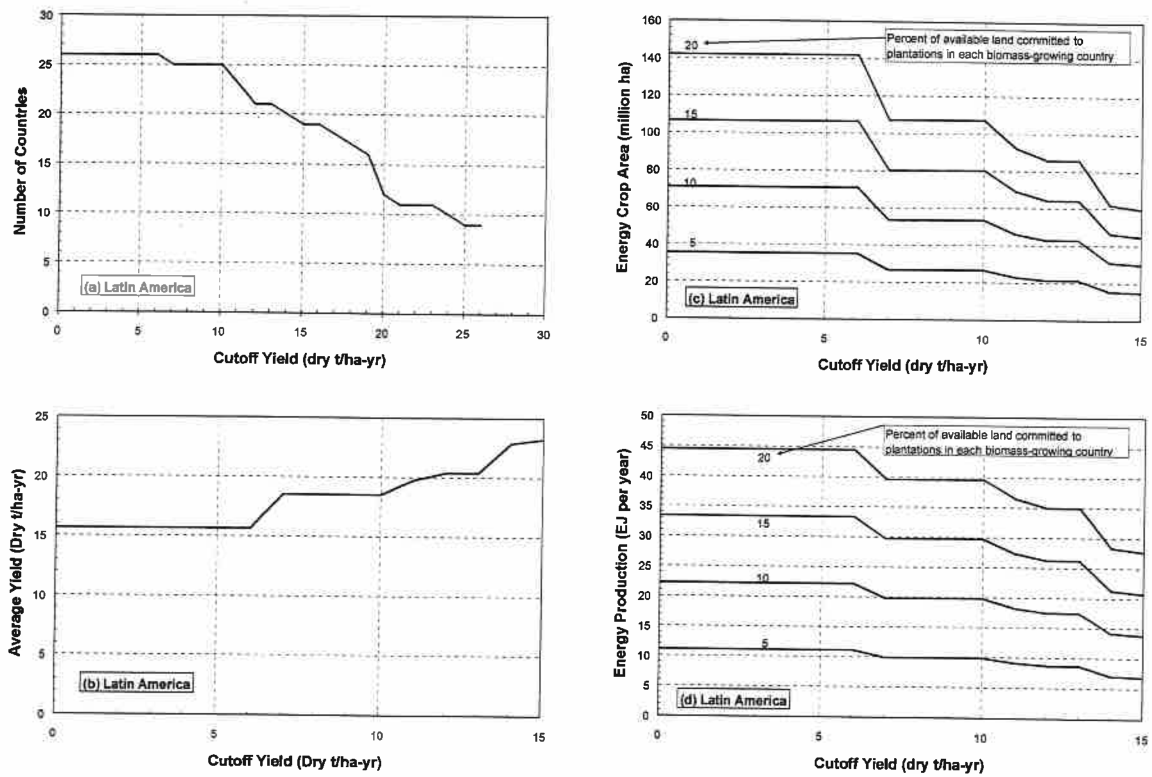
Figure 9.7. Analysis of biomass energy production potential in Africa as a function of the "cutoff yield," that is, the yield (in dry tonnes per hectare per year) below which it is assumed that a country cannot economically produce biomass (Marrison and Larson 1996).

(a) Total number of countries with mean national yields higher than the cutoff yields.

(b) Area-weighted average yield for the set of countries with country-average yields equal to or higher than the cutoff yield.

(c) Biomass energy area as a function of the cutoff yield, assuming biomass is planted on 5%, 10%, 15%, or 20% of available noncrop, nonforest, nonwilderness land in each of the countries with a country-average yield higher than the cutoff value.

(d) Energy production for (c) above.



(a) Latin America
Number of Countries
Cutoff Yield (dry t/ha-yr)
(c) Latin America
Percent of available land committed to plantations in each biomass-growing country
Energy Crop Area (million ha)
Cutoff Yield (dry t/ha-yr)
(b) Latin America
Average Yield (Dry t/ha-yr)
Cutoff Yield (Dry t/ha-yr)
(d) Latin America
Percent of available land committed to plantations in each biomass-growing country
Energy Production (EJ per year)
Cutoff Yield (dry t/ha-yr)

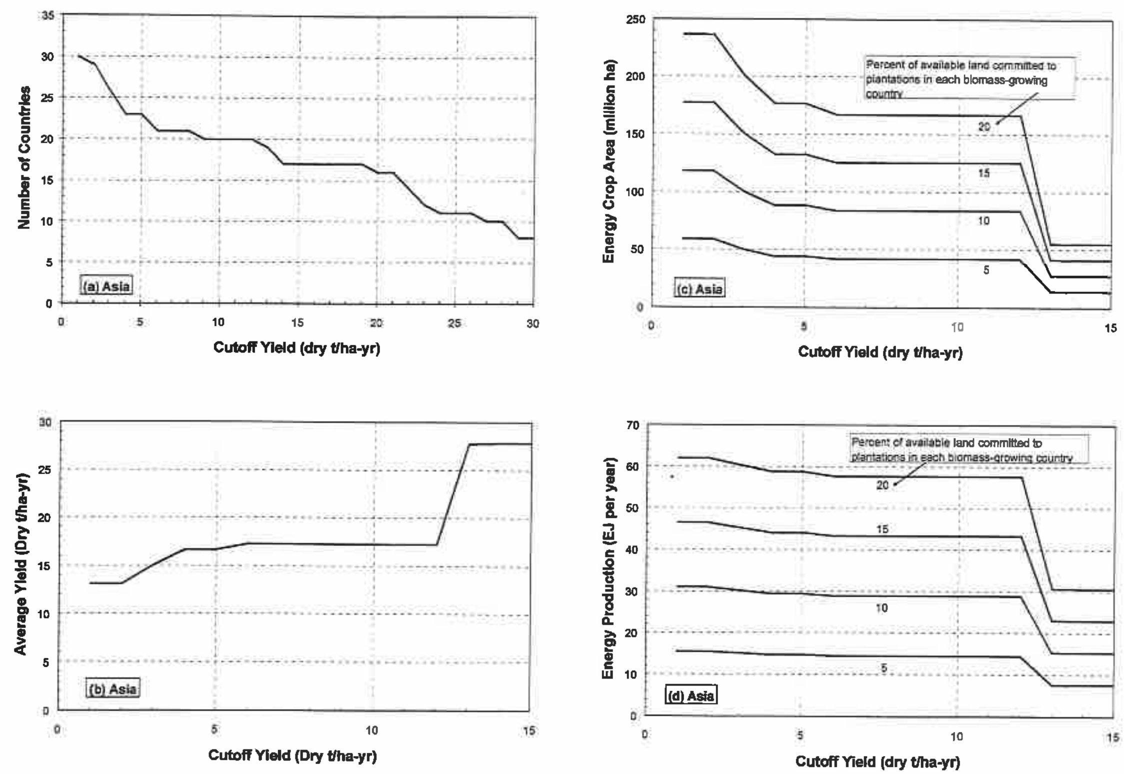
Figure 9.8. Analysis of biomass energy production potential in Latin America as a function of the "cutoff yield," the yield (in dry tonnes per hectare per year) below which it is assumed that a country cannot economically produce biomass (Larson et al. 1995).

(a) Total number of countries with country-average yield higher than the cutoff yield.

(b) Average yield for the set of countries with country-average yields higher than the cutoff yield.

(c) Biomass energy area as a function of the cutoff yield, assuming biomass is planted on 5%, 10%, 15%, or 20% of available noncrop, nonforest, nonwilderness land in each of the countries with a country-average yield higher than the cutoff value.

(d) Total biomass energy production as a function of cutoff yield, assuming biomass is planed on 5%, 10%, 15%, or 20% of available noncrop, nonforest, nonwilderness land in each of the countries with a country-average yield higher than the cutoff value.



(a) Asia
Number of Countries
Cutoff Yield (dry t/ha-yr)
(b) Asia
Average Yield (Dry t/ha-yr)
Cutoff Yield (Dry t/ha-yr)
(c) Asia
Energy Crop Area (million ha)
Percent of available land committed to plantations in each biomass-growing country
Cutoff Yield (dry t/ha-yr)
(d) Asia
Energy Production (EJ per year)
Percent of available land committed to plantations in each biomass-growing country
Cutoff Yield (dry t/ha-yr)

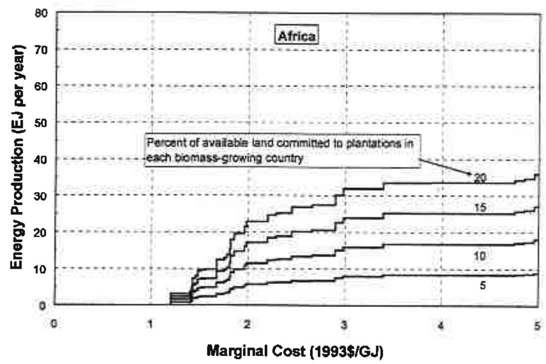
Figure 9.9. Analysis of biomass energy production potential in Asia as a function of the "cutoff yield," the yield (in dry tonnes per hectare per year) below which it is assumed that a country cannot economically produce biomass (Larson et al. 1995).

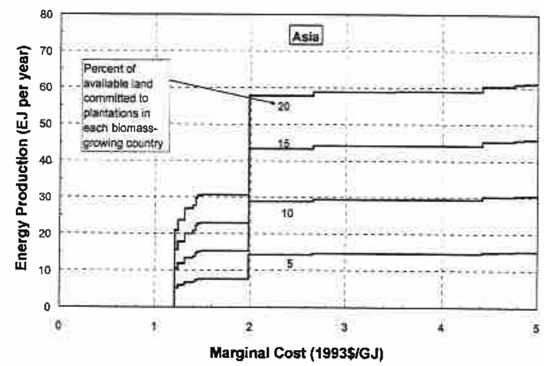
(a) Total number of countries with country-average yield higher than the cutoff yield.

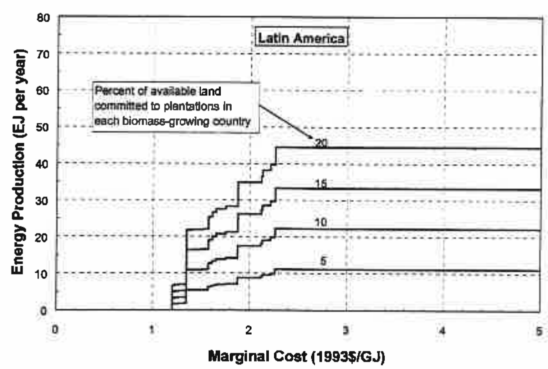
(b) Area-weighted average yield for the set of countries with country-average yields equal to or higher than the cutoff yield.

(c) Biomass energy area as a function of the cutoff yield, assuming biomass is planted on 5%, 10%, 15%, or 20% of available noncrop, nonforest, nonwilderness land in each of the countries with a country-average yield higher than the cutoff value.

(d) Total biomass energy production as a function of cutoff yield, assuming biomass is planted on 5%, 10%, 15%, or 20% of available noncrop, nonforest, nonwilderness land in each of the countries with a country-average yield higher than the cutoff value.


Africa
Energy Production (EJ per year)
Marginal Cost (1993$/GJ)
Percent of available land committed to plantations in each biomass-growing country
20
15
10
5
0
10
30
40
50
60
70
80
1
2
3
4


Asia
Energy Production (EJ per year)
Marginal Cost (1993$/GJ)
Percent of available land committed to plantations in each biomass-growing country
20
15
10
5


Latin America
Energy Production (EJ per year)
Marginal Cost (1993$/GJ)
Percent of available land committed to plantations in each biomass-growing country
20
15
10
5

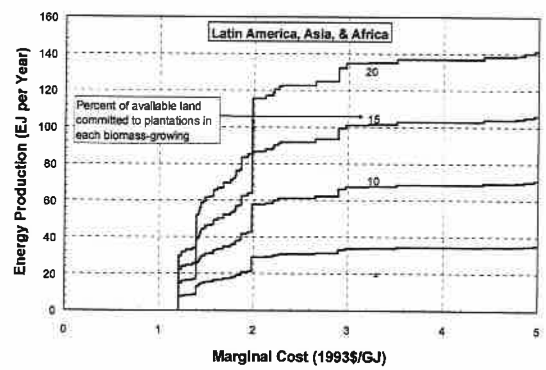

Latin America, Asia, & Africa
Energy Production (EJ per Year)
Marginal Cost (1993$/GJ)
Percent of available land committed to plantations in each biomass-growing
20
15
10

Figure 9.10. Biomass cost-supply curves for Africa, Latin America, Asia, and the sum of all three regions in 2025 showing the cumulative total energy production with increasing delivered cost of biomass. The four lines represent the use of 5%, 10%, 15%, and 20%, respectively, of available noncropland, nonforest, nonwilderness land in each country in which biomass can be produced at or below the cost shown on the x-axis. The cost of biomass (in 1993$/GJ) is $9.1442 \times Y^{-0.5949}$, where Y is yield in t/ha/yr. This relationship is based on figure 9.6.

roughly the same in 1990 (around 125 million hectares) as it was 20 years earlier, despite population growth averaging about 2.4% per year during these two decades. Cultivable noncropland has also remained stable at about 40 million hectares. In looking to the future land requirements for agriculture, Ravindranath and Hall noted that the average yield of India's most important crop, rice, was 1.7 t/ha/yr, or about half the Asian average, one-third of the yield in China and Japan, and one-fifth the Korean yield. They also note that in some states of 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 cropping intensities, including the cultivation of at least two crops per year through irrigation, Ravindranath and Hall concluded that there are good prospects for doubling or tripling average annual yields in India, and thereby for doubling or tripling food production without increasing cropped area. Such a scenario leaves substantial amounts of land for other uses and suggests the results of Larson et al. for Asia, discussed above, may be plausible.

Ravindranath and Hall proposed the use of degraded lands in India for biomass energy production. They cited three relatively disaggregated estimates of the area of degraded land in India, with totals ranging from 66 to 106 million hectares from a total land area in India of about 300 million hectares. Excluding degraded land that is presently under cultivation reduces the range of these estimates to 61 to 71 million hectares. Gautam (1997) cited a recent independent estimate of 76 million hectares. For comparison, the total noncrop, nonforest, nonwilderness area estimated for India in the analysis by Larson et al. is 83 million hectares.

A Case Study of Biomass Energy Plantations in the Northeast of Brazil

The modeling exercise described in the previous section has a number of shortcomings. The assumption of a single average annual precipitation level for a country is a simplifying approximation that could be refined to a much finer grid; the likelihood of generating misleading results with this assumption increases with the size of the country and is likely to be especially significant for large countries such as China and India. Likewise, the model neglects production-limiting factors other than precipitation (including terrain details, such as topography, and cultural factors) that could limit the potential for biomass energy even where rainfall is adequate.

Moreover, the yield-precipitation relationship used to estimate biomass yields is based on commercial experience with Eucalyptus in Brazil; ideally, energy crops would be selected for a given region to suit the ecology of that region, and the yield-precipitation relationship is likely to vary with the crop. Much more detailed country-level and subcountry-level analyses are needed to provide a good understanding of the practical potential for biomass energy plantations.

The northeast of Brazil is one region that has been examined in detail (Carpentieri et al. 1993). The nine states comprising the northeast region of Brazil account for 18% of Brazil's land area, or nearly 10% of South America. The population density in the northeast region is the lowest among the three most populated regions in Brazil. The only significant conventional energy resource indigenous to the region is hydroelectric power, the economic potential for which was fully utilized by the start of the twenty-first century.

Given the high per capita land availability and the near exhausting of indigenous conventional energy sources in Northeast Brazil, the utility responsible for electricity there (Companhia Hidroeletrica do Sao Francisco [CHESF]) began studies of the biomass energy production potential in the region in the early 1980s. The CHESF studies mapped key physical aspects of the region (soil type and quality, rainfall, topography, and elevation, for example) 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 studies estimated that the land area potentially available for plantations was 50 million hectares, or one-third of the total area of the region. Biomass yields were estimated to range from less than 3 dry tons per hectare per year on the worst lands to over 20 t/ha/yr on the best sites, with 12.5 t/ha/yr as the regional average. The total biomass production potential in the northeast was estimated to be 12.6 EJ/yr, about 75% of which would be available for a delivered cost of less than $2/GJ (table 9.3).[10] For comparison, the modeling exercise of Larson et al. estimated that if 10% of the potentially available land in all of Brazil were committed to biomass energy plantations, some 7.4 EJ/yr could be produced in 2025 (average yield of 23.4 t/ha/yr on 16 million hectares). The CHESF studies suggest a much higher potential than this for the Brazilian Northeast alone, because the CHESF studies indicate that much more than 10% of the land in the sparsely populated northeast could be committed to plantations without running into serious land-use conflicts.

That the biomass energy production potential of Northeast Brazil is so large is surprising because a large part of the region is semi-arid. Furthermore, roughly half the area identified by CHESF as suitable for plantations is characterized as having soil that is being degraded by wind erosion, water erosion, or chemical deterioration (Oldeman 1991). A smaller percentage of the area has also been characterized as susceptible to desertification, based on a set of criteria that included physical (soils, water resources), social (land ownership structure), economic (present use of land), and other indicators (Fereira et al. 1994).

Given its encouraging analysis of the biomass energy production potential in Northeast Brazil, CHESF is now starting to implement a biomass-electricity generating program (Waldheim and Carpentieri 1998).

Environmental Issues

To many people, the growing of biomass for energy on a large scale is viewed as a massive assault on nature. And intensive agricultural management practices, which might also characterize

TABLE 9.3

STATE-BY-STATE DISTRIBUTION OF AREA SUITABLE FOR BIOMASS PLANTATIONS IN NORTHEAST BRAZIL BY BIOCLIMATIC REGION, WEIGHTED AVERAGE YIELD, WEIGHTED AVERAGE DELIVERED BIOMASS COST, AND TOTAL BIOMASS ENERGY PRODUCTION POTENTIAL

State	Total Area of State (1,000 ha)	Area Available for Biomass Plantations by Bioclimatic Region (1,000 ha)						Area-Weighted Average		Total Potential Biomass (TJ/yr)
		I	II	III	IV	V	Total	Yield (dry t/ ha/yr)	Cost (1993$/ GJ)	
Alagoas	2,911	32	318	126	21	2	498	14.9	1.77	148
Bahia	56,698	589	3,636	7,511	3,761	732	16,228	12.1	1.93	3,920
Ceara	14,569	62	80	303	499	—	944	10.6	2.04	201
Maranhao	32,956	3,233	3,396	9,533	41	—	16,203	15.1	1.75	4,905
Paraiba	5,396	1	161	172	172	—	506	11.8	1.94	120
Pernambuco	10,102	138	108	215	319	342	1,120	9.4	2.17	211
Piaui	25,466	—	—	7,585	6,527	—	14,112	10.3	2.06	2,917
Rio G. de Norte	5,317	—	40	111	221	89	461	8.4	2.29	78
Sergipe	2,186	—	—	384	4	—	387	13.1	1.86	102
Total	155,600	4,054	7,738	25,939	11,563	1,165	50,459	12.5	1.90	12,600

Source: Based on Carpentieri et al. (1993). See Larson et al. (1995) for details.

biomass energy plantations, are being challenged by environmentalists concerned about resulting chemical contamination of groundwater, loss of soil quality, and other factors. Unless biomass energy systems can be designed to deal effectively with such concerns, it will be difficult for large-scale biomass energy systems to play a major role in the world's energy future because they are unlikely to gain wide public support.

There is no doubt that biomass can be grown for energy in ways that are environmentally undesirable. It is also possible, however, to improve the land environmentally relative to present use through the production of biomass for energy. The environmental outcome depends sensitively on how the biomass is produced. Environmental issues associated with plantations are beginning to be widely addressed (Beyea et al. 1992; Davidson 1987; Gustafsson 1994; OTA 1993; Sawyer 1993; Shell and WWF 1993; WEC 1994; and Kanowski in this volume).

Consider first the challenge of sustaining the productivity of the land. Because the harvesting of biomass removes nutrients from the site, care must be taken to ensure that these nutrients are restored. With thermochemical processes for biomass conversion, such as biomass-gasifier/gas turbine power plants, 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. But nitrogen lost to the atmosphere at the conversion facility must be replenished.

There are several options for restoring fixed nitrogen in 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. (So doing also helps maintain soil quality and reduce erosion through the addition of organic matter to the soil.) Also, 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. Thermochemical biomass conversion processes allow much more flexibility than is possible with agriculture in meeting fixed nitrogen requirements this way. In agriculture, the market dictates the choice of feedstocks within a narrow range of characteristics. Conversion to energy based on thermochemical processes 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 of crop establishment. If the energy crop is an annual crop (e.g., sorghum), the erosion and herbicide pollution problems are similar to those for annual row-crop agriculture; the cultivation of such crops should be avoided on erodible lands. The choices for biomass energy crops, however, also include fast-growing trees that are harvested only every 3 to 8 years and replanted perhaps every 15 to 24 years and perennial grasses that are harvested annually but replanted perhaps only once in a decade. In both cases, erosion would be sharply reduced, on average, as would the need for herbicides (table 9.4).

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 and thereby minimize or even eliminate the use of chemical pesticides. A good plantation design will typically include areas set aside for native flora and fauna to harbor natural predators for plantation pest control and blocks of crops characterized by different clones and/or species. If a pest attack breaks out on one block, a now common practice in well-managed plantations is to let the attack run its course, allowing predators from the set-aside areas to help halt the outbreak (Hall et al. 1993).

Biomass plantations are often criticized because the range of species they support is much narrower than that of natural forests. While this relationship is generally true, the criticism is not always relevant. It would be if a virgin forest were replaced with a biomass plantation. But it would not be relevant if a plantation and associated natural reserves were established on degraded lands or on excess agricultural lands; in

TABLE 9.4

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/yr)	Herbicide Application Rate (kg/ha/yr)	Soil Erosion Rates (tonnes/ha/yr)
Annual crops			
Corn	135–60–80	3.06	21.8[a]
Soybeans	20[b]–45–70	1.83	40.9[a]
Perennial energy crops			
Herbaceous	50[c]–60–60	0.25	0.2
Short-rotation woody	0[c]–15–15	0.39	2.0

Source: Hohenstein and Wright (1994).

[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.

these instances, the restored lands may be able to support a more diverse ecology than was possible previously. If biomass energy crops were to replace monoculture food crops, the effect on the local ecology would depend on the plantation crop species chosen, but in many cases the shift would be to a less ecologically simplified landscape.

As already noted, establishing and maintaining natural reserves at plantations can be helpful in controlling crop pests while providing ecological benefits. Preserving biodiversity on a regional basis, however, will require, inter alia, land-use planning in which patches of natural vegetation are connected via a network of undisturbed corridors (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.

Socioeconomic Issues

The potential socioeconomic effects of biomass energy plantations on local populations must also be taken into account. These can be either positive or negative. Two key issues are the potential for employment and income generation and the potential for displacing local populations from their lands.

Because it is an employment-intensive activity, the growing of biomass will generate rural jobs. Carpentieri et al. (1993) estimated that large-area (contiguous tens of thousands of hectares) commercial plantations in Brazil were generating 1.9 to 3.6 direct jobs per square kilometer. Parikh and Reddy (1997) indicated that 20 jobs per square kilometer were created at one small-scale fuelwood plantation site in India. Although these employment levels may be relatively modest, they are important locally, and additional indirect jobs are likely to also be created. Moreover, the income generation from biomass energy plantations would often compare favorably to income generation from food crops. In Brazil, where the selling price of biomass might typically be $2/GJ (table 9.3), the gross annual revenues generated by a plantation would be $400 to $600 per hectare, assuming biomass yields of 10–15 dry tons/ha/yr. Such revenues are comparable to the revenues that are generated from soybean production in Brazil today.[11] Although gross annual revenues might be comparable, the cost of inputs 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. For example, the amount of fertilizer and herbicide used would be substantially lower (table 9.4). Moreover, unlike the situation with Brazilian soybeans, which are largely exported, biomass would be used locally to generate electricity, which in turn could be consumed in income-generating industries within the region.[12]

The prospect that low-cost energy from advanced biomass conversion systems will attract energy-intensive industries (and associated high-paying jobs) to rural areas is perhaps the single most important benefit that biomass plantations could offer to rural populations.[13] The new industries could provide the income needed in rural areas for modernization of agriculture and also help stem urban migration.[14] Whereas the displaced farmers who left the land in industrializing countries a century ago were generally able to find jobs in the cities, finding jobs in the cities of developing countries today is much harder because most industries are far more capital-intensive and labor-saving than they were a century ago.

It is also possible that large-scale biomass energy plantations would displace local populations engaged in land-use activities that they do not want to abandon. This concern derives from the assumption that contiguous, large-area plantations are required to take advantage of economies of scale to achieve sufficiently low biomass production costs to make bioenergy competitive, as well as to make contributions of biomass to global energy supply of the magnitude envisaged in the IPCC LESS constructions. The introduction of farm forestry as an alternative to large-scale biomass plantations has been effective in addressing this concern in Brazil (Larson et al. 1994).

In a typical farm-forestry program 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 farmer's 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 programs in Brazil started in earnest only in the mid-1980s.) Yield reductions are often offset by substantially lower costs to companies for establishing farm forests. Limited survey data indicate that establishment costs per hectare for farmer-contracted area range from 2% to 42% of that for company-owned land. The limited data suggest that delivered costs for biomass are not much different from farm-forests than from 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 were established in less than a decade. This is not an insignificant quantity by comparison to the estimated 6 to 7 million hectares of large-scale plantations that have been established in the country since the 1960s. Farmer-owned plantations account for as much as 20% of some forestry companies' total planted area, and some companies have a goal of raising this fraction to 50% or more.

Three recent developments are spurring the growth in farm forestry in Brazil: (1) the federal tax incentives introduced in 1966 to encourage tree planting were eliminated in 1988, making it much less

TABLE 9.5

CALCULATED AREA AVAILABLE FOR PLANTATIONS IN 2025 AND CORRESPONDING TOTAL ENERGY PRODUCTION FOR BIOMASS GROWN AT A COST OF $2/GJ OR LESS (INCLUDING DELIVERY AND CHIPPING) IN DEVELOPING COUNTRIES

	"Available" land planted (by percent)			
	5	10	15	20
Africa				
Biomass area (million ha)	17	33	50	66
Biomass energy (EJ/yr)	5.7	11.4	17.1	22.8
Electricity				
Potential bio-electricity production (10^9 kWh/yr)	635	1,269	1,904	2,538
1995 electricity consumption (10^9 kWh/yr)[a]	577	577	577	577
Transportation fuel				
Potential bio-hydrogen production (EJ/yr)	3.5	6.9	10.4	13.8
Potential bio-hydrogen as oil replacement (EJ/yr)[b]	6.9	13.8	20.8	27.7
1994 gasoline + diesel consumption (EJ/yr)[a]	2.8	2.8	2.8	2.8
Asia				
Biomass area (million ha)	14	28	41	55
Biomass energy (EJ/yr)	7.7	15.3	23.0	30.7
Electricity				
Potential bio-electricity production (10^9 kWh/yr)	852	1,704	2,556	3,408
1995 electricity consumption (10^9 kWh/yr)[a]	1,829	1,829	1,829	1,829
Transportation fuel				
Potential bio-hydrogen production (EJ/yr)	4.7	9.3	14.0	18.6

Potential bio-hydrogen as oil replacement (EJ/yr)[b]	9.3	18.6	27.9	37.2
1994 gasoline + diesel consumption (EJ/yr)[a]	11.5	11.5	11.5	11.5
Latin America				
Biomass area (million ha)	21	43	64	86
Biomass energy (EJ/yr)	8.7	17.5	26.2	35.0
Electricity				
Potential bio-electricity production (10^9 kWh/yr)	972	1,943	2,915	3,886
1995 electricity consumption (10^9 kWh/yr)[a]	711	711	711	711
Transportation fuel				
Potential bio-hydrogen production (EJ/yr)	5.3	10.6	15.9	21.2
Potential bio-hydrogen as oil replacement (EJ/yr)[b]	10.6	21.2	31.8	42.5
1994 gasoline + diesel consumption (EJ/yr)[a]	7.8	7.8	7.8	7.8
Total Developing Regions				
Biomass area (million ha)	52	104	155	207
Biomass energy (EJ/yr)	21.1	44.3	66.4	88.5
Electricity				
Potential bio-electricity production (10^9 kWh/yr)	2,458	4,916	7,374	9,833
1995 electricity consumption (10^9 kWh/yr)[a]	3,120	3,120	3,120	3,120
Transportation fuel				
Potential bio-hydrogen production (EJ/yr)	13.4	26.9	40.3	53.7
Potential bio-hydrogen as oil replacement (EJ/yr)[b]	26.9	53.7	80.6	107.4
1994 gasoline + diesel consumption (EJ/yr)[a]	22.1	22.1	22.1	22.1

[a]EIA 1996.

[b]This is the amount of petroleum-derived liquid fuel (gasoline or diesel fuel) that would be consumed by today's internal combustion engine vehicles to travel the same distance as fuel cell vehicles consuming hydrogen as fuel. The fuel cell vehicle is assumed to have twice the fuel economy of today's internal combustion engine vehicle.

NOTES

1. An estimated 220 billion dry tons of new organic matter is produced annually by photosynthesis. The higher heating value of a dry ton of biomass ranges from about 15 GJ (for some industrial waste streams) to about 20 GJ (for many woody biomass species).

2. This assumes a plantation establishment cost of $1,350/ha, the upper range of an estimate for Northeast Brazil (Carpentieri et al. 1993), a plantation yield of 15 dry tons per hectare per year, a power plant efficiency of 40%, and an average power plant capacity factor of 75%.

3. This assumes a power plant installed cost of \$1,300/kW$_e$ (Elliott and Booth 1993) and a cost for transmission, distribution, and additional general electric utility investment of \$890/kW$_e$, the average expected in developing countries in the period 1989–99 (Moore and Smith 1990).

4. For comparison, industrial tree plantations in tropical regions were established at an average rate of 2.6 million hectares per year, 1981–90 (FAO 1992).

5. These figures assume 1994 World Bank population projections (Bos et al. 1994), which show population growing from 5.52 billion in 1993, to 9.58 billion in 2050, to 11.0 billion in 2100.

6. The rate of change in cereal yields was used as a surrogate for the rate of change in total crop production in Marrison and Larson's analysis for Africa and in an extension of their analysis to Latin America and Asia (Larson et al. 1995). For Africa, Latin America, and Asia, cereals production in 1994 accounted for 87%, 55%, and 82% of total crop production, respectively (USDA 1994).

7. Wilderness includes desert areas.

8. Alcamo et al. (1994), in applying an integrated model of the global environment and climate change, IMAGE 2.0, came to a different conclusion about the availability of land for biomass energy plantations. They used the model to examine future land-use patterns in Africa under a variety of scenarios, including the production of biomass for energy on dedicated plantations. The model predicted that by 2050 the land pressure in Africa will be such that most natural forest would have to be converted into either cropland or biomass energy plantations. The reasons for the large discrepancy between the results of Marrison and Larson and those implied by the analysis of Alcamo et al. are not entirely clear. One important difference is that Alcamo et al. assumed a larger fraction of animal

protein in overall nutritional intake levels. Another contributing factor may be that the analysis of Alcamo et al. used land cover data of Olson et al. (1985), which has some significant limitations (Leemans 1994).

9. In these calculations, there are countries for which cropland requirements in 2025 are calculated to be less than actual cropland in 1990, despite growing populations. For the present analysis, it is assumed that this "spare" cropland in 2025 is potentially available for other uses, including biomass energy production.

10. For comparison, total primary energy use in Northeast Brazil in 1990, including hydroelectric power generation, was only about 1.1 EJ.

11. The average revenue per hectare for soybean production in the United States between 1990 and 1992 was $486/ha/yr (Bureau of the Census 1993). The revenue might be similar in Brazil because state-of-the-art yields for soybean production in Brazil are probably comparable to U.S. yields.

12. The comparison of soybeans with biomass production does not imply that the two would compete for the same land. As discussed earlier, it might be desirable to target degraded areas for multiyear rotation biomass energy production. Such areas may not be suitable for an annual crop like soybeans.

13. One concern that is sometimes raised about such a rural industrialization strategy is that it would require first having in place a sufficient amount of energy-consuming industrial activity to justify the building of energy production facilities. However, a rural industrialization strategy propelled by biomass would not necessarily require a high level of coordination between construction of energy-supplying and local energy-consuming industries (although such coordination would be desirable). For example, in the case of electricity from biomass, if initially there were insufficient local demand to utilize all the locally generated electricity, the excess could be transported by wire to urban centers (as hydroelectricity is transported from remote sites in many countries today). Even though this electricity would not be as cheap as that made available near the plant site, the extra electric transmission costs should not be prohibitive because biopower plants would provide mainly baseload power and transmission lines would tend be operated at high capacity factors, thus reducing unit costs. (This arrangement is in contrast to the situation where centralized power generation near urban centers is used to provide electricity for rural consumers; in this case the lines are often poorly utilized because of the

sporadic demand profiles of the rural electricity consumers [Sinha and Kandpal 1991].)

14. Urban centers in many developing countries are growing much faster than the countries themselves. As agriculture is modernized, the displaced farmers migrate to cities to seek jobs and better social services than those available in rural areas. But jobs are often not available in urban centers. As a result many of these migrants end up living without steady jobs in and around the urban centers in crime-ridden shantytowns that have few amenities such as running water, sewage systems, or electricity.