CO2 Mitigation Potential of Biomass Energy Plantations in Developing Regions

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1. Introduction

Biomass can make major contributions to the global commercial energy economy in ways that help promote rural development, reduce local environmental problems, and reduce greenhouse gas emissions through fossil fuel substitution,[1] if the biomass is produced sustainably and if biomass energy systems are modernized.

A recent assessment by Johansson et al. [1993] of the potential for renewable energy--part of a major study prepared as an input to the 1992 UN Conference on Environment and Development in Rio de Janeiro--indicates that sustainably produced biomass energy could be the largest single contributor to global energy supply in a renewables-intensive global energy scenario (RIGES), providing 35% (206 EJ) of the total demand for primary energy by 2050 (Fig. 1a).[2] Global CO_2 emissions in 2050 are 25% less than in 1985 in the RIGES. In the RIGES, the majority of biomass energy supplies come from dedicated, high-yielding energy plantations covering some 430 million hectares worldwide, an area equivalent to nearly 10% of the land now in cropland (1480 million hectares) plus permanent pasture (3320 million hectares). Three-quarters of the plantation biomass would come from developing regions, and five-sixths of this would be accounted for by Africa and Latin America (Table 1).

A recent "global energy prognosis" scenario analysis carried out by the Shell International Petroleum Company's Group Planning Division envisages essentially the same magnitude of biomass

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[1] Until recently, interest in biomass as a mechanism for coping with greenhouse warming has focussed on the growing of trees to sequester carbon. However, under a wide range of conditions, the growing of biomass as a fossil fuel substitute for use in modern biomass energy systems would provide substantially greater CO_2 mitigation benefits than the alternative strategy of sequestering carbon in planted forests [Hall, Mynick, Williams, 1991a; 1991b; Marland and Marland, 1992]. Biomass substituted for coal can be as effective as carbon sequestration, per tonne of biomass, in reducing CO_2 emissions; however, fuel substitution can be carried out indefinitely, while carbon sequestration can be effective only until the planted trees reach maturity. Also, far greater biomass resources can be committed to fossil fuel substitution at any given time than to carbon sequestration, because *(i)* producers will tend to seek for energy applications biomass species with higher annual yields, and *(ii)* biomass for energy can be obtained from sources other than planted forests (e. g., biomass from plantations of perennial grasses and from waste residues of existing agricultural and forest product industries). Moreover, biomass energy is potentially no more costly and in some instances even less costly than the displaced fossil fuel energy under a range of circumstances, so that the net cost of displacing CO_2 emissions would often be near zero or even negative.

Sequestration strategies will be preferred to fossil fuel substitution strategies 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.

[2] The assessment was prepared as input to the United Nations Conference on Environment and Development (UNCED). The study was commissioned by the UN Solar Energy Group for Environment and Development (UNSEGED), a high-level group of experts convened by the United Nations under the mandate of the General Assembly Resolution A/45/208 of 21 December 1990. That resolution requested that the UNSEGED prepare a comprehensive and analytical study on new and renewable sources of energy aimed at providing a significant input to the 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: *Renewable Energy: Sources for Fuels and Electricity*, Thomas B. Johansson, Henry Kelly, Amulya K.N. Reddy, and Robert H. Williams, eds., Island Press, Washington, D.C., 1993. The energy supply projections in Figure 1a are for the Renewables-Intensive Global Energy Scenario (RIGES) described by the editors in the overview chapter [Johansson et al., 1993]. For the construction of the RIGES, the future demands for electricity and for solid, liquid and gaseous fuels were assumed to be those projected for each major world region in the "high economic growth, high energy efficiency" scenario of the Response Strategies Working Group of the Intergovernmental Panel on Climate Change [Response Strategies Working Group, 1991]. For each region, energy supplies were matched to these demand levels, taking into account endowments of fossil and renewable energy sources, prospective relative costs, rates of turnover of energy-producing equipment, and prospective penetration rates for new technology under polices favorable to the accelerated development of renewable energy.

use in 2050 as the RIGES [Kassler, 1994]. See Fig. 1b and Table 2.[3]

Most energy analysts are surprised by such visions of large contributions to energy from biomass, 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 photosynthetic 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. And finally, concerns about the socio-economic impacts of large bioenergy plantations have also been raised. All such concerns are dealt with in this paper, although the central thrust of the paper is to provide an analytical basis for the plausibility of large-scale biomass energy from dedicated biomass energy plantations or farms.

This paper begins with brief discussions of: (*i*) the importance of modernization in enabling biomass to become a major contributor to the energy economy, and (*ii*) the lifecycle CO_2 emissions that would be associated with electricity and fluid fuels production from biomass and from fossil fuels. This is followed by the core analyses of the paper: (*i*) a country-by-country analysis (using FAO land-use data) of the potential land availability for biomass production in 2025, and (*ii*) a more-detailed case study of biomass plantations in Northeast Brazil. The final two sections of the paper involve environmental and socio-economic issues associated with extensive biomass energy production.

2. Modernization of Biomass Production, Conversion, and Use

While it is true that the trend has been a shift away from biomass energy as incomes rise, the shift is associated with the quality of the energy carrier utilized by consumers rather than with the primary energy source. For example, in the case of cooking fuels, consumer preferences are known to shift from dung to crop residues, fuelwood, coal, charcoal, kerosene, liquified petroleum gas, natural gas, and electricity, in increasing order, as incomes rise [Dutt and Ravindranath, 1993]. The key to making biomass energy widely attractive in energy markets is to grow suitable feedstocks and convert them into modern, easy-to-use energy carriers that are competitive with conventional energy. Modernization makes possible favorable economics, system-wide energy and CO_2 balances, and environmental impacts.

Moreover, for developing regions, the simultaneous modernization of biomass production for energy and biomass production for food makes it possible for biomass to make major contributions to energy supply while minimizing competition with food production. These "two modernizations" can be pursued synergistically. The availability of low-cost modern energy carriers (especially 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].

In the production phase, modernization implies the choice of biomass feedstocks that: (*i*) offer the potential for high yields, low cost, and low adverse environmental impacts, and (*ii*) are suitable for use in modern energy systems. Efforts should be made to find the optimal combinations of feedstocks, conversion technologies, and end-use systems. This has not been done for the most familiar "new" bioenergy systems, which involve the production of synthetic fuels from grains, sugar cane, sugar beets, or rape seed; since these crops were originally optimized for food production, their use as energy crops tends to be suboptimal.

In the quest for optimal combinations, conversion processes that begin with thermochemical gasification look especially promising. Such processes offer enormous flexibility in the choice of

[3] 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.

feedstock, because the only important feedstock properties are high yields, low costs, and low environmental impacts; the many other properties required of food crops (e.g. tastiness, starch content) are not relevant. This flexibility increases the prospects that these three objectives can be met simultaneously.

In conversion, 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 from where it is produced can be costly. Thus conversion facilities must have relatively modest scales if biomass is to be competitive with conventional energy. Technologies that offer high conversion efficiencies at such scales are needed. The key to attractive economics at modest scales is the potential for mass-produced 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 Goldemberg, 1995].

Power generation will be the first large market for modernized biomass. In electric power generation, the scales characteristic of conventional power plants [300 to 800 MW_e for coal and 600 to 1200 MW_e for nuclear power plants] are much too large for biomass. At present, the best prospects for making biopower attractive when plantation biomass is used as fuel[4] is technology based on combined cycles that are closely coupled to thermochemical gasifiers--so-called integrated gasification/combined cycle (IGCC) power systems, at scales ranging from 25 to 150 MW_e [Williams and Larson, 1993]. Gas turbines that are directly derived from jet engines (so-called aeroderivative gas turbines), which offer high thermodynamic performance and low unit capital costs at modest scales, are especially good candidates for biomass IGCC applications. Biomass IGCC systems have good prospects for being competitive with much larger coal-fired IGCC plants, even if the biomass is somewhat more expensive than coal--because the costly sulfur cleanup technology needed for coal is not needed for most biomass,[5] and because the prospects are good for achieving the economies of factory-based mass production of small, standardized units [Elliott and Booth, 1993].

The production of synthetic fuels for transportation at competitive cost is more challenging than the production of electricity, so that the transport fuel market will probably develop after the power generation market. The major problem is that any synthetic fuel, whether derived from biomass or coal, is inherently more costly than conventional hydrocarbon fuels, which require very little processing from the forms in which they are recovered from nature. The prospects are poor that synthetic fuels will ever be able to compete with conventional hydrocarbon fuels on a per unit of energy basis. *What is needed are synthetic fuels that are inherently more valuable than conventional hydrocarbon fuels.*

Identification of candidate synthetic fuels that meet this criterion requires looking to the end-use device. Synthetic fuels that can be used in fuel-cell vehicles (FCVs) would be more valuable than conventional hydrocarbon fuels used in internal-combustion-engine vehicles (ICEVs) because: (*i*) FCVs

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[4] If low-cost biomass residues (e.g. at sawmills) are used as fuel, attractive power generation economics can be realized with conventional steam-electric power plants operated in either the power-only or the combined-heat-and- power mode. The low cost of the fuel compensates for: (*i*) the high unit capital cost (which arises from the strong sensitivity of the capital cost to scale), and (*ii*) the relatively low efficiencies that are characteristic of steam-electric plants in the size range of tens of megawatts. But it is difficult to achieve favorable economics at these scales with steam-electric technology when more costly but potentially far more abundant plantation biomass is used as fuel.

[5] Today sulfur is removed in coal IGCC plants using "cold-gas" sulfur cleanup equipment, which dictates the use of oxygen-blown gasifiers, since "hot-gas" sulfur cleanup technology is not commercially proven. But because most biomass contains very little sulfur, less costly air-blown gasifiers can be used in biomass IGCC plants. Since the capital costs of oxygen production plants are very scale sensitive, coal IGCC plants will be much larger than biomass IGCC plants.

will typically be 2 1/2 to 3 times more fuel-efficient, and (*ii*) they will require less maintenance. Thus FCVs powered by appropriate synthetic fuels have good prospects for being competitive on a lifecycle cost basis with conventional hydrocarbon-fueled ICEVs, even if the synthetic fuel cannot compete on a cost-per-unit-of-energy basis [Williams, 1993].

Two synthetic fuels that are good candidates for use in FCVs are methanol and hydrogen [Williams, Larson, Katofsky, and Chen, 1995]. As in the case of electricity generation, there are good prospects for producing such fuels from biomass at about the same cost as from coal, if the conversion equipment is designed to exploit the unique characteristics of the biomass feedstock.[6] While at present it is less costly to produce methanol or hydrogen from natural gas, both biomass and coal would become competitive if the industrial natural gas price were to approximately double, which is generally expected to take place in many regions in the 2010-2020 time frame.

The production of synthetic fuels suitable for use in FCVs from biomass feedstocks that offer the potential for high yield and low cost would make it possible to produce far more useful energy from biomass per hectare than with the more conventional biofuels that are derived from food crops (e.g. ethanol from grain, sugar beets, or sugar cane, or rape methyl ester from rape seed--see Table 3 and Figure 2a). Moreover, if these fuels were used in FCVs, the levels of energy services (measured in vehicle-km driven per hectare per year) that could be provided are far greater than what could be realized using the more traditional food-crop-based fuels in ICEVs (see Table 3 and Figure 2b).[7]

3. Lifecycle CO_2 Emissions from the Production and Use of Electricity and Transport Fuels

The amount of CO_2 extracted from the atmosphere during biomass growth will equal the amount of CO_2 released in using the harvested biomass for energy. Thus if biomass energy crops are grown at the same rate as they are used for energy purposes, there is no net direct contribution of CO_2 to the atmosphere from the growing and use of biomass for energy.

But considering the entire system for producing and using biomass for energy, net emissions could be positive if fossil fuels are used, e.g. to operate machinery and to produce fertilizers and other inputs. For some food-based energy crops, lifecycle CO_2 emissions are at best marginally less than for fossil fuels. For example, for ethanol derived from corn (maize), estimates of net fuel cycle emissions of CO_2 have ranged from somewhat more [Ho, 1989] to somewhat less [Marland and Turhollow, 1990] than for gasoline.

But for the processes that are the focus of the present analysis, which involve bioenergy systems based on the use of intensively managed plantation crops that are good candidates for optimized modern bioenergy systems, net lifecycle emissions are much less than for fossil fuel energy

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[6] As in the case of power generation, this is due in part to the advantages arising from the low sulfur content of biomass. But, in addition, the low nitrogen-containing "syngas" that is produced as the first step in the production of methanol or hydrogen from biomass or coal can be generated using a less costly gasifier with biomass than is feasible with coal, because biomass is much more reactive than coal and can be gasified at lower temperatures. Syngas consisting mainly of CO and H_2 is produced from coal by partial oxidation in oxygen-blown gasifiers; the burning of some coal in place this way generates the high temperatures needed for gasifying coal. But with biomass, a low nitrogen-containing syngas can be generated instead by gasification in steam instead of oxygen; the relatively low-temperature heat needed to drive the reactions is provided through a heat exchanger from an external air-blown combustor. Such indirectly heated gasifiers are inherently less costly than the oxygen-blown gasifiers required for coal, when the cost of producing oxygen is taken into account.

[7] In principle any fuel can be used in a fuel-cell vehicle, if there is a ready means of converting the fuel into a hydrogen-rich gaseous mixture onboard the vehicle. This is easily done with methanol, which can be "reformed" with steam into a mixture of H_2 and CO_2 at relatively low temperatures (~ 200 °C). It is not practical to reform most other fuels (including ethanol) onboard the vehicle, because the reformers must be operated at much higher temperatures. Other fuels can be converted into a hydrogen-rich gaseous mixture using a process called "partial oxidation," but this process is less energy-efficient than reforming [Williams, Larson, Katofsky, and Chen, 1995].

systems. This prospect holds for both short-rotation woody crops and for perennial grasses, largely because the biomass energy produced is far greater than the fossil fuel inputs required for production [Turhollow and Perlack, 1991. In what follows the energy balances for hybrid poplar production (Table 4) are assumed for the calculations of the lifecycle CO_2 emissions associated with the production of electricity and transport fuels from this plantation crop.

For two biomass power- generating technologies [a conventional steam Rankine cycle (with a heat rate of 14.40 MJ/kWh)[8] and an IGCC (with a heat rate of 9.00 MJ/kWh) that is likely to be commercially available around the year 2000] estimated lifecycle CO_2 emissions (in grams C per kWh of electricity generated) are shown in Table 5. The biomass is assumed to be grown sustainably, so that all of the CO_2 emissions are associated with activities involved in producing the biomass. Total emissions are 16 g/kWh with the biomass steam cycle and 10 g/kWh with the biomass IGCC technology. For comparison, natural gas power plants would release 120 g/kWh with present combined cycle technology (8.00 MJ/kWh) and 103 g/kWh with advanced combined cycles (6.92 MJ/kWh), and coal-fired power plants would release 237 g/kWh with conventional pulverized coal supercritical steam-electric technology (9.47 MJ/kWh), 220 g/kWh with IGCC technology (8.78 MJ/kWh), and 181 g/kWh with future molten carbonate fuel cell technology (7.23 MJ/kWh).

Lifecycle emissions of CO_2 for transportation fuels are compared here for automobiles on a unit of service basis (grams of C per km of driving), for methanol and hydrogen used in both ICEVs and FCVs, in relation to emissions for a gasoline ICEV of comparable performance. The performance characteristics of the FCVs are estimates of what is plausibly achievable for cars in the 2005-2010 time frame [Williams, 1993; Ogden et al., 1994]. The ICEVs have gasoline-equivalent fuel consumption rates[9] of 9.09, 8.06, and 7.87 liters/100 km when operated on reformulated gasoline, methanol, and hydrogen respectively, while the FCVs have gasoline-equivalent fuel consumption rates of 3.83 and 3.29 l/100 km when operated on methanol and hydrogen, respectively (see note a, Table 6). Table 6 shows the estimated lifecycle CO_2 emissions for ICEVs and FCVs that would be fueled by methanol or hydrogen produced from natural gas or from coal, and for gasoline ICEVs for comparison. For these fossil fuel options, lifecycle CO_2 emissions would be lowest (35-44% of the emissions of the gasoline ICEV) for the cases where natural gas-derived fuels are used in FCVs.

Lifecycle emissions would be considerably lower if the methanol or hydrogen were made from sustainably grown biomass. The emissions will depend to some extent on the thermochemical gasification process used to convert the biomass to fuel. Table 7 shows the estimated emissions assuming a partial-oxidation gasification technology (IGT) and an indirectly-heated gasification technology (BCL). For the process with the higher efficiency in converting the biomass to fuel (BCL), the lifecycle carbon emissions associated with use of biomass-derived methanol (hydrogen) in FCVs would be 7% (15%) of the emissions from the gasoline ICEV. Emissions would be still lower [4% (9%) of the emissions from the gasoline ICEV] if the electricity used in the process of making the fuels from biomass were generated from biomass rather than from fossil fuels (Table 7, last two rows).

4. Potential Land Availability and Biomass Energy Production

Are there sufficient land resources to both feed future populations and to provide the levels of biomass energy production in developing regions implied in the RIGES? To address this question, the prospects for using degraded lands for plantation biomass are briefly reviewed, and the general issues associated with the potential for conflict with food production are discussed. Then the results of a modeling exercise for estimating the plantation biomass production potential for 2025 in Africa, Latin America, and Asia are presented. To conclude this section, the findings of a detailed case study of the

[8] In this paper heating values of fuels are higher (gross) heating values.

[9] The gasoline-equivalent fuel consumption rate for a fuel is defined as the gasoline consumption rate that would release the same amount of energy on a higher heating value basis.

plantation biomass production potential for the Northeast of Brazil are discussed.

Using Degraded Lands for Biomass Energy

To help insure a minimum of competition between land use for agriculture and for energy production, it has been proposed that in developing countries degraded lands be targeted 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 over 2000 million hectares of such lands in developing countries. Grainger further estimates that some 621 million hectares of these lands are suitable for reforestation. Also, Houghton [1990] has estimated that the 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[10] by 2000 that was set in the 1989 Noordwijk Declaration [Ministerial Conference, 1989]. This is comparable to the biomass energy plantation establishment rate required in the first quarter of the 21st century for Africa, Latin America, and centrally-planned Asia to meet biomass energy goals envisaged in the RIGES. 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 the advanced biomass conversion technologies (mainly biomass IGCC systems in the period to 2010). The firms involved would have strong incentives to find ways to restore the lands in sustainable ways, because they would require secure supplies of biomass feedstocks throughout the lifetimes (~ 30 years) of their capital-intensive investments in the energy conversion facilities.[11] 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 [OTA, 1992; Parham et al., 1993]. Other difficulties that must be surmounted reflect general conditions in many developing regions, e.g., complex or disputed land ownership, lack of roads to transport biomass to processing facilities and also 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 that is 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

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[10] For comparison, industrial tree plantations in tropical regions were established at average rate of 2.6 million hectares per year, 1981-1990 [FRA Project, 1992].

[11] The investment required for establishing plantations is likely to be dwarfed by the downstream investments in conversion. For Brazil the costs of plantation establishment have been estimated to range from \$720 to \$1350 per hectare [Carpentieri et al., 1993]. Assume that: (*i*) the high end of this plantation establishment cost is typical for degraded lands, (*ii*) plantation yields average 15 dry tonnes per hectare per year, and (*iii*) the produced biomass is used in biomass IGCC plants having a heat rate of 9.0 MJ/kWh, and (*iv*) these power plants operate on average at 75% of rated capacity. The plantation area required to support a 30 MW_e biomass IGCC plant would be 5,900 hectares, for which the establishment cost would be \$8 million. For comparison, the unit capital cost of these power plants in mass production is estimated to be \$1300/kW_e [Elliott and Booth, 1993], and the average cost of transmission plus distribution plus general electric utility investment is expected to be \$890/kW_e (1993 \$) in developing countries in the period 1989-1999 [Moore and Smith, 1990], so that the total estimated downstream investment is \$66 million. While the plantation establishment cost is only about 1/10 of the total investment, the entire investment would be jeopardized if there were no secure supply of biomass feedstock.

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 would be 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 plans that result in 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 Pimental, 1994], calling attention, for example, to the recent downturn in world cereal production per capita [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 recent decline in world cereals production per capita has been the reduction in the amount of land committed to cereals production, especially in the US, 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] argues that, with productivity improvements, world food requirements to the middle of the next century could plausibly be met without expanding cropland. Similarly, Smil [1994] concludes 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 due largely to an expected continuing of yield increases--may be reasonable. Worldwide average grain yields have been increasing at an average linear rate of 40 kg per hectare per year since 1960 (Fig. 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 yield increase from 2.6 tonnes per hectare per year in 1993 [USDA, 1994] to 4.5 t/ha/yr in 2050 and 5.2 t/ha/yr in 2100.[12] 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.[13]

If continuing improvements in crop yields are to be realized globally, it must be feasible and

[12] These figures assume the most recent 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.

[13] It is also worth noting that the target yield for 2100 is about 94% of the 1993 US yield, 30% higher than the Chinese average, and 18% above the South Korean yield.

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 needed to modernize agriculture there. As noted earlier, the income needed for the inputs to modernize agriculture could come from rural industrialization that is spurred, at least in part, by the availability of low-cost electricity from biomass.

There are two levels of concern regarding the chemical inputs to agriculture: *(i)* chemical contamination of the environment associated with high specific levels of inputs (e.g. kg fixed N/ha/yr), and (*i*) a set of issues posed by the overall rate of nitrogen fixation in the world,[14] 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. However, various strategies can be pursued to reduce the intensity of chemical inputs substantially without reducing yields (see, for example, Worrell et al. [1994]; Kinzig and Socolow [1994]), just as many ways have been found over the last two decades to make more efficient use of energy. Also, Waggoner points 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[15] 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 points out that the use of more fixed nitrogen (say) to increase yields can be minimized if efforts aim to optimize all factor 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 8); 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 should weigh the environmental impacts 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 (see Section 5 below).

A Preliminary Country-by-Country Analysis of Potential Land Availability and Bioenergy Production

While 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 sub-country levels. What follows are the results of country-by-country modeling exercises carried out for Africa, Latin America, and Asia for the year 2025.

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[14] Perhaps the most serious concern is the potential for upsetting the ecological balance of nature via overfertilization of the biosphere [Kinzig and Socolow, 1994]. Because the effect of extra fertilizer on plant growth rates will vary from species to species, the mixes of species of flora and also of the fauna that are supported by these flora in the food web will change as a result of higher rates of nitrogen fixation.

[15] Herbicides account for more than half of all pesticides [Waggoner, 1994].

Africa. Recently, Marrison and Larson [1995] have estimated the land availability and associated bioenergy production potential for 50 African countries in the year 2025. The results of their baseline scenario for each of these countries are presented in Appendix A.

For their baseline scenario they assume that Africa's population in 2025 is 2.5 times the 1990 level[16] 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--much slower than the global average rate of 40 kg/ha/year--Fig. 3).[17] Average crop yields in 2025 would be 1.43 times the 1990 average for Africa, but would be below the 1990 Brazilian level and far below the 1990 level in the United States (Fig. 3). Marrison and Larson further assume for their baseline scenario 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 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 Organzation of the United Nations--see WRI [1994]).[18] 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 estimate this potentially available land area to be some 1.1 billion hectares in 2025.[19]

Marrison and Larson project 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 (Fig. 4), where there is significant industrial plantation experience. For high-precipitation regions, where annual precipitation is greater than 1900 mm (as is found in 6 countries in Africa--see Appendix A), they assume a maximum yield of 30 dry tonnes per hectare per year--a limit that is assumed to be set not by precipitation but by nutrients or sunlight.

The average yield for all Africa in the baseline scenario is 8.5 t/ha/yr, or about 170 GJ/ha/yr.[20] For comparison, Fig. 5 shows actual biomass yields (in GJ/ha/yr) for a variety of biomass systems in place around the world, including the average yield of eucalyptus on 80,000 hectares of plantations owned by Aracruz (Brazil), about 450 GJ/ha/year, and the yield for the best Aracruz stand, over 1000 GJ/ha/yr.

Marrison and Larson calculate the total potential biomass energy production in Africa as a function of an assumed "cut-off" yield--the yield below which biomass energy production is assumed

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16 Marrison and Larson assume for their analysis the 1992 baseline population projection to the year 2025 of the United Nations [UN, 1993].

17 The rate of change in cereal yields is 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 this analysis in this report to Latin America and Asia (see below). For Africa, Latin America, and Asia, cereals production in 1994 accounted for 87%, 55%, and 82% of total crop production, respectively [USDA, 1994].

18 Wilderness includes desert areas.

19 Alcamo, et al [1994], in applying an integrated model of the global environment and climate change, IMAGE 2.0, come to a different conclusion about the availability of land for biomass energy plantations. They use 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 predicts that by 2050 the land pressure in Africa will be such that most forest would have to be converted into either cropland or biomass energy plantations. The reasons for the discrepancy between the results of Marrison and Larson and those implied by the analysis of Alcamo, et al. are not clear. One contributing factor could be that Alcamo's analysis uses land cover data of Olson [1985], which has some significant limitations [Leemans, 1994].

20 Eucalyptus has a higher heating value energy content of approximately 20 GJ/dry tonne.

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. Fig. 6 shows an estimate of the cost of delivered eucalyptus wood chips from industrial plantations in Brazil as a function of yield. Below about 5 t/ha/yr, the estimated cost per unit of delivered biomass energy rises sharply.

Total calculated primary biomass energy production in Africa falls with increasing cut-off yield and with decreasing percentage of potentially available area in each country that is planted with biomass. With zero cut-off yield and 10% of the potentially available land area in each country used for biomass production for energy, some 18.4 EJ could be produced (Fig. 7d).[21] Assuming a cut-off yield of 5 t/ha/yr, the energy production would decrease to 16.0 EJ, the number of biomass producing countries would fall by ten (Fig. 7a), the total planted area would fall from 111 million ha to 64 million ha (Fig. 7c), and the average yield for all Africa would increase from 8.3 t/ha/yr to 12.6 t/ha/yr (Fig. 7b). If total biomass energy production of 18.9 EJ is a target (as in the RIGES), then the percentage of available non-cropland in biomass producing countries that would need to be committed to biomass is as shown in Fig. 7e. Assuming a cut-off of 5 t/ha/yr, 11.8% of the potentially available land (76 million hectares) would be required in each of the 40 biomass-producing countries.[22] The percentage does not exceed 15% for cut-off yields up to about 10 t/ha/yr (Fig. 7e).

The general economics of biomass production can be indicated by constructing supply curves that show how much biomass can be produced as a function of marginal biomass cost. Such curves aggregated to the level of all of Africa are shown in Fig. 8a. In the construction of this curve it was assumed that the cost of delivered biomass varies with yield as shown in Fig. 6, so that there is a one-to-one correspondence between a maximum allowable cost and a corresponding cut-off yield. The four curves shown correspond to allowable biomass production on 5%, 10%, 15%, and 20% of the potentially available land in each country. Fig. 8a shows that for all of Africa 12.5 EJ/yr (19 EJ/yr) could be produced at costs of $2/GJ or less if 10% (15%) of the potentially available land in each country were used for biomass plantations. Since a cost no higher than $2/GJ corresponds to a cutoff yield of 10 t/ha/yr (Fig. 6), the average yield would be 17 t/ha/yr (Fig. 7b), the number of producing countries would be 34 (Fig. 7a), and total land requirements for all of Africa would amount to 45 (65) million hectares (Fig. 7c).

Marrison and Larson also examined the sensitivity of the potential biomass energy production for Africa as a whole to alternative assumptions for 2025 about the size of the population, the level of food imports, the increase in food crop yields, the extent to which natural forests are converted to other uses (zero forest conversion is assumed in the baseline scenario), and yield. Table 9 summarizes the impact of adjusting these assumptions. In each case examined there, 10% of potentially available land in each country is assumed to be used for biomass energy crops.

Whereas the medium variant of the UN projections for population in 2025 was assumed for the baseline scenario, the low UN variant involves 7.2% less people and the high UN variant involves 6.5% more people in 2025 [UN, 1993]. For the lower population growth variant, biomass energy production would increase 4.6% (as less land is required for food crops). For the higher population growth variant, biomass energy production would be reduced by about 4.0%.

For food imports, two variants from the baseline scenario (net imports fixed at 1990 levels) were considered: *(i)* zero net imports, and *(ii)* net imports increased in proportion to total consumption. Reducing imports to zero reduces energy production by 5.1%. With increased imports, more land is available and energy production increases by 9.8%.

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[21] Table 5 in Appendix A shows the country-by-country estimates of biomass energy production, assuming 10% of available non-crop, non-forest, non-wilderness area in each country is used for biomass energy production.

[22] Compared to this 76 million hectares and an average yield of 12.6 t/ha/yr, the total land and average yield for biomass plantations in Africa in 2025 in the RIGES are 95 million hectares and 10 t/ha/yr, respectively [Johansson et. al., 1993].

For foodcrop yields, two variants from the baseline scenario assumption of a 43% improvement, 1990-2025 were considered. In the first, average food crop yields remain at 1990 levels and potential energy production would be 22% below the production in the baseline scenario. In the second, yields are doubled by 2025 and energy production increases by 18%.

In all of the above analyses, it was assumed that none of the forest area in 1990 is converted to other uses. But deforestation is continuing, and some conversion of forests may well take place by 2025. If it is assumed that individual farmers establish new cropland in equal proportions from pasture, 'other', *and* forest land, but that no forest land is converted to energy plantations, the potential energy production on remaining pasture and 'other' land is 13% higher than in the baseline scenario. If, in addition to some forest being converted to cropland, 1% of forest also becomes available for energy plantations, an additional 1.7 EJ/yr could be produced from biomass (equivalent to 9% of biomass energy production in the baseline scenario).[23] (This land could become available, for example, if natural forest were converted to cropland, degraded, and then abandoned).

Finally, energy production would be less or more if yields turn out to be lower or higher than those predicted by the assumed yield-precipitation relationship. Different yields might arise if factors other than precipitation limit production, if feedstocks other than Eucalyptus are grown, or as a result of technological progress.[24] Potential biomass energy production would change in the same proportion as the change in the yield.

Overall, the analysis by Marrison and Larson suggests that land resources are sufficient to support a biomass-intensive energy future in Africa without compromising food production needs.

Latin America and Asia. Estimates of the potential for biomass energy from plantations in 2025 are presented here for 26 countries in Latin America and for 36 countries in Asia. This estimates were calculated using the same methodology and algorithms used by Marrison and Larson for Africa [1995]. Detailed country-by-country results are presented for the baseline scenario in Appendix B for Latin America and in Appendix C for Asia.

In both Asia and Latin America, crop yields have increased since 1972 at higher rates than in Africa (e.g. see Fig. 3 for Asia and for Brazil). 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 US yield of 4.64 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. Within each of these regions, there are countries for which cropland requirements in 2025 are calculated to be less than actual cropland in 1990, despite growing populations (see Appendices B and C). For the present analysis, it is assumed that this "spare" cropland in 2025 is potentially available for other uses, including biomass energy production. The non-cropland, non-forest, non-wilderness 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.

Fig. 9 for Latin America and Fig. 10 for Asia show the calculated biomass energy production potential as a function of the assumed cut-off yield and assuming several different fractions of the available area are used for bioenergy. Assuming zero cut-off yield and 10% of the available area is used for biomass, Latin America would produce 22 EJ/yr (Fig. 9d) and Asia would produce 31 EJ/yr (Fig. 10d) of biomass energy. Fig. 8b and Fig. 8c show biomass supply curves for Latin America

[23] The relationship between the proportion of forest land used for energy, and the extra energy production is linear, i.e., for every 1% of forest land planted, an extra 1.7 EJ/yr would be produced.

[24] Note from Figure 4 that theoretical yields can be up to twice the yield indicated by the assumed yield-precipitation relationship.

and Asia, respectively, and Fig. 8d shows an integrated biomass supply curve for Africa, Latin America, and Asia. Table 9 shows the results of sensitivity analysis for Asia and Latin America, along side the results for Africa.

That Asia might plausibly become a major bioenergy producer without compromising food production needs is surprising, because of the high population densities in Asia. This conclusion 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 (Fig. 3). The assumed crop yields in 2025 for Asia are not implausible, however. For cereals the yield in 2025 is 5.4 t/ha/yr, about the same as the average 1993 yield in the United States (5.5 t/ha/yr). Nevertheless, because it is contrary to conventional thinking about land use constraints in Asia, more detailed country-level and sub-country level assessments are needed.

One such assessment has been carried out for India by Ravindranath and Hall [1994], who observe that total area under crops in India was 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 non-cropland has also remained stable at about 40 million hectares.) In looking to the future land requirements for agriculture, Ravindranath and Hall note that the average yield of India's most important crop, rice, is 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 (i.e., cultivation of at least two crops per year through irrigation), Ravindranath and Hall conclude 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 is consistent with the results presented in Fig. 10.

Ravindranath and Hall propose use of degraded lands in India for biomass energy production. They cite three relatively disaggregated estimates of the degraded land area in India, with totals ranging from 66 to 106 million hectares. (The total land area of India is about 300 million hectares.) Excluding degraded land that is presently under cultivation reduces the range of these estimates to 61 to 71 million hectares. For comparison, the total non-crop, non-forest, non-wilderness area estimated for India in the analysis discussed above is some 83 million hectares (see Table 4 in Appendix C).

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

The modeling exercise described above for estimating the biomass plantation potential for Africa, Latin America, and Asia has a number of shortcomings. The assumption of a single precipitation index for a country is a simplifying approximation that should be refined to a much finer grid, as better information becomes available; 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 details of the terrain such as hilliness and cultural factors) that could limit the potential for biomass energy even where rainfall is adequate. Moreover, the yield-precipitation relationship used to estimate yields is based on commercial experience with Eucalyptus in Brazil; ideally, energy crops should be selected for a given region to suit the ecology of that region, and the yield-precipitation relationship may vary with the crop. Much more detailed country-level and sub-country-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 some detail in this regard [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 will be fully utilized 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 Hidroeletrica do Sao Francisco--CHESF) began studies of the biomass energy production potential in the region over a decade ago. 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 studies estimated that the land area potentially available for plantations is some 50 million hectares, or 1/3 of the area of the region (Fig. 11). Based on a yield-precipitation correlation developed from industrial eucalyptus plantations in Brazil, 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 over a total planted area of some 50 million hectares.[25] The total biomass production potential in the Northeast was estimated to be some 12.6 EJ/yr, about 75% of which would be available for a delivered cost of less than $2/GJ (Table 10).[26] For comparison, in the modeling exercise described above for all of Brazil it was estimated that if 10% of the potentially available land were committed to biomass energy plantations, some 7.4 EJ/yr could be produced, at an average yield of 23.4 t/ha/yr on 16 million hectares. The CHESF studies suggest a much higher potential for the Brazilian Northeast than the modeling exercise indicates as the potential for all of Brazil, because the CHESF studies indicate that much more than 10% of the land in the sparsely populated Northeast can be committed to plantations without running into serious land-use conflicts.

That the biomass energy production potential of the region is so large is surprising because a large part of the region is semi-arid (which is reflected in the fact that the average yield in the Northeast is only slightly more than half the average yield for all of Brazil estimated in the country-wide modeling exercise discussed above). 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 [Oldeman, 1991]. A smaller percentage of the area has also been characterized as susceptible to desertification, based on a set of criteria that includes physical (soils, water resources, etc.), social (e.g., land ownership structure), economic (e.g., 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 developing plans for implementing a biomass-electricity generating program [Carpentieri et al., 1993].

5. 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 biomass energy plantations, are being challenged by environmentalists concerned about resulting chemical contamination of groundwater, loss of soil quality, and aesthetic degradation of landscapes. Unless such concerns can be effectively dealt with, so as to gain 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.

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[25] The yield-precipitation correlation shown in Fig. 4 and used in developing country-by-country estimates of potential biomass production earlier in this section is similar to the correlation used in the CHESF studies. See Carpentieri, et al. [1993].

[26] Total primary energy use in the Northeast in 1990 was only about 1.1 EJ.

There is no doubt that biomass can be grown for energy in ways that are environmentally undesirable. However, it is also possible 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 addressed in a wide variety of fora [Beyea et al., 1992; Davidson, 1987; Gustafsson, 1994; OTA, 1993; Sawyer, 1993; Shell and WWF, 1993; WEC, 1994].

Consider first the challenge of sustaining the productivity of the land. Since 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 IGCC 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.

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 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. Energy conversion technology 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 would be similar to those for annual row-crop agriculture; the cultivation of such crops should be avoided on erodible lands. However, the choices for biomass energy crops 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 11).

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 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 harbor natural predators for plantation pest control (Fig. 12) 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 and to let predators from the set-aside areas help halt the outbreak [Hall et al., 1993].

Biomass plantations are often 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 would be if a virgin forest were replaced with a biomass plantation. However, it would not be relevant if a plantation and associated natural reserves were established on degraded lands or on excess agricultural lands; in these instances, the restored lands would probably 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. 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 (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.

6. Some Socio-Economic Aspects of Biomass Energy Systems in Developing Countries

Besides concerns about environmental impacts, the socio-economic impacts of biomass energy plantations on the local populations must 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.

The Potential for Employment and Income Generation

Because it is an employment-intensive activity, the growing of biomass will generate rural jobs. Carpentieri, et al. [1993] estimate that large-area (contiguous tens of thousands of hectares) commercial plantations in Brazil would generate 1.9 to 3.6 direct jobs per square kilometer. While this level of employment is relatively modest, it could be important locally. 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 10), the gross revenues generated by a plantation would be $400 to $600 per hectare, assuming biomass yields of 10-15 dry tonnes/ha/yr. Such revenues are comparable to the revenues that would be generated from soybean production in Brazil today.[27] While 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 use would be substantially lower (Table 11). 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 additional income-generating industries within the region.[28]

The prospect that low-cost electricity from biomass IGCC plants will attract energy-intensive industries to rural areas[29]--industries that generally offer good-paying jobs--is perhaps the single most important benefit that biomass plantations could offer to rural populations. This could provide the income needed in rural areas for modernization of agriculture, as noted above, and also help stem

[27] The average revenue per hectare for soybean production in the USA between 1990 and 1992 was $486/ha [Bureau of the Census, 1993]. The revenue might be similar in Brazil, since state-of-the-art yields for soybean production in Brazil are probably comparable to US yields.

[28] The comparison of soybeans with biomass production does not imply that the two would compete for the same land. As discussed in Section 4, 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.

[29] 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 electricity-consuming industrial activity to justify the building of any power plants. However, a rural industrialization strategy propelled by biopower would not necessarily require a high-level of coordination between power plant construction and the construction of local energy-consuming industries, although such coordination would be desirable. If initially there were 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). 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; transmission lines would tend be operated at high capacity factors, thus reducing unit costs. (This 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.)

urban migration.[30]

Small-Scale Biomass Production--the Farm Forestry Alternative

A concern that is sometimes raised is that large-scale biomass energy plantations would displace local populations engaged in land-use activities that they do not want to abandon--despite the prospect of new well-paying jobs that would be generated if the biomass were used to provide electricity that attracts new industries to the area. If this proves to be a problem in a given region, farm forestry might be pursued as an alternative to large-scale biomass plantations.

It is often assumed 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 a scenario like the RIGES. However, large plantations may not be necessary in order 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 [Larson, et al., 1994]. Similar activities have been reported elsewhere.

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 less than a decade ago.) Yield reductions are often offset by substantially lower costs to companies for establishing farm forests. Limited survey data (Table 12) indicates that establishment costs per hectare for farmer-contracted area range from 2% to 42% of the cost 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 have been established in less than a decade. (Fig. 13 illustrates the growth of privately-financed forest farming in one state in Brazil.) 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 (Table 12), and some companies have a goal of raising this fraction to 50% or more.

Three recent developments are spurring the growth in farm forestry: *(a)* 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; *(b)* in regions where natural forests were being cut for wood (especially the states of Minas Gerais and Sao Paulo), natural

[30] 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 often end up living without steady jobs in and around the urban centers in crime-ridden shantytowns that have little or no amenities such as running water, sewage systems, or electricity.

While the displaced farmers who left the land a century ago in the now industrialized countries were generally able to find jobs in the cities, finding jobs in the cities of developing countries today is much harder because most of the industries are far more capital-intensive and labor-saving than a century ago in the now-industrialized world.

forests within reasonable transportation distances have essentially been completely cut, with insufficient replanting to meet local needs; and *(c)* objections of environmentalists and others (largely on aesthetic grounds) to "over-planting" of trees have discouraged expansion of large tracts of company-owned plantations. (In the state of Espirito Santo, for example, Aracruz Florestal is now prohibited by law from purchasing additional land for eucalyptus planting.)

The overall result of the small-farm forestry programs 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.

7. Closure

While many uncertainties remain, this preliminary analysis indicates a large potential for biomass energy plantations in developing regions, if biomass energy systems and agricultural systems are simultaneously modernized.

Figure 8d indicates that the total potential biomass supply for Africa plus Latin America plus Asia in 2025 at delivered biomass costs of \$2/GJ or less would be 68 EJ/yr (105 EJ/yr) if 10% (15%) of the land potentially available for biomass plantations (land that is not needed for cropland in 2025 and is not now forestland or wilderness) were made available for biomass plantations in each country. For comparison, energy crop production in developing regions in 2025 amounts to 56 EJ/yr in the RIGES (Table 1).

The global potential for CO_2 emissions reduction from plantation biomass depends on the fossil fuel energy systems that would be displaced by this biomass. Consider a scenario for the year 2025 in which 68 EJ/yr is produced on plantations in developing countries.

One limiting variant of this scenario is where all the biomass is used to produce only electricity in biomass IGCC plants that displace only electricity that would otherwise have been generated in coal IGCC plants. The amount of electricity produced (some 7560 TWh/yr) would be about 13 times the coal-based power generated in developing countries in 1985 [Johansson et al., 1993]. Total global CO_2 emissions reduction that would arise from displacing the same amount of electricity generated in coal IGCC plants is 1.6 Gt C/yr (based on data in Table 5).

Another limiting scenario is where this same amount of biomass is used to produce only methanol for use in FCVs to displace gasoline that would be used in comparable ICEVs. In this case 68 EJ/yr of biomass could support $29*10^{12}$ v-km of automotive travel[31] (which is 5.5 times the amount of automotive travel in the world in 1985[32]), and the global CO_2 emissions reduction would be some 2.0 Gt C/yr (based on data in Tables 5 and 6).

To improve upon the present country-level-average-value analysis, much more disaggregated data on rainfall are needed, different biomass feedstocks should be investigated, and considerations of production-limiting factors other than precipitation (including topography and various socio-economic factors) should be taken into account. High priority should be given to research aimed at a better understanding of what is required to restore degraded lands to states where they can support biomass energy plantations.

More attention should also be given to understanding how intensively managed agricultural production can be made "environmentally friendly," and how the environmental impacts would

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[31] For the BCL indirectly heated gasifier, the overall thermal efficiency of producing methanol from biomass is 57.6%, assuming that the electricity needed to produce methanol is generated from biomass and taking this extra biomass energy input into account [Williams et al., 1995]. Thus 39 EJ of methanol can be produced from 68 EJ of biomass. It is assumed that methanol FCVs have a gasoline-equivalent fuel economy of 3.83 l/100 km (see note a, Table 6), or 1.33 MJ/km.

[32] In 1985 there were 389 million cars in the world, and the average amount of driving per car was 13,500 km/yr [Lashoff and Tirpak, 1990].

compare for intensive and extensive strategies for expanding agricultural production. At this point it appears as though the potential for reducing overall environmental impacts is greater for intensive than for extensive agricultural expansion strategies.

While it is certainly possible to produce biomass for energy on large scales in environmentally unsatisfactory ways, it appears that there are many opportunities to provide energy from biomass energy systems in ways that are environmentally attractive. The experience with existing industrial plantations should be reviewed in this regard, and promising policies that would generate the incentives needed to promote environmentally attractive practices should be identified.

Finally, a better understanding is needed of the appropriate scales for the growing of biomass for energy on a region-by-region basis, to ensure that there are environmental and socio-economic benefits from biomass energy plantations not just for a country or for the world at large but for the local population as well.

Table 1. Total biomass supplies for energy (EJ per year) for the renewables-intensive global energy supply scenario (RIGES) of Johansson, et al. [1993].

REGION	2025				2050			
	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

Table 2. Global primary energy use (in EJ per year) in 2050 for two energy scenarios for 2050: the Renewables-Intensive Global Energy Scenario (RIGES) of Johansson, et al. [1993] and the Sustained Growth Scenario of the Shell International Petroleum Company [Kassler, 1994].

Energy Supply Source	Actual, 1985	Shell Scenario, 2050	RIGES, 2050
Coal	90	188	59
Oil	127	141	64
Natural gas	65	141	108
Nuclear	15	94	12
Hydroelectricity	21	78	32
Intermittent Renewables	--	297	64
Biomass[a]	55	219	206
Geothermal/Ocean	--	31	1
Solar Electrolytic Hydrogen	--	--	33
"Surprise"	--	31	--
TOTALS	373	1220	580

(a) Includes non-commercial biomass energy, which amounted to 50 EJ per year in 1985. In the RIGES there is no non-commercial biomass energy in 2050.

Table 3. Energy yield for alternative biomass feedstock/conversion technologies.

Option	Feedstock Yield (dry t/ha/yr)	Transport Fuel Yield (GJ/ha/yr)	Transport Services Yield[b] (10^3 v-km/ha/year)
Rape methyl ether (Netherlands, year 2000)[c]	3.7 of rapeseed	47	21 (ICEV)
EthOH from maize (US)[d]	7.2 of maize	76	27 (ICEV)
EthOH from wheat (Netherlands, year 2000)[e]	6.6 of wheat	72	26 (ICEV)
EthOH from sugar beets (Netherlands, year 2000)[f]	15.1 of sugar beets	132	48 (ICEV)
EthOH from sugar cane (Brazil)[g]	38.5 of cane stalks	111	40 (ICEV)
EthOH, enzymatic hydrolysis of wood (present technology)[h]	15 of wood	122	44 (ICEV)
EthOH, enzymatic hydrolysis of wood (improved technology)[g]	15 of wood	179	64 (ICEV)
MeOH, thermochemical gasification of wood[i]	15 of wood	177	64/133 (ICEV/FCV)
H_2, thermochemical gasification of wood[h]	15 of wood	213	84/189 (ICEV/FCV)

(b) The fuel economy of the vehicles used (in liters of gasoline-equivalent) are assumed to be: 6.30 for rape methyl ether (assumed to be the same as for diesel), 7.97 for ethanol, 7.90 for methanol, and 7.31 for hydrogen used in internal combustion engine vehicles (ICEVs); and 3.81 for methanol and 3.24 for hydrogen used in fuel cell vehicles (FCVs) [DeLuchi, 1991]. Note that 1 liter of gasoline equivalent = 0.0348 GJ, HHV.

(c) Per tonne of seed: 370 liters of rape methyl ether plus (not listed) 1.4 tonnes of straw [Lysen et al., 1992].

(d) For wet milling, assuming the US average maize yield, 1989-1992; per tonne of grain: 440 liters of ethanol plus (not listed) 0.35 tonne of stover (out of 1 tonne of total stover, assuming the rest must be left at the site for soil maintenance), 275 kg of corn gluten cattle feed, and 330 kg of CO_2 [Wyman et al., 1993].

(e) Per tonne of seed: 455 liters of ethanol plus (not listed) 0.6 tonnes of straw [Lysen et al., 1992].

(f) Per tonne of sugar beet: 364 liters of ethanol [Lysen et al., 1992].

(g) For the average sugar cane yield in Brazil in 1987 (63.3 tonnes of harvested cane stems, wet weight); per tonne of wet cane stems : 73 liters of ethanol [Goldemberg et al., 1993]. In addition, (not listed) the dry weight of the attached tops and leaves amounts to 0.092 tonnes and that for the detached leaves amounts to 0.188 tonnes per tonne of wet stems--altogether some 18 dry tonnes per hectare per year [Alexander, 1985].

(h) Per tonne of feedstock: 338 liters of ethanol plus (not listed) 183 kWh (0.658 GJ) of electricity, present technology; 497 liters of ethanol plus (not listed) 101 kWh (0.365 GJ) of electricity, improved technology [Wyman et al., 1993].

(i) For the indirectly-heated Battelle Columbus Laboratory biomass gasifier; per tonne of feedstock: 11.8 GJ of methanol or 14.2 GJ of hydrogen; per tonne of feedstock, external electricity requirements are 107 kWh (0.38 GJ) for methanol or 309 kWh (1.11 GJ) for hydrogen [Williams et al., 1994].

Table 4. Average annual energy inputs for hybrid poplar production in the U.S. based on present or future technology [Turhollow and Perlack, 1991].[a]

	Total Average GJ Per Hectare Per Year			
Present production technology	Diesel fuel	Natural gas	Electricity	Total energy
Establishment	0.14	--	--	0.14
Fertilizers				
N (50 kg/ha/yr)	0.16	2.73	0.15	3.04
P_2O_5 (15 kg/ha/yr)	0.05	0.05	0.09	0.19
K_2O (15 kg/ha/yr)	0.03	0.03	0.04	0.10
Pesticides	0.29	0.10	0.02	0.41
Equipment	0.17	--	--	0.17
Harvesting	7.31	--	--	7.31
Hauling	2.40	--	--	2.40
TOTAL ENERGY				
GJ per hectare	10.55	2.90	0.30	13.76
GJ per dry tonne	0.93	0.26	0.03	1.22
Future Production Technology				
Establishment	0.14	--	--	0.14
Fertilizers				
N (50 kg/ha/yr)	0.16	2.73	0.15	3.04
P_2O_5 (15 kg/ha/yr)	0.05	0.05	0.09	0.19
K_2O (15 kg/ha/yr)	0.03	0.03	0.04	0.10
Pesticides	0.29	0.10	0.02	0.41
Equipment	0.17	--	--	0.17
Harvesting	11.69	--	--	11.69
Hauling	3.07	--	--	3.07
TOTAL ENERGY				
GJ per hectare	15.61	2.90	0.31	18.82
GJ per dry tonne	0.84	0.16	0.02	1.02

(a) Establishment fuel use is about 651 GJ/ha and is apportioned over the 18 year life of the tree crop. Pesticides include application of 7 kg/ha of active ingredient (a.i.) of herbicide during the establishment year and 2 kg/ha (a.i.) during the second growing season. Pesticides also include 2.1 kg/ha (a.i.) of insecticide and 2.7 kg/ha of fungicide during each rotation. Equipment fuel is for spreading and spraying. Harvesting energy includes severing, baling, loading, unloading, and chipping. Harvest fuel consumption is 13.41 GJ/dry tonne. Hauling fuel use is 41 GJ/dry tonne over a distance of 40 km. Annual after-loss productivity is 11.3 and 18.5 dry tonnes/ha/yr for present and future production conditions, respectively.

Table 5. Lifecycle carbon emissions from the production of electricity from coal, natural gas, and biomass with alternative generating technologies.

Fuel →	COAL[a]			NATURAL GAS[b]		BIOMASS[c]	
Technology →	Steam	IGCC	IGMCFC	CC	ACC	Steam	IGCC
Activity	CO_2 EMISSIONS (GRAMS CARBON PER KWH GENERATED)						
Biomass production[d]							
Establishment	---	---	---	---	---	0.17	0.11
Fertilizers	---	---	---	---	---	3.11	1.94
Herbicides	---	---	---	---	---	0.46	0.29
Equipment	---	---	---	---	---	0.20	0.13
Harvesting	---	---	---	---	---	8.77	5.48
Hauling	---	---	---	---	---	2.88	1.80
Subtotal	---	---	---	---	---	15.60	9.75
Coal or natural gas recovery[e]	2.5	2.3	1.9	6.1	5.3	---	---
CO_2 from natural gas wells[f]	---	---	---	2.4	2.1	---	---
Coal transportation[g]	1.3	1.2	1.0	---	---	---	---
Feedstock conversion[h]	233.1	216.0	177.8	111.0	96.0	352.8	220.5
Photosynthetic credit[i]	---	---	---	---	---	-352.8	-220.5
TOTAL EMISSIONS	236.9	219.5	180.7	119.5	103.4	15.6	9.8

(a) "Steam" refers to a supercritical pulverized coal steam plant, IGCC refers to a coal integrated gasifier/gas turbine combined cycle, and IGMCFC refers to an integrated-gasifier/molten carbon fuel cell.

(b) CC refers to a state-of-the-art natural gas fired combined cycle and ACC refers to an advanced combined cycle.

(c) Steam refers to a state-of-the-art biomass steam rankine system. IGCC refers to a an integrated gasifier/combined cycle plant.

(d) Assumed biomass yield (11.3 dry tonnes per hectare per year, after counting harvesting and handling losses) and energy inputs for short-rotation intensive culture production of hybrid poplar are from Turhollow and Perlack (1993). Energy inputs are as follows. Plantation establishment requires 14 GJ/ha/yr of diesel fuel. Fertilizers require 0.24 GJ/ha/yr diesel fuel, 2.810 GJ/ha/yr natural gas, and 25.55 kWh/ha/yr electricity. Pesticides require 0.29 GJ/ha/yr diesel fuel, 0.10 GJ/ha/yr natural gas, and 1.825 kWh/ha/yr electricity. Equipment requires 0.17 GJ/ha/yr diesel fuel. Harvesting requires 7.31 GJ/ha/yr diesel fuel. Hauling requires 2.4 GJ/ha/yr diesel fuel.

(e) Estimated energy use during feedstock recovery is as follows, based on Tables 3 and 4 in DeLuchi (1991). Natural gas recovery: 0.0524 GJ/GJ of natural gas, 1% of which is crude oil, 2% diesel fuel, 95% natural gas, 1.5% electricity, and 0.5% gasoline. For coal recovery: 0.0083 GJ/GJ of coal, 5% of which is crude oil, 48% diesel fuel, 1% natural gas, 37% electricity, 3% gasoline, and 6% coal.

(f) Based on estimated emissions of CO_2 from natural gas wells of 1,102 gCO_2/GJ of gas (200 gC/GJ) [Table 7 in DeLuchi (1991)].

(g) For natural gas, transportation energy use is zero because the power plants are assumed to be located at the wellhead. Energy requirements by fuel type for coal transport are from Tables 3 and 4 in DeLuchi (1991); total energy use is 0.0075 GJ/GJ of coal, 1.3% of which is crude oil, 74.2% of which is diesel fuel and 25.8% is residual fuel.

(h) The assumed heat rates (higher heating value basis) are as follows: coal-steam, 9.47 MJ/kWh; coal-IGCC, 8.78 MJ/kWh; and coal-IGMCFC, 7.23 MJ/kWh [Technology and Fuels Assessment Department, 1993]; natural gas CC, 8.00 MJ/kWh [Technology and Fuels Assessment Department, 1993] and natural-gas ACC, 6.92 MJ/kWh; biomass-steam, 14.40 MJ/kWh, and IGCC, 9.00 MJ/kWh [Elliott and Booth, 1993].

(i) Assumes an uptake of 485.1 kg of carbon per dry tonne of biomass.

Table 6. Lifecycle carbon emissions from the production of alternative energy carriers from fossil fuel feedstocks and their use in alternative automobiles.

Energy carrier	Reformulated gasoline	Methanol				Hydrogen			
Feedstock	Crude Oil	Natural Gas		Coal		Natural Gas		Coal	
Vehicle type[a]	ICEV	ICEV	FCV	ICEV	FCV	ICEV	FCV	ICEV	FCV
ACTIVITY	CO_2 EMISSIONS (GRAMS OF CARBON PER KM OF VEHICLE TRAVEL)[b]								
Gas well CO_2[c]	-	1.20	0.57	-	-	0.92	0.38	-	-
Feedstock recovery[d]	1.77	1.61	0.76	1.14	0.54	1.23	0.51	0.93	0.39
Feed production[e]	-	1.44	0.68	-	-	1.10	0.46	-	-
Feedstock transport[f]	0.81	-	-	0.61	0.29	-	-	0.50	0.21
Fuel production[g]									
From feedstock	8.70	9.00	4.26	60.32	28.54	42.43	17.72	87.21	36.42
External electr.	1.55	3.89	1.84	5.23	2.47	4.27	1.78	14.49	6.05
Fuel transport to refueling station[h]	0.57	2.18	1.04	1.25	0.59	-	-	-	-
Compressors at refueling station[i]	-	-	-	-	-	9.92	4.14	9.92	4.14
End use	58.22	46.55	22.02	46.55	22.02	-	-	-	-
TOTAL EMISSIONS									
Grams C per km	71.61	65.86	31.17	115.08	54.45	59.86	25.00	113.05	47.21
% of gasoline ICEV	100	92	44	161	76	84	35	158	66

(a) The gasoline ICEV is a year-2000 version of the 1990 Ford Taurus with an assumed fuel economy of 9.09 liters/100 km. The methanol and hydrogen vehicles considered here would be comparable-duty vehicles. The ICEV operating on methanol and hydrogen has an assumed gasoline-equivalent fuel economy of 8.06 and 7.87 lit/100 km, respectively. The methanol FCV has an assumed gasoline-equivalent fuel economy of 3.83 lit/100 km. The hydrogen FCV has an assumed gasoline-equivalent fuel economy of 3.29 lit/100 km. See Ogden, et. al., [1994].

(b) The following carbon emission rates are assumed in this analysis for fuels (in kg C/GJ): crude oil, 18.73; residual fuel, 19.42; gasoline, 18.31; diesel fuel, 18.65; coal, 24.60; natural gas, 13.87; and methanol, 16.41. Carbon emissions from electricity use are assumed to be 189.72 g C/kWh, which corresponds to emissions from primary energy sources representing the average mix of US electric power generating sources (56.34% coal, 9.43% natural gas, and 3.18% residual fuel), their respective average heat rates (10.86 MJ/kWh, 10.73 MJ/kWh, and 10.70 MJ/kWh), and transmission and distribution losses of 7.4%. Emissions from production and delivery of fuels to power plants are also included in the total per-kWh emissions.

(c) Based on estimated emissions of CO_2 from natural gas wells of 1,102 gCO_2/GJ of gas (200 gC/GJ) [Table 7 in DeLuchi (1991)].

(d) Estimated energy use during feedstock recovery is as follows, based on Tables 3 and 4 in DeLuchi (1991). Crude oil recovery: 0.0254 GJ/GJ of gasoline, 13% of which is consumed as crude oil, 14% as diesel fuel, 50% as natural gas, 17% as electricity, 4% as gasoline, and 10% as residual fuel. For natural gas recovery: 0.0279 GJ/GJ of natural gas, 1% of which is crude oil, 4% diesel fuel, 92% natural gas, 1% electricity, and 1% gasoline. For coal recovery: 0.0083 GJ/GJ of coal, 5% of which is crude oil, 48% diesel fuel, 1% natural gas, 37% electricity, 3% gasoline, and 6% coal.

(e) Estimated energy use during feedstock production is as follows, based on Tables 3 and 4 in DeLuchi (1991). Crude oil and coal: energy requirements are included in recovery. For natural gas: 0.0245 GJ/GJ of natural gas, 98% of which is natural gas and 2% is electricity.

(f) Energy requirements by fuel type for crude oil and coal transport are from Tables 3 and 4 in DeLuchi (1991). Estimated energy use during feedstock transportation is as follows, based on Tables 3 and 4 in DeLuchi (1991). Crude oil: 0.0116 GJ/GJ of gasoline, 13% of which is crude oil, 7.4% is electricity, and 91.3% is residual fuel. For natural gas, transportation energy use is zero because the fuel production facilities are assumed to be located at the wellhead. For coal: 0.0075 GJ/GJ of coal, 1.3% of which is crude oil, 74.2% of which is diesel fuel and 25.8% is residual fuel.

(g) Energy requirements for fuel production from feedstock are estimated to be as follows. For gasoline, 0.1847 GJ/GJ of gasoline, 77% of which is natural gas, 5% is electricity, 1% is residual fuel, and 16% is coal [Tables 3 and 4 in DeLuchi (1991)]. For natural gas and coal, the fraction of feedstock energy not converted to fuel is (1 - ER), where ER is the energy ratio given by Williams, et al. [1994]: for natural gas, ER = 0.704 for methanol production and 0.897 for hydrogen production; for coal, ER = 0.649 for methanol and 0.774 for hydrogen. Williams, et al. [1994] also give electricity that must be supplied from external sources per unit of methanol produced from natural gas (7.274 kWh/GJ) and coal (9.771 kWh/GJ) and per unit of hydrogen produced from natural gas (8.193 kWh/GJ) and coal (22.957 kWh/GJ).

(h) Energy requirements associated with gasoline and methanol delivery to the refueling station are based on Tables 3 and 4 in DeLuchi (1991). For gasoline, 0.0084 GJ/GJ of gasoline are needed, of which 6.9% is electricity, 70.5% is diesel fuel, and 22.6% is residual fuel. For methanol from natural gas, 0.0378 GJ/GJ of methanol are needed, of which 3% is electricity, 26% is diesel fuel, and 72% is residual fuel. For methanol from coal, 0.019 GJ/GJ are needed, of which 12% is electricity, 69% is diesel fuel, and 19% is residual fuel. Transport energy requirements for methanol from natural gas are higher than methanol from coal because DeLuchi assumes that methanol is produced from remote natural gas sources, while methanol from coal is produced much closer to the point of use. Hydrogen is assumed to be sufficiently compressed at the production facility for pipeline delivery to the refueling station with no additional energy inputs.

(i) Compression at the refueling station (from 50 to 8400 psia with 85% compressor efficiency) requires 19.06 kWh/GJ of hydrogen [Williams et al, 1994].

Table 7. **Lifecycle carbon emissions from the production of methanol and hydrogen from biomass and their use in alternative automobiles.**

Energy carrier	Methanol				Hydrogen			
Gasifier type	IGT		BCL		IGT		BCL	
Vehicle type[a]	ICEV	FCV	ICEV	FCV	ICEV	FCV	ICEV	FCV
ACTIVITY	CO_2 EMISSIONS (GRAMS OF CARBON PER KM OF VEHICLE TRAVEL)[b,c]							
Feedstock Production[d]								
Establishment	0.06	0.03	0.05	0.03	0.05	0.02	0.04	0.02
Fertilizers	1.08	0.51	1.00	0.48	0.89	0.37	0.81	0.34
Herbicides	0.16	0.08	0.15	0.07	0.13	0.06	0.12	0.05
Equipment	0.07	0.03	0.07	0.03	0.06	0.02	0.05	0.02
Harvesting	3.04	1.44	2.84	1.34	2.50	1.04	2.28	0.95
Hauling	1.00	0.47	0.93	0.44	0.82	0.34	0.75	0.31
Subtotal	5.39	2.55	5.04	2.38	4.44	1.86	4.06	1.70
Photosynthetic credit[e]	- 122.03	- 57.74	- 113.98	- 53.93	- 100.48	- 41.96	- 91.83	- 38.35
Fuel Production[f]								
From feedstock	75.49	35.72	67.43	31.91	100.48	41.96	91.83	38.35
External electricity from fossil fuels	5.00	2.37	4.84	2.29	15.36	6.41	11.30	4.72
Subtotal	80.49	38.09	72.27	34.20	115.84	48.37	103.14	43.07
Fuel transport to refueling station[g]	1.25	0.59	1.25	0.59	-	-	-	-
Compressors at refueling station[h]	-	-	-	-	9.92	4.14	9.92	4.14
End use	46.55	22.02	46.55	22.02	-	-	-	-
TOTAL NET EMISSIONS								
Grams C per km	11.64	5.51	11.12	5.26	29.72	12.41	25.28	10.56
% of gasoline ICEV	16	7.7	16	7.3	4.2	17	35	15
Total net emissions if external electricity for fuel production is generated from biomass[i]								
Grams C per km	6.95	3.29	6.59	3.12	15.29	6.39	14.67	6.13
% of gasoline ICEV	9.7	4.6	9.2	4.4	21	8.9	21	8.6

(a) See note *(a)* of Table 6.

(b) The following carbon emission rates are assumed in this analysis for fuels (in kg C/GJ): crude oil, 18.73; residual fuel, 19.42; gasoline, 18.31; diesel fuel, 18.65; coal, 24.60; natural gas, 13.87; methanol, 16.41; and biomass, 24.50.

(c) Carbon emissions from electricity use are assumed to be 189.72 g C/kWh, which corresponds to emissions from primary energy sources representing the average mix of US electric power generating sources (56.34% coal, 9.43% natural gas, and 3.18% residual fuel), their respective average heat rates (10.86 MJ/kWh, 10.73 MJ/kWh, and 10.70 MJ/kWh), and T&D losses of 7.4%. Emissions associated with production and delivery of the fuels to power plants are also included in the total per-kWh emissions. The carbon emissions associated with electricity production from biomass (instead of fossil fuels) is also calculated. See note *(i)* below.

(d) Assumed biomass yield (11.3 dry tonnes per hectare per year, after counting harvesting and handling losses) and energy inputs for short-rotation intensive culture production of hybrid poplar are from Turhollow and Perlack (1993). Average annual energy inputs are as follows. Plantation establishment requires 14 GJ/ha/yr of diesel fuel. Fertilizers require 0.24 GJ/ha/yr diesel fuel, 2.810 GJ/ha/yr natural gas, and 25.55 kWh/ha/yr electricity. Pesticides require 0.29 GJ/ha/yr diesel fuel, 0.10 GJ/ha/yr natural gas, and 1.825 kWh/ha/yr electricity. Equipment requires 0.17 GJ/ha/yr diesel fuel. Harvesting requires 7.31 GJ/ha/yr diesel fuel. Hauling requires 2.4 GJ/ha/yr diesel fuel.

(e) Assumes an uptake of 485.1 kg of carbon per dry tonne of biomass.

(f) The fraction of biomass feedstock that is not converted to fuel is (1 - ER), where ER are the energy ratios given by Williams et al., [1994]. For methanol and hydrogen production with the IGT gasifier, ER = 0.566 and 0.669, respectively. For methanol and hydrogen production with the BCL gasifier, ER = 0.606 and 0.732, respectively.
Electricity that must be supplied from external sources per unit of methanol production with the IGT and BCL gasifiers is 9.35 kWh/GJ and 9.041 kWh/GJ, respectively. Per unit of hydrogen production with the IGT and BCL gasifiers, external electricity requirements are 29.50 kWh/GJ and 21.71 kWh/GJ, respectively. This electricity is assumed to be provided by the average US electric utility power mix--see note *(c)*. An estimate is also made assuming the electicity is produced from biomass instead [see note *(i)*].

(g) The energy requirements for methanol delivery to the refueling station are assumed to be the same as for methanol derived from coal. See note *(h)* of Table 4. Hydrogen is assumed to be sufficiently compressed at the production facility for pipeline delivery to the refueling station with no additional energy inputs.

(h) Compression at the refueling station (from 50 to 8400 psia with 85% compressor efficiency) requires 19.06 kWh/GJ of hydrogen. This is assumed to be provided by electricity generated using the average generating mix in the US.

(i) The external electricity requirements for fuel production could be met by electricity produced from biomass, rather than from fossil fuels. The biomass consumption for electricity production is based on a heat rate corresponding to that estimated for a biomass-gasifier/steam-injected gas turbine power station. From Figure 5.5 in Katofsky (1993), this heat rate is (in GJ/kWh): $0.0036/(0.3239 + 0.00059*MW_e)$, where MW_e is the required electricity production capacity.

Table 8. Total and specific chemical inputs for alternative agricultural scenarios for the European Union in 2015.[a]

Scenario	Cropland in the European Union (10^6ha)	Nitrogen Use in Fertilizer		Pesticide Use	
		Total input (10^6 tonnes/yr)	Specific input (kg-N/ha/yr)	Total input (10^6 kg a.i./yr)[b]	Specific input (kg a.i./ha/yr)[b]
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

(a) 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 tehre 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.

(b) Here, kg a.i. = kilograms of active ingredients.

Table 9. Sensitivity of calculated total biomass energy production potential in 2025 for Africa, Latin America, and Asia. The "Baseline scenario" assumes that 10% of non-crop, non-forest, non-wilderness area is used for biomass energy production.[a]

	AFRICA		LATIN AMERICA		ASIA	
Scenario	Total Bioenergy (EJ/year)	Percent Change From Baseline	Total Bioenergy (EJ/year)	Percent Change from Baseline	Total Bioenergy (EJ/year)	Percent Change from Baseline
Baseline scenario	18.4	---	22.3	---	31.2	---
High population	17.7	- 4.0	21.6	- 3.0	29.9	- 4.2
Low population	19.3	+ 4.6	22.6	+ 1.6	32.5	+ 4.3
Zero net food imports	17.5	- 5.1	21.8	- 2.2	30.6	- 1.9
Net imports at 1990 proportion	20.2	+ 9.8	22.9	+ 3.0	31.6	+ 1.2
Food Crop Yield fixed at 1990 level	14.4	- 21.7	18.5	- 17.2	19.3	- 38.2
Food Crop Yield double 1990 level	21.7	+ 17.9	23.7	+ 6.4	31.8	+ 2.1
Forest land also used for food crops	20.8	+ 13.0	22.5	+ 1.0	31.3	+ 0.5
Forest used for food and 1% for energy	22.5	+ 22.1	25.3	+ 13.8	33.5	+ 7.4

(a) See Appendix A (Africa), B (Latin America), and C (Asia) for country-by-country details of the baseline scenario calculations.

Table 10. State-by-state distribution of area suitable for biomass plantations by bioclimatic in Northeast Brazil, weighted average yield, weighted average delivered biomass cost, and total biomass energy production potential.[a]

STATE	Total Area (10^3 ha)	Bioclimatic Region					Total Area Available for Plantations (10^3 ha)	Weighted Average Yield (dry t/ha/yr)	Weighted average delivered biomass cost (1993$/GJ)[b]	Total Potential Biomass (TJ/yr)
		I	II	III	IV	V				
		Average yield (dry tonnes/ha/year)[c]								
		20.7	15.5	13.2	7.1	2.8				
		Area Available for Plantations (10^3 ha)								
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 Gr. 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
TOTALS	155,600	4,054	7,738	25,939	11,563	1,165	50,459	12.5	1.90	12,600

(a) Source: Carpentieri, et al. [1993]. Totals may not add due to rounding.

(b) Production plus transport costs for logs with 33% moisture content assuming a 10% discount rate (from [Carpentieri et al., 1993] converted to 1993 $ from 1988 $ using the US GDP deflator) to which chipping costs of $0.28/GJ [Perlack and Wright, 1994] have been added. Biomass costs are the same for planted areas in different states that fall under the same bioclimatic classification. The delivered costs for chips (in 1993$) by bioclimatic region (BCR) are: BCR I, $1.58/GJ; BCR II, $1.74/GJ; BCR III, $1.86/GJ; BCR IV, $2.54; and BCR V, 4.69. The production costs shown in this table and discussed in this note are also shown in Fig. 6 as a function of yield.

(c) Eucalyptus stemwood of diameter 7 cm or larger.

Table 11. Typical fertilizer and herbicide application rates and soil erosion rates for selected food and energy crop production systems in the United States [Hohenstein and Wright, 1994].

Cropping System	N-P-K application rates (kg/ha/year)	Herbicide application rate (kg/ha/year)	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	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.

Table 12. Some corporate farmer forestry programs in Brazil, based on information provided by individual companies [Larson et al., 1994].

Company →	Aracruz	Champion	Cenibra	Riocell	Pains	Ripasa	Inpacel	Bahia Sul
Location (state)	Espirito Santo	Sao Paulo	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[a] ($/ha)	1,250	n.a.	1,670	960	n.a.	917	712	427
Average productivity of planted area (dry tonnes/ha/year)[b]	22.3[c]	n.a.	17.8[d]	19.2[d]	n.a.	17.3[d]	19.8[d]	21.8[d]
Average delivered cost of wood ($/dry tonne)[e]	39	n.a.	48	30	n.a.	n.a.	22	16
Farmer-Forestry Program								
Year program 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[f]	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)[e]	n.a.	16	42	n.a.	n.a.	n.a.	n.a.	n.a.
Percent of farms intending to commit total area to trees	n.a.	8	27	0	n.a.	6	2	0

(a) Includes land rent, sapling production, land preparation, planting, fertilizers, herbicides.

(b) 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.

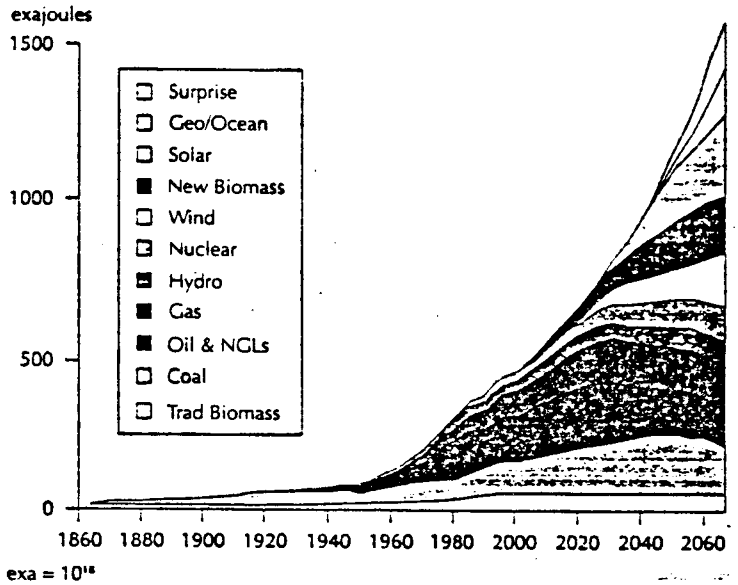
(c) Includes only stem wood with diameter 7 cm or larger.

(d) 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.

(e) Calculated from costs in $/solid m^3, assuming a wood density of 0.5 dry tonnes per cubic meter.

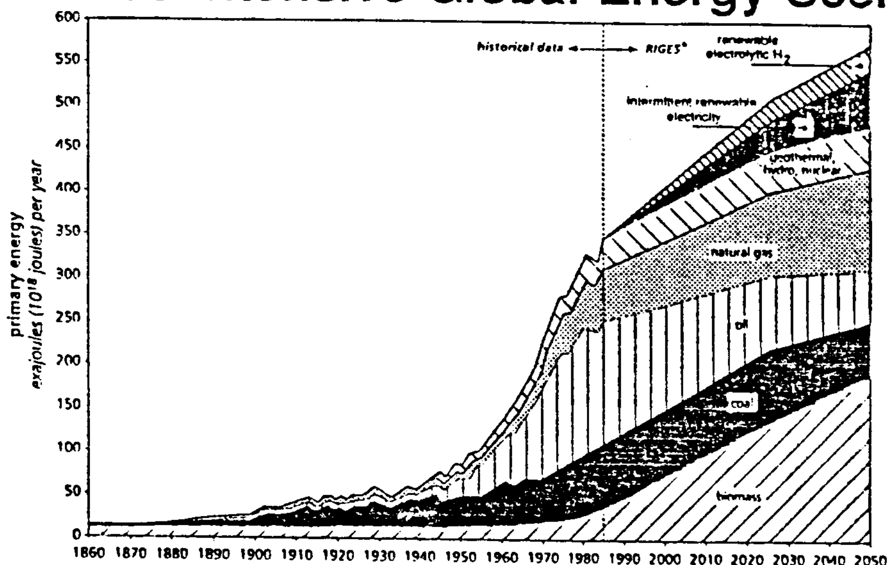
(f) Pains has a goal of contracting over 56,000 hectares under their farmer forestry program, which would involve some 4,000 farmers.

Shell International Petroleum Company Projected World Energy Use (Sustained Growth Scenario)



Source: P. Kassler, *Energy for Development*, Selected Paper, Shell International Petroleum Co., Shell Centre, London, 1994.

Renewables Intensive Global Energy Scenario



Source: T.B. Johansson, H. Kelly, A.K.N. Reddy, and R.H. Williams, "Renewable Fuels and Electricity for a Growing World Economy," Ch. 1 in *Renewable Energy: Sources for Fuels and Electricity*, Island Press, Washington, DC, 1993.

Fig. 1. Two biomass-intensive future global energy scenarios, *(a)* (lower graph) as envisaged for the renewables-intensive global energy scenario (RIGES) of Johansson, et al. [1993] (see footnote 1); the historical data are from Davis [1990]), and *(b)* (upper graph) as in the Shell International Petroleum Company (Group Planning Division) "Sustainted Growth Scenario" [Kassler, 1994].

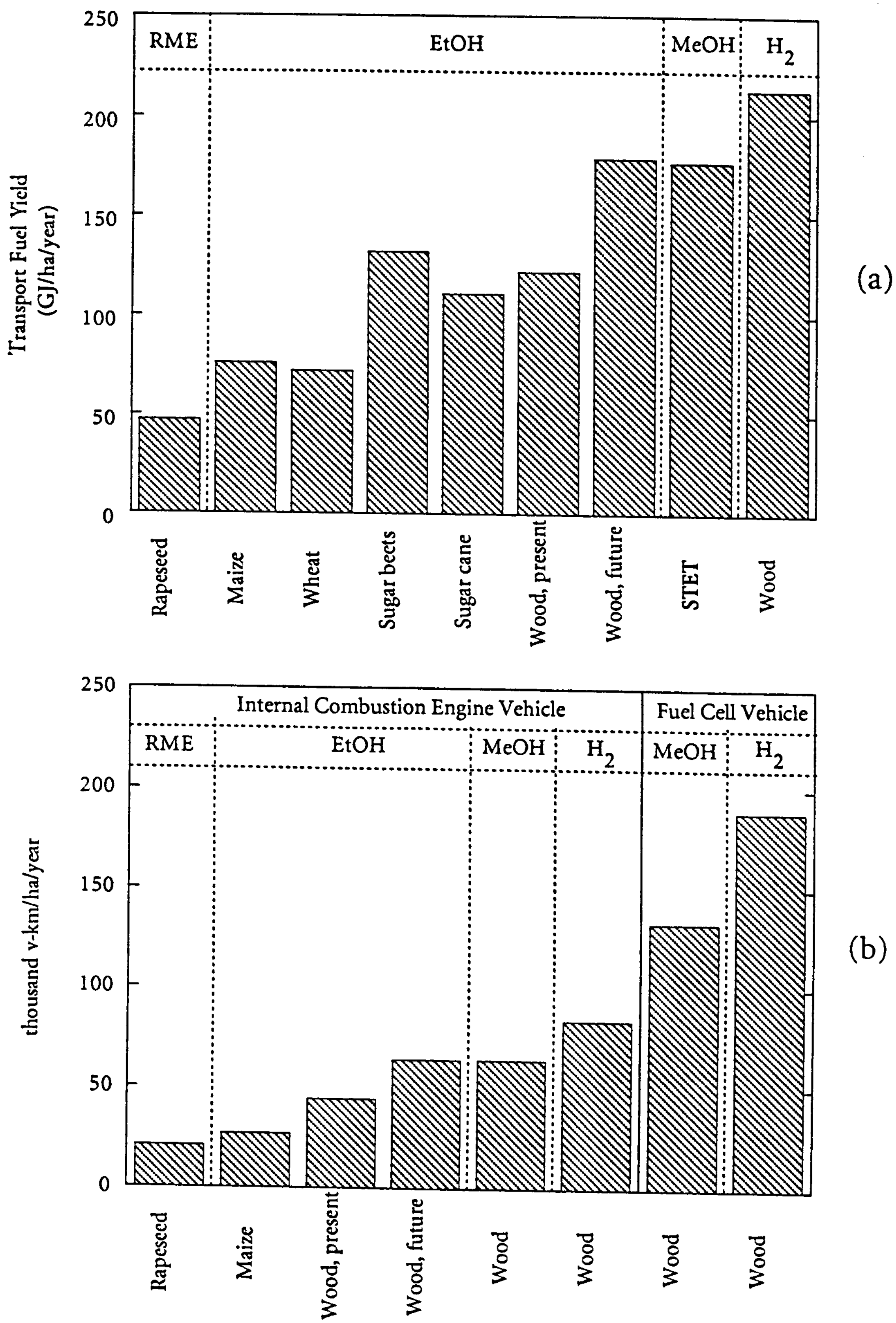


Fig. 2. Yields of *(a)* transport fuels and *(b)* transport services per hectare per year for alternative biomass feedstocks, conversion technologies, and vehicle technologies. For details see Table 3.

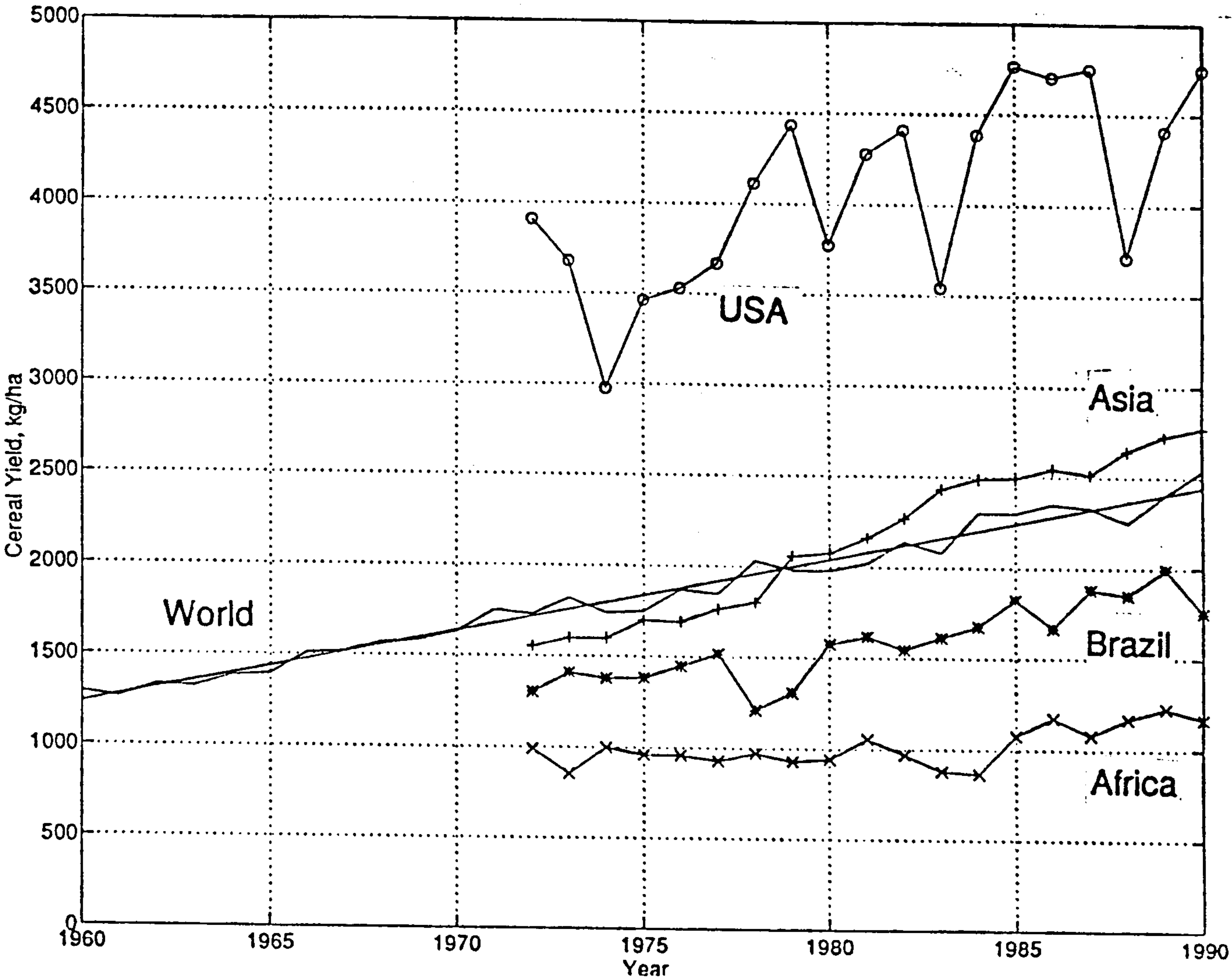


Fig. 3. Average cereal yields for the world (the data and a linear curve fit are shown) and for the United States, Brazil, Asia, and Africa. Over the period 1972 to 1990, yields increased a total of 28% in Africa, 77% in Asia, 49% in Brazil, and 33% in the United States. The sub-world data are from FAO [1991 and earlier years], and are the data cited by Marrison and Larson [1995]. The world data are from the US Department of Agriculture [USDA, 1994].

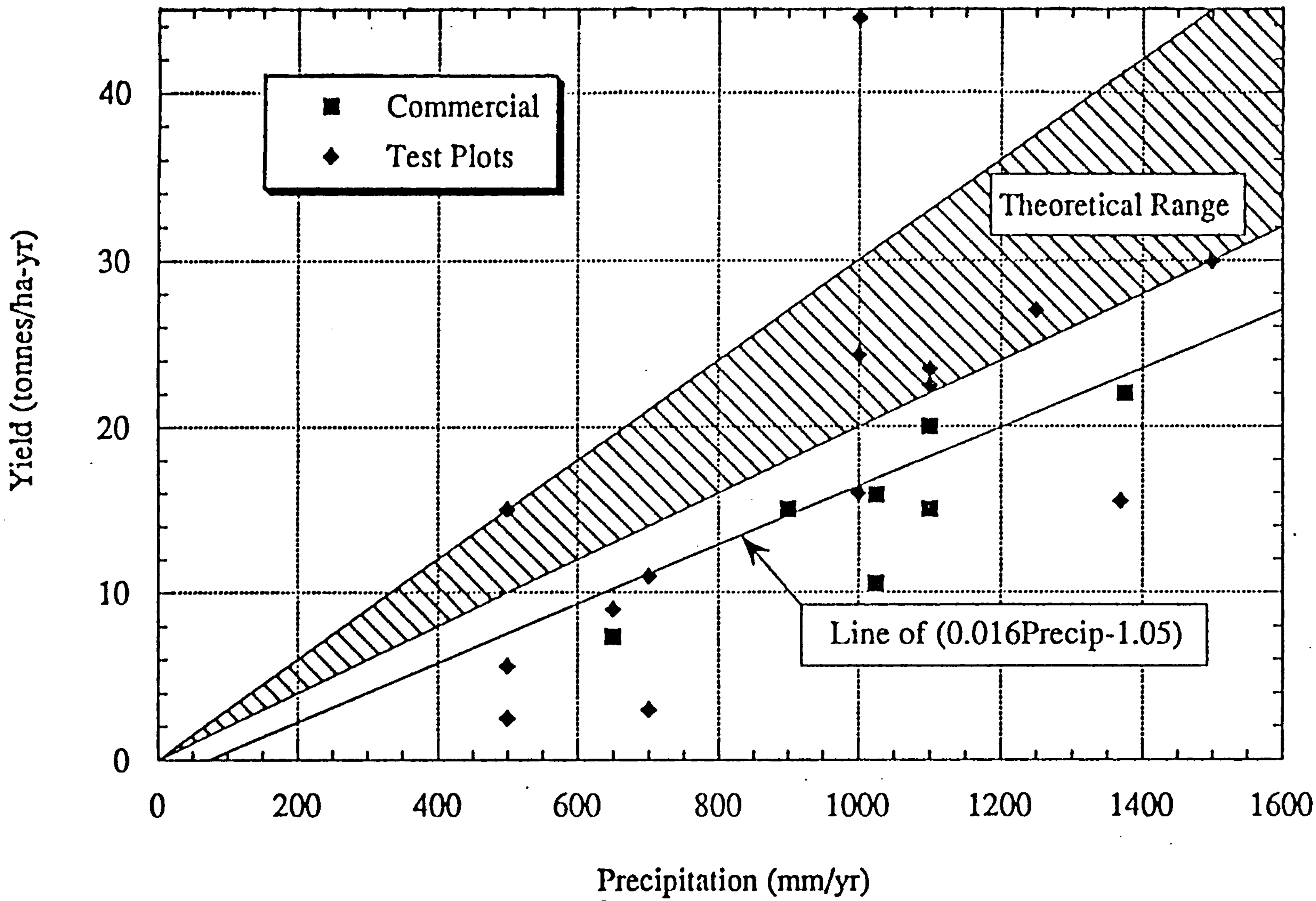


Fig. 4. Relation of eucalyptus yields (dry tonnes per hectare per year) to precipitation, based on data from modern commercial plantations in Brazil. (Yield includes only stemwood larger than 7 cm diameter) [Carpentieri et al., 1993]. Test-plot data are from Brazilian research programs [Carpentieri et al., 1993]. Also shown is an estimate of the theoretically achievable range when water is the only constraint on growth [Alves, 1990]. Alves bases the estimates on the yield of *E. globulus* in Mediterranean areas. With no limitations in sunlight or nutrients, the water use efficiency is estimated to be between 2 and 2.8 grams of biomass produced/kilogram of water. This is equivalent to 0.02 tonnes/ha per millimeter of precipitation. The indicated regression equation, a best fit of the commercial yield data, is used to calculate biomass production in each country of Africa (Appendix A), Latin America (Appendix B), and Asia (Appendix C). (The approximate higher heating value energy content of eucalyptus is 20 GJ/dry tonne.)

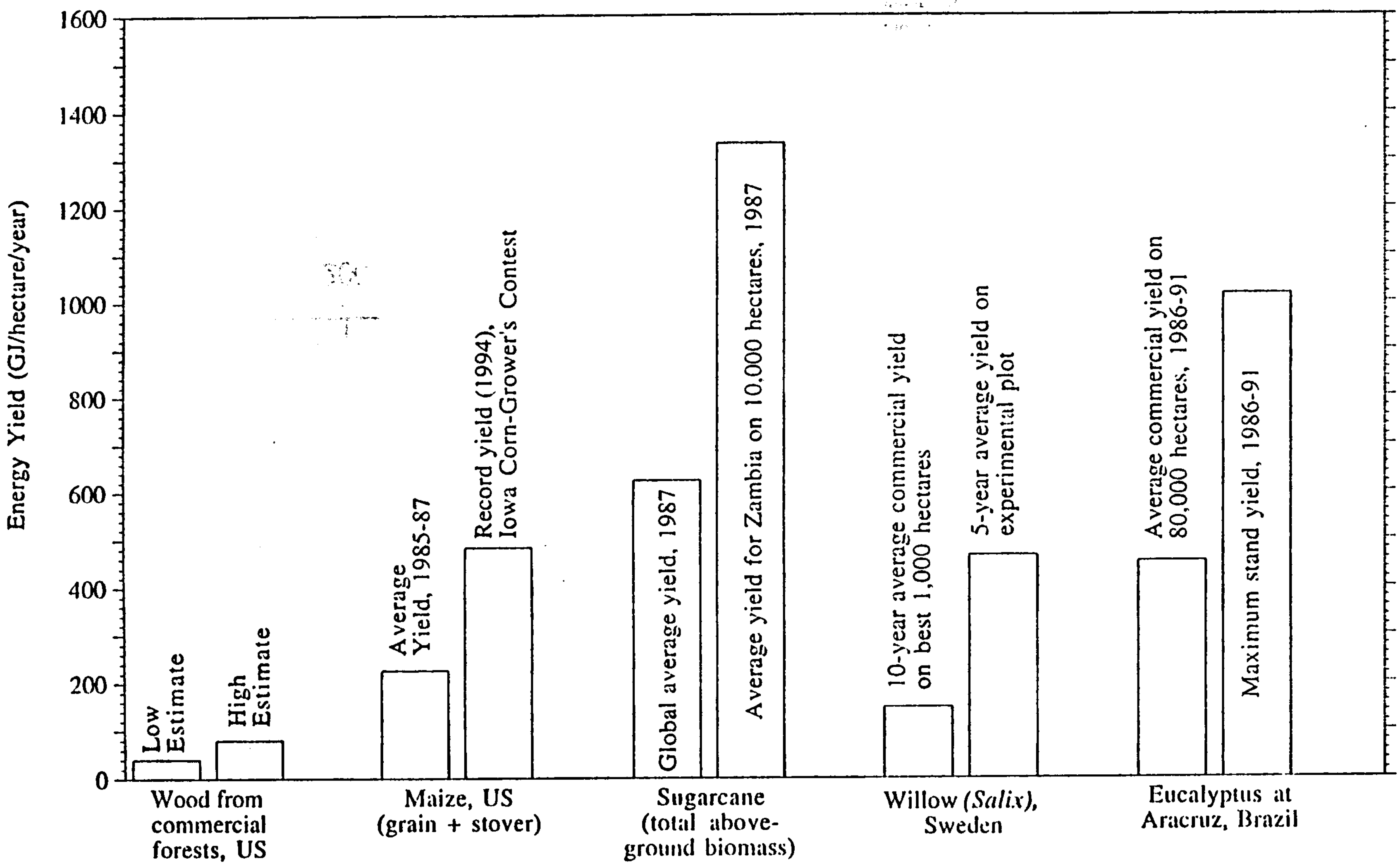


Fig. 5. Actual biomass energy yields (in GJ per hectare per year) for various activities [IPCC, 1995].

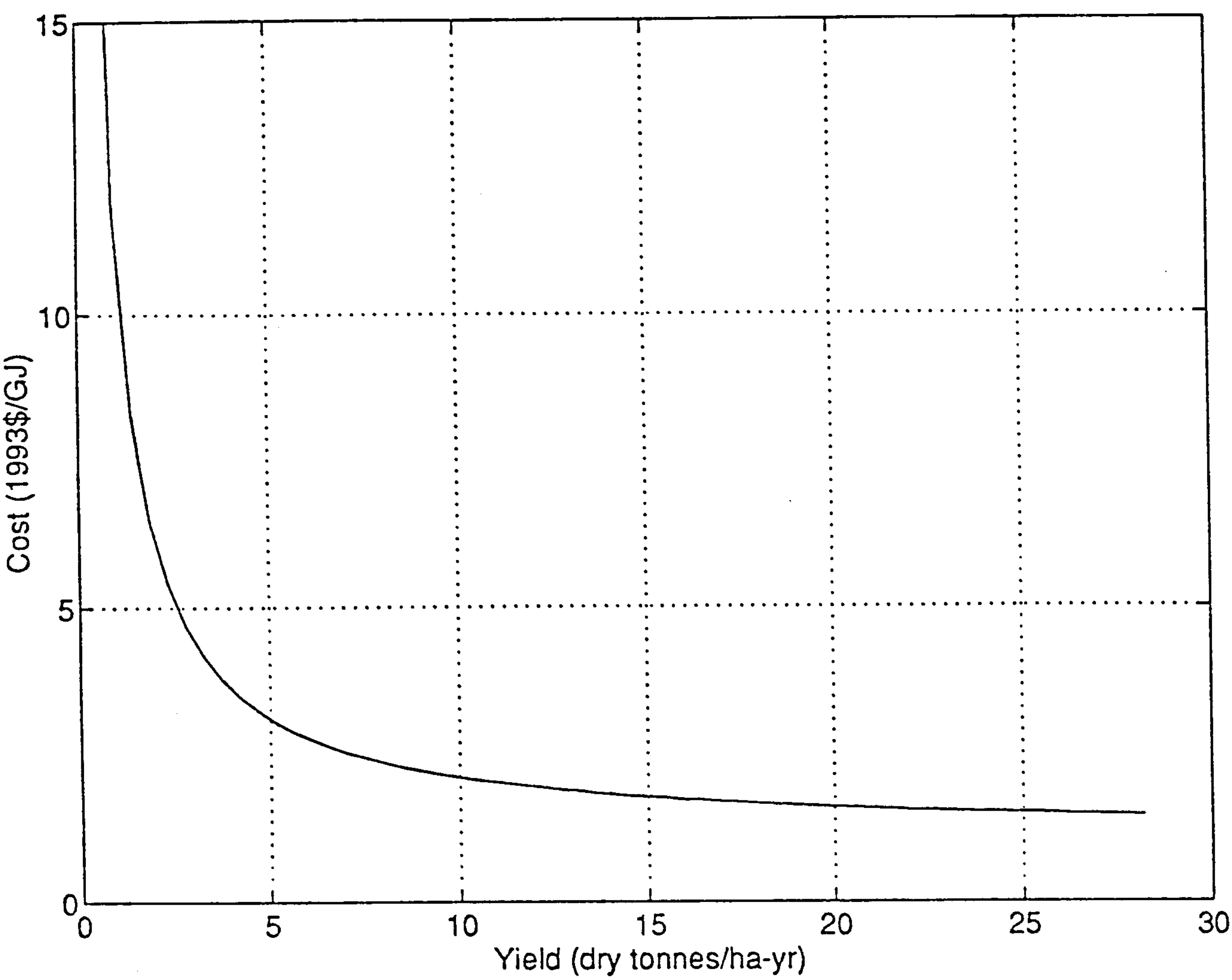


Fig. 6. Estimated average cost (1993 US$/GJ) of delivered eucalyptus chips in Brazil as function of yield. The estimated costs include establishment, maintenance, harvesting, and 85 km transport of 7 cm or larger diameter eucalyptus logs with 35% moisture content in Brazil, based on commercial plantations in primarily Central and South-Central Brazil [Carpentieri et al., 1993], plus $0.28/GJ for chipping [Perlack and Wright, 1994].

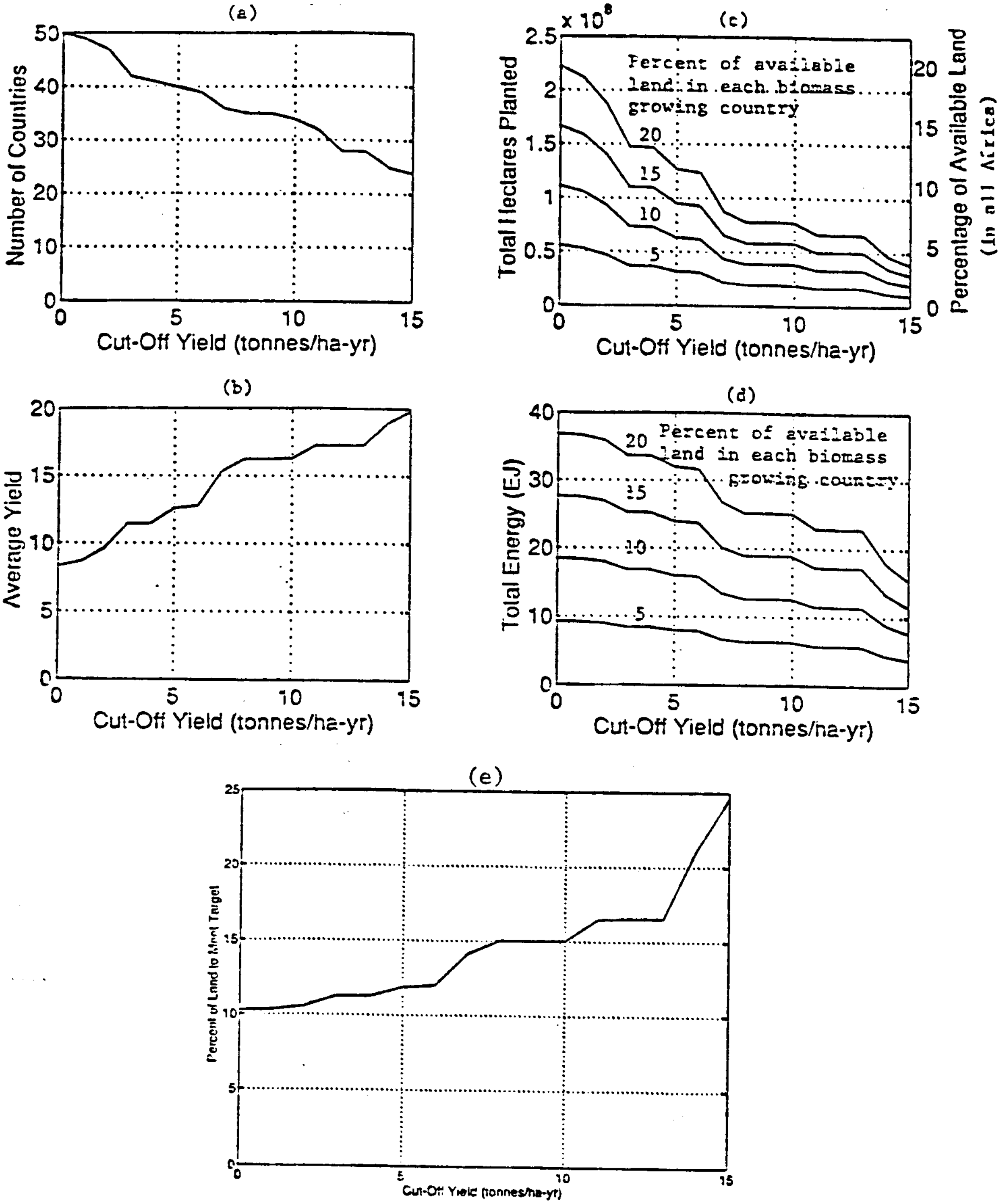


Fig. 7. Analysis of biomass energy production potential in Africa as a function of the "cut-off yield", i.e., the yield (in dry tonnes per hectare per year) below which it is assumed that a country cannot economically produce biomass. See Appendix A and Marrison and Larson [1995] for details.

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

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

(c) Biomass energy area as a function of the cut-off yield, assuming biomass is planted on 5%, 10%, 15%, or 20% of available non-crop, non-forest, non-wilderness land in each of the countries with a country-average yield higher than the cut-off value. The left axis shows actual planted area. The right axis shows the corresponding percentage of the total available non-cropland, non-forest, non-wilderness in all Africa.

(d) Total biomass energy production as a function of cut-off yield, assuming biomass is planted on 5%, 10%, 15%, or 20% of available non-crop, non-forest, non-wilderness land in each of the countries with a country-average yield higher than the cut-off value.

(e) Percentage of non-crop, non-wilderness, non-forest land needed in 2025 in each biomass-growing country in Africa 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.

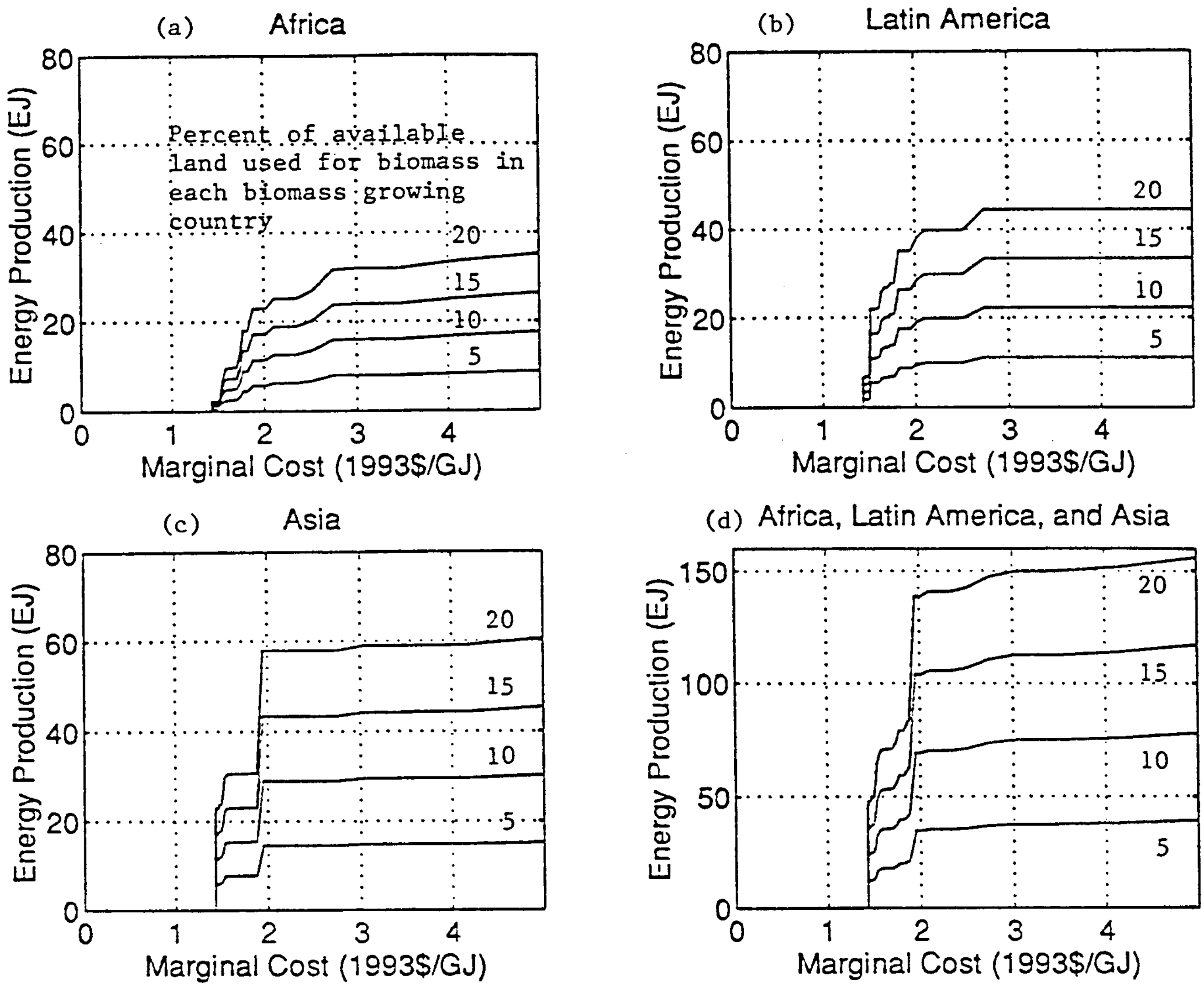


Fig. 8. Biomass cost-supply curves for Africa, Latin America, Asia, and the sum of all three regions in 2025 showing the cumulative total energy production with increasing delivered cost of biomass. The four lines represent the use of 5%, 10%, 15%, and 20%, respectively, of available non-cropland, non-forest, non-wilderness land in each country in which biomass can be produced at or below the cost shown on the x-axis. The cost of biomass is assumed to change with yield as indicated in Fig. 6.

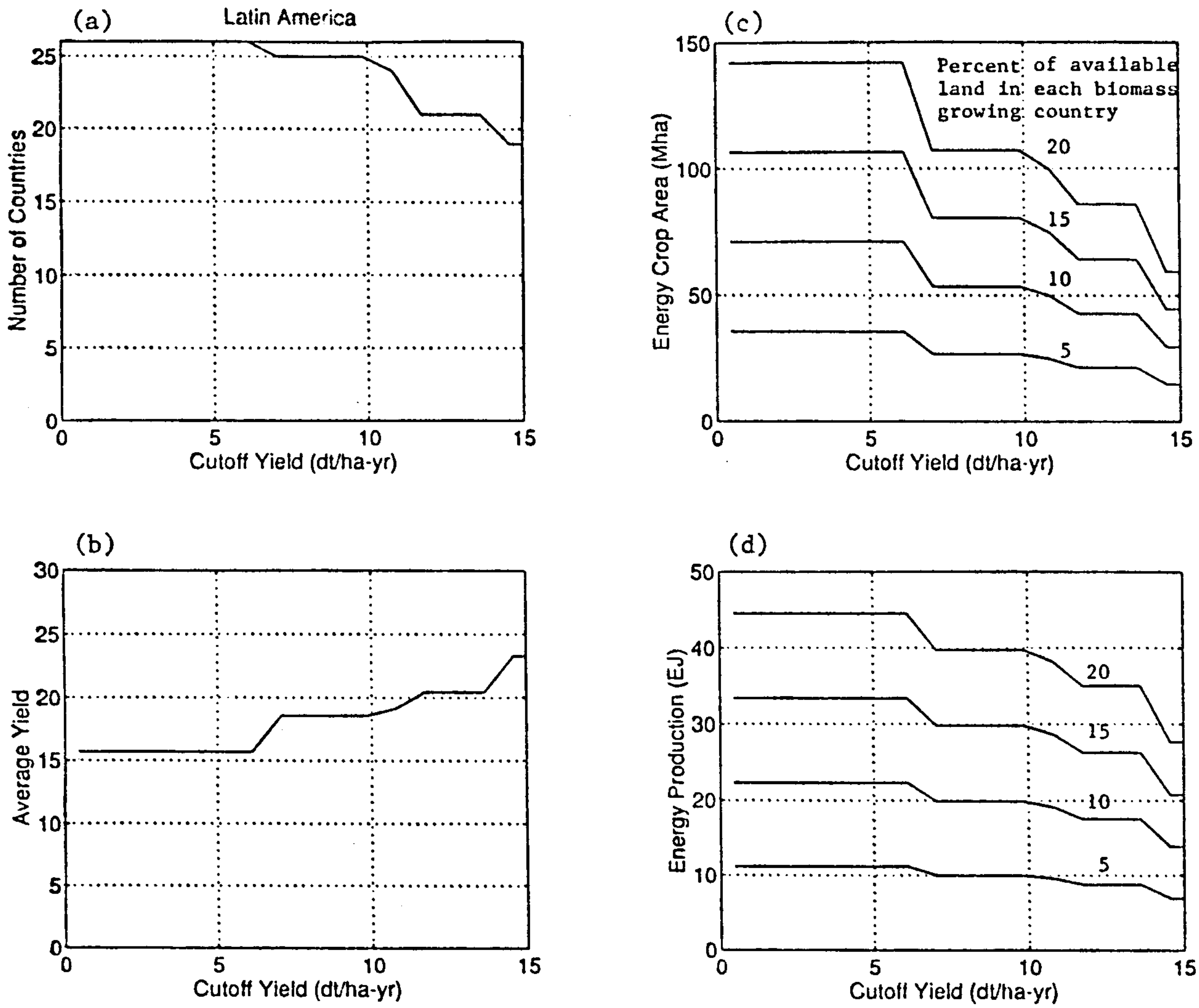


Fig. 9. Analysis of biomass energy production potential in Latin America as a function of the "cut-off yield", i.e., the yield (in dry tonnes per hectare per year) below which it is assumed that a country cannot economically produce biomass. See Appendix B for details.

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

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

(c) Biomass energy area as a function of the cut-off yield, assuming biomass is planted on 5%, 10%, 15%, or 20% of available non-crop, non-forest, non-wilderness land in each of the countries with a country-average yield higher than the cut-off value. The left axis shows actual planted area. The right axis shows the corresponding percentage of the total available non-cropland, non-forest, non-wilderness in all Latin America.

(d) Total biomass energy production as a function of cut-off yield, assuming biomass is planted on 5%, 10%, 15%, or 20% of available non-crop, non-forest, non-wilderness land in each of the countries with a country-average yield higher than the cut-off value.

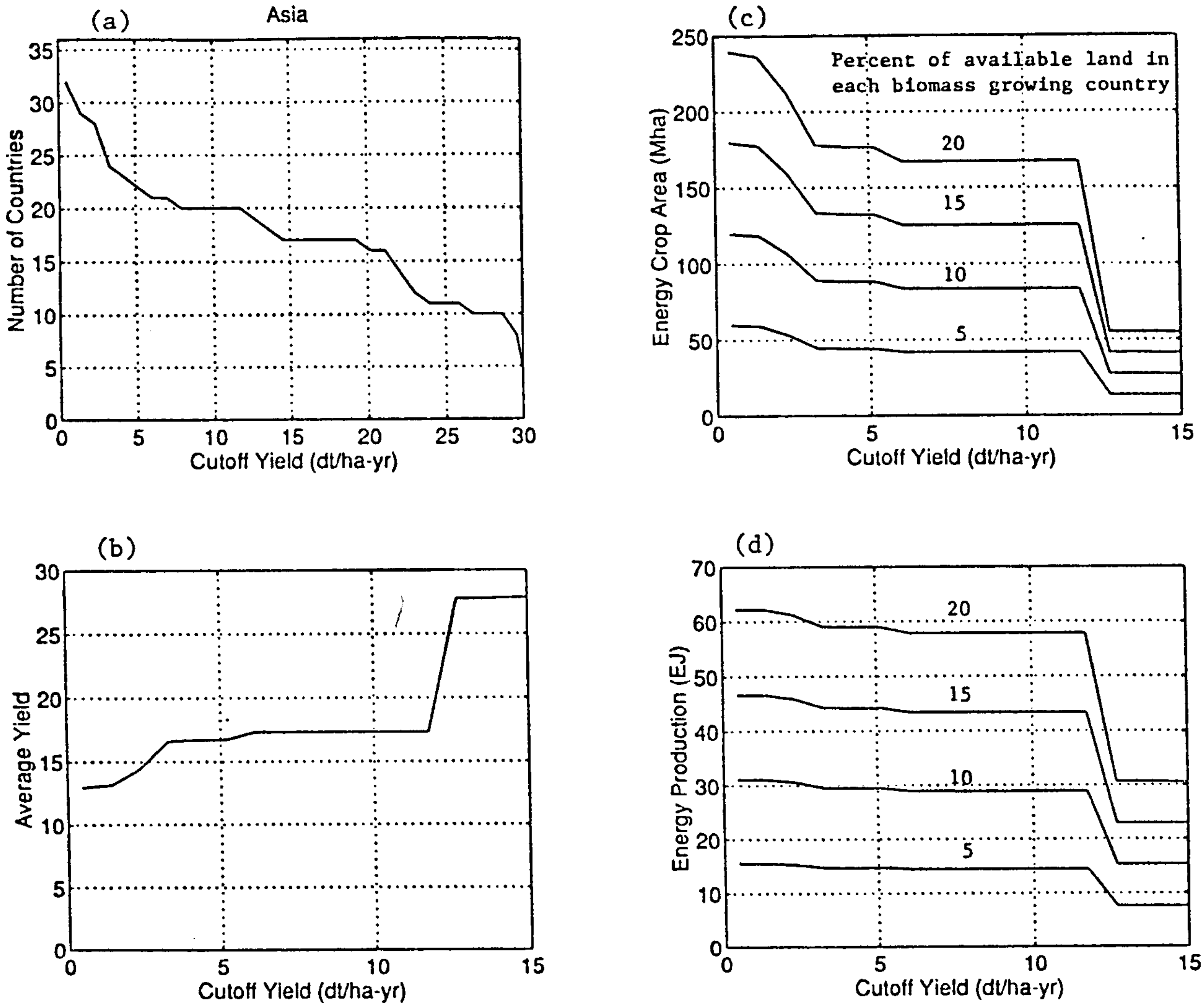


Fig. 10. Analysis of biomass energy production potential in Asia as a function of the "cut-off yield", i.e., the yield (in dry tonnes per hectare per year) below which it is assumed that a country cannot economically produce biomass. See Appendix C for details.

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

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

(c) Biomass energy area as a function of the cut-off yield, assuming biomass is planted on 5%, 10%, 15%, or 20% of available non-crop, non-forest, non-wilderness land in each of the countries with a country-average yield higher than the cut-off value. The left axis shows actual planted area. The right axis shows the corresponding percentage of the total available non-cropland, non-forest, non-wilderness in all Asia.

(d) Total biomass energy production as a function of cut-off yield, assuming biomass is planted on 5%, 10%, 15%, or 20% of available non-crop, non-forest, non-wilderness land in each of the countries with a country-average yield higher than the cut-off value.

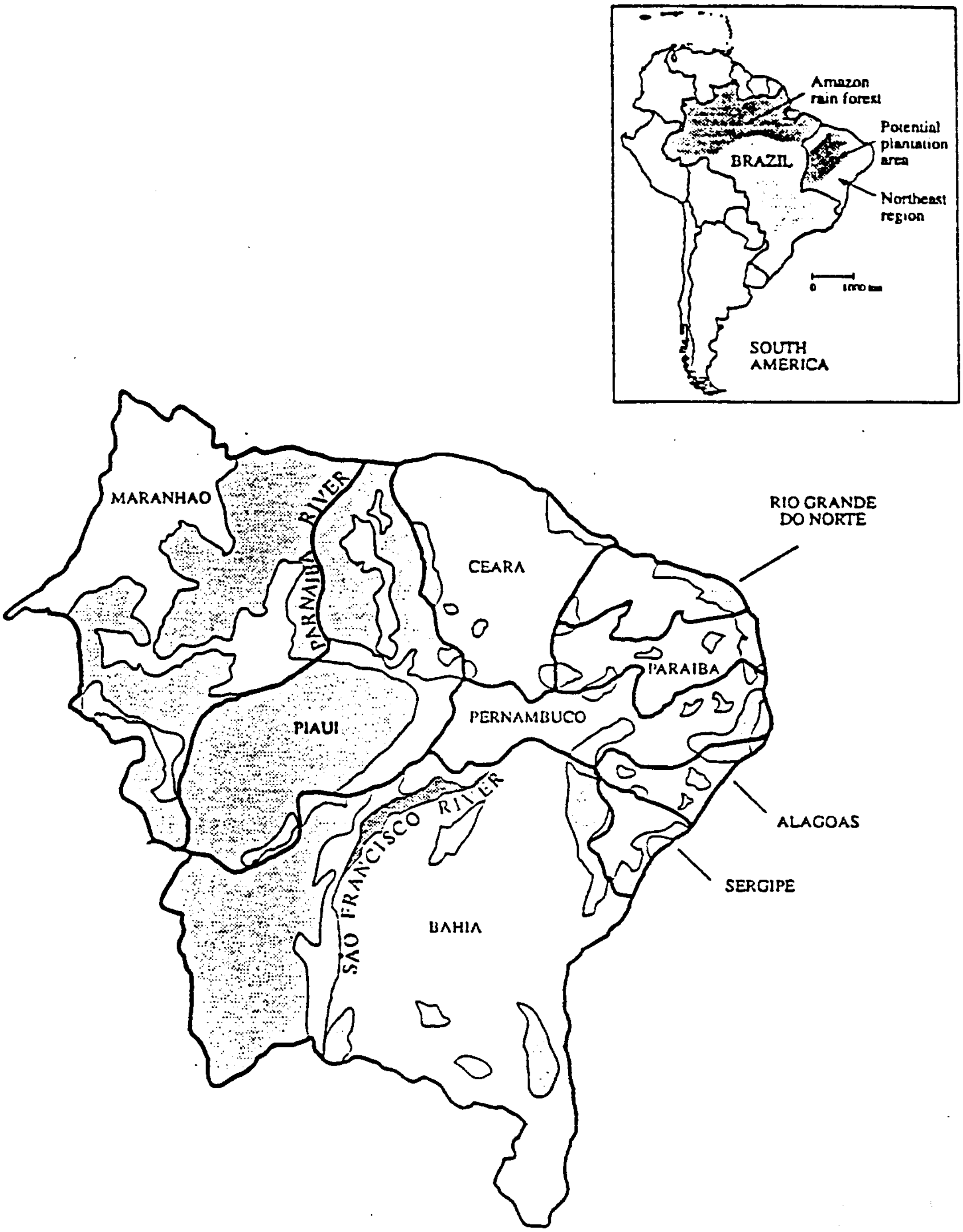


Fig. 11. The large map shows the areas (shaded) identified by CHESF as available and suitable for establishing biomass energy plantations in Northeast Brazil. The total shaded area is approximately 50 million hectares (see Table 10). The inset shows the location of the Northeast region within South America. Source: [Carpentieri et al., 1993].

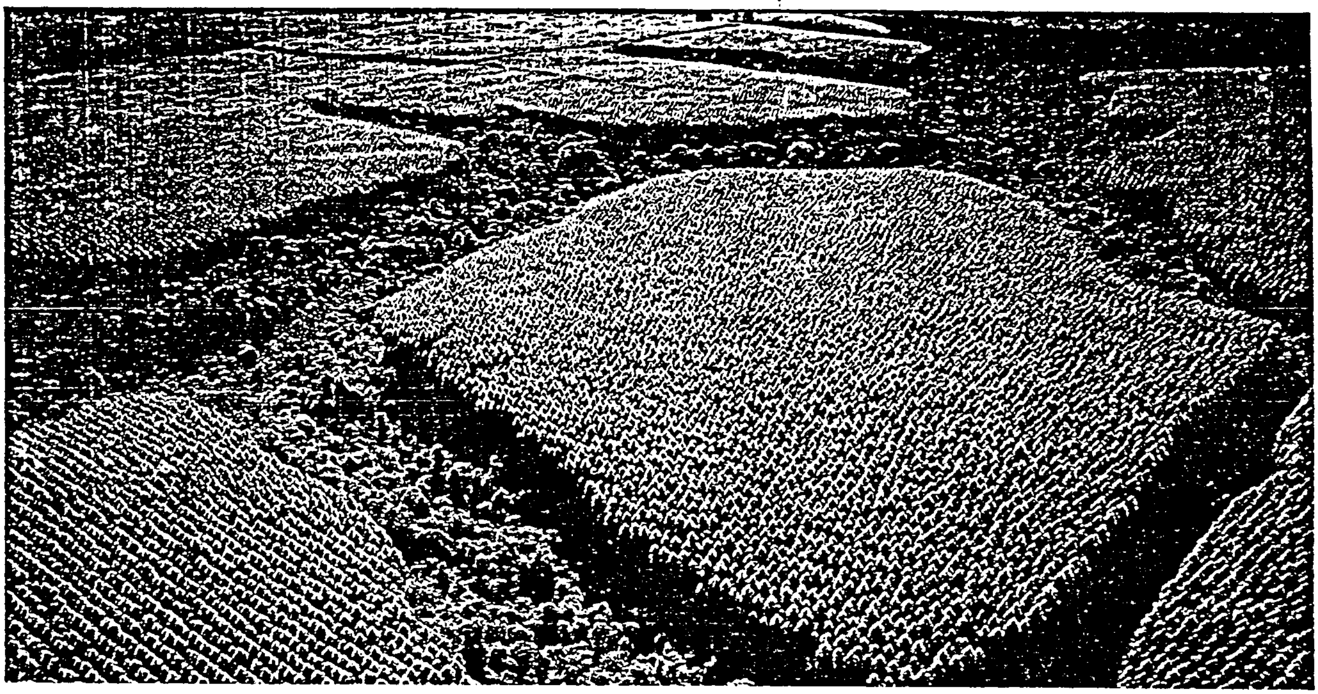


Fig. 12. Aerial photograph of a plantation owned by Bahia Sul in the south part of the state of Bahia, Brazil. The irregular-appearing, interconnected regions are natural vegetation.

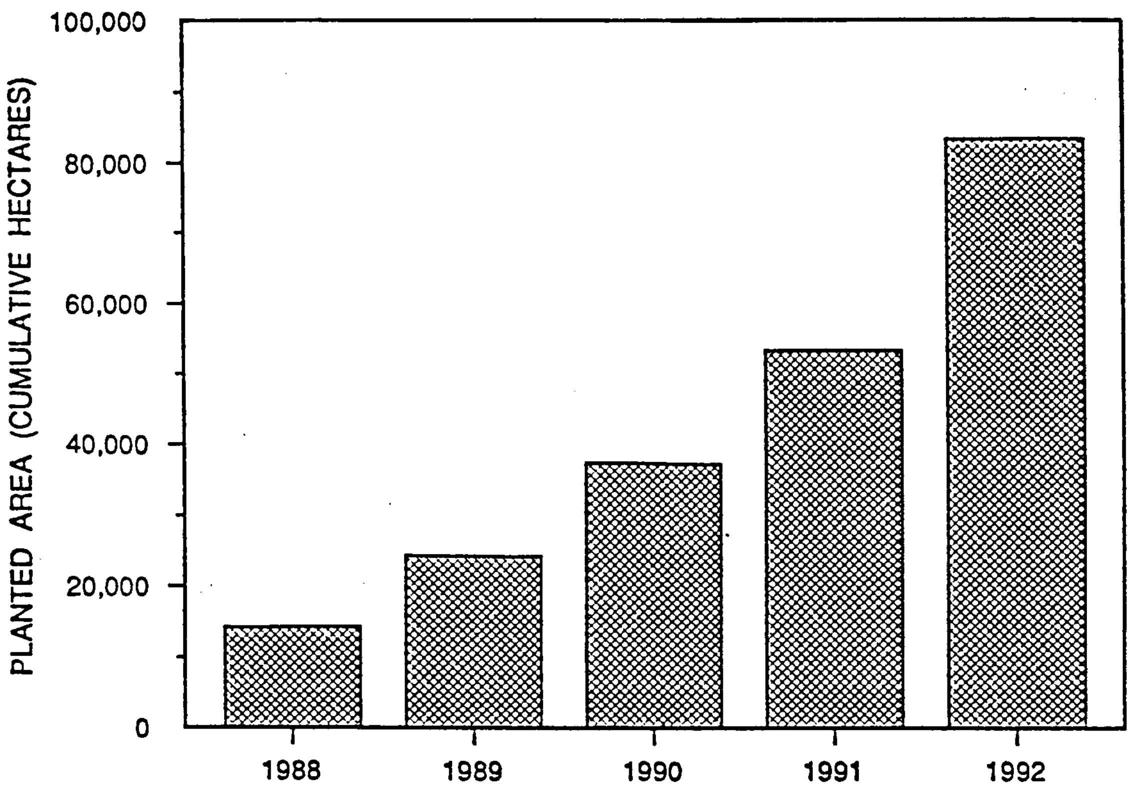


Fig. 13. Small and medium-sized farm area planted with trees, 1988 through 1992, in Minas Gerais, Brazil, and financed by private forestry companies. The 1992 figure is a projection. The average growth rate from 1988 to 1992 is 35% per year. Farm area under trees established before 1988 is not included in the chart. Also, planted areas established with public funding are not shown. Source: [Larson et al., 1994].

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Appendix A

Detailed Tables Associated with Calculation of Bioenergy Potential in

AFRICA

Notes:

- Table notes refer to sources and equations given in Marrison and Larson [1995].
- For detailed explanation of the algorithm used in the calculations to generate tables in Appendices A, B, and C, see Marrison and Larson [1995].
- Table A.5 assumes that 10% of available non-crop, non-forest, non-wilderness land is used for biomass energy production. Figure 7 shows results assuming 5, 10, 15, or 20% of available land is used.

Table A.1. Food needs for Africa by country.

Country	Population in 1990 (thousands)†	Population in 2025 (thousands)†	Calories Needed / Calories Available*	Multiplication of Food Supply^x
Algeria	24960	51830	1.00	2.08
Angola	9194	26619	1.30	3.76
Benin	4622	12354	1.02	2.73
Botswana	1238	2853	1.00	2.30
Burkina Faso	8993	22633	1.04	2.62
Burundi	5492	13392	1.16	2.84
Cameroon	11524	29262	1.05	2.67
Cape Verde	363	774	1.00	2.13
Cent. Afr. Rep.	3008	7046	1.12	2.63
Chad	5553	12907	1.32	3.06
Comoros	543	1646	1.23	3.74
Congo	2229	5757	1.00	2.58
Cote d'Ivoire	11980	37942	1.00	3.17
Djibouti	440	1159	1.00	2.63
Egypt	52426	93536	1.00	1.78
Equat. Guinea	352	798	1.00	2.27
Ethiopia	49831	130674	1.43	3.75
Gabon	1159	2896	1.00	2.50
The Gambia	861	1875	1.01	2.20
Ghana	15020	37988	1.02	2.58
Guinea	5755	15088	1.05	2.76
Guinea-Bissau	964	1978	1.00	2.05
Kenya	23585	63826	1.08	2.91
Lesotho	1747	3783	1.00	2.17
Liberia	2575	7234	1.00	2.81
Libya	4545	12873	1.00	2.83
Madagascar	12010	33746	1.04	2.93
Malawi	9582	24926	1.11	2.89
Mali	9214	24580	1.05	2.81
Mauritania	2024	4993	1.00	2.47
Mauritius	1075	1397	1.00	1.30
Morocco	25061	47477	1.00	1.89
Mozambique	14200	36290	1.41	3.60
Namibia	1439	3751	1.16	3.03
Niger	7731	21287	1.02	2.81
Nigeria	108542	285823	1.02	2.69
Rwanda	7027	20595	1.19	3.49
Senegal	7327	17078	1.00	2.33
Sierra Leone	4151	9800	1.25	2.95
Somalia	8677	23401	1.19	3.21
South Africa	37959	73211	1.00	1.93
Sudan	25203	60602	1.16	2.80
Swaziland	751	1739	1.00	2.32
Tanzania	25993	74172	1.05	3.00
Togo	3531	9377	1.08	2.86
Tunisia	8057	13425	1.00	1.67
Uganda	17560	45933	1.09	2.84
Zaire	37391	104530	1.12	3.14
Zambia	8138	20981	1.00	2.58
Zimbabwe	9947	22889	1.04	2.40
Africa Total	641549	1580726	1.09	2.65

Source:
† [UN-93].
* [WRI-92, Table 16.3].
^x MFS defined by equation 2.

Table A.2. Required increase in cropland, 2025 versus 1990, for Africa by country.

Country	Multiplication of Production†	Cropland in 1990# (thousand ha)	Cropland in 2025ˣ (thousand ha)	Increase in Cropland (thousand ha)
Algeria	6.63	7613	35286	27673
Angola	7.04	3583	17642	14059
Benin	3.08	1853	3988	2135
Botswana	4.50	1373	4321	2948
Burkina Faso	2.75	3423	6572	3149
Burundi	2.90	1334	2708	1374
Cameroon	3.27	7004	15995	8991
Cape Verde	10.06	39	274	235
Cent. Afr. Rep.	3.05	2006	4275	2269
Chad	3.27	3205	7335	4130
Comoros	9.37	99	648	549
Congo	9.20	167	1074	907
Cote d'Ivoire	4.35	3653	11124	7471
Djibouti	3.15	0	0	0
Egypt	2.52	2571	4539	1968
Equat. Guinea	2.67	230	429	199
Ethiopia	4.40	13930	42892	28962
Gabon	6.25	452	1974	1522
The Gambia	3.37	174	410	236
Ghana	3.05	2700	5766	3066
Guinea	3.28	727	1665	938
Guinea-Bissau	2.35	335	549	214
Kenya	2.92	2424	4948	2524
Lesotho	3.24	320	724	404
Liberia	3.91	372	1017	645
Libya	10.36	2147	15551	13404
Madagascar	3.09	3079	6654	3575
Malawi	3.10	2391	5191	2800
Mali	2.93	2087	4279	2192
Mauritania	4.91	199	683	484
Mauritius	22.27	106	1650	1544
Morocco	2.15	8985	13481	4496
Mozambique	7.11	3097	15405	12308
Namibia	3.67	662	1700	1038
Niger	2.95	3599	7414	3815
Nigeria	2.74	31335	59999	28664
Rwanda	3.66	1149	2944	1795
Senegal	3.09	5226	11276	6050
Sierra Leone	3.68	1801	4636	2835
Somalia	4.52	1038	3279	2241
South Africa	1.74	13172	16017	2845
Sudan	3.31	12499	28956	16457
Swaziland	2.78	164	319	155
Tanzania	3.07	5240	11260	6020
Togo	3.24	1438	3262	1824
Tunisia	3.23	4700	10626	5926
Uganda	2.89	6705	13559	6854
Zaire	3.99	7850	21890	14040
Zambia	2.79	5238	10220	4982
Zimbabwe	2.29	2796	4468	1672
Africa Total	3.47	186290	450897	264607

† This is $MFP_{fixed\ imp}$ from equation 1.

[WRI-92, Table 17.1].

ˣ This is CLR_{2025} from equation 5.

Table A.3. Non-agricultural land areas in 1990 in Africa by country.

Country	Pasture Land 1990† (thousand ha)	Forest 1990† (thousand ha)	'Other' Land 1990† (thousand ha)	Wilderness 1990# (thousand ha)
Algeria	31168	4699	194693	140424
Angola	29000	53040	39047	27049
Benin	442	3570	5197	1209
Botswana	33000	10930	11370	31255
Burkina Faso	10000	6720	7237	750
Burundi	913	65	253	0
Cameroon	8300	24760	6476	1320
Cape Verde	25	1	338	0
Cent. Afr. Rep.	3000	35820	21472	20917
Chad	45000	12890	64825	61254
Comoros	15	35	74	0
Congo	10000	21200	2783	11837
Cote d'Ivoire	13000	7880	7267	4268
Djibouti	200	6	2112	0
Egypt	0	31	96943	42540
Equat. Guinea	104	1295	1176	0
Ethiopia	45000	27300	23870	19716
Gabon	4700	20000	615	7333
The Gambia	90	168	568	0
Ghana	5000	8210	7092	0
Guinea	6150	14700	3009	0
Guinea-Bissau	1080	1070	327	0
Kenya	38100	2380	14065	11221
Lesotho	2000	0	715	2133
Liberia	5700	1780	1780	1420
Libya	13300	678	159829	65497
Madagascar	34000	15830	5245	691
Malawi	1840	3850	1327	791
Mali	30000	7010	82922	58814
Mauritania	39250	4450	58623	71370
Mauritius	7	57	14	0
Morocco	20900	7915	6830	0
Mozambique	44000	14500	16812	6130
Namibia	38000	18180	25487	22239
Niger	9267	2120	111685	65633
Nigeria	40000	12500	7242	1526
Rwanda	480	560	278	0
Senegal	5700	5942	2385	1586
Sierra Leone	2204	2073	1084	0
Somalia	43000	9080	9616	10460
South Africa	81378	4515	23039	0
Sudan	98000	45440	81661	79377
Swaziland	1175	107	275	0
Tanzania	35000	41180	7184	7053
Togo	1790	1620	591	0
Tunisia	2952	620	7264	1901
Uganda	1800	5660	5790	530
Zaire	15000	174970	28940	11763
Zambia	30000	28990	10111	15075
Zimbabwe	4856	19290	11725	0
Africa Total	885886	685687	1413138	805082

† [WRI-92, Table 17.1 with wilderness subtracted].

[WRI-92, Table 17.1].

Table A.4. Non-forest, non-wilderness, non-cropland (i.e., pasture and 'other' lands) in Africa in 1990 by country and percentage of this land required for new cropland in 2025.

Country	Pasture+Other 1990† (thousand ha)	% of PO to go to New Crop Land*	10% of Remaining P+O Land 2025 (thousand ha)
Algeria	88298	31	6062
Angola	52846	26	3878
Benin	4898	43	276
Botswana	19292	15	1634
Burkina Faso	16697	18	1354
Burundi	1166	117	0
Cameroon	14282	62	529
Cape Verde	363	64	12
Cent. Afr. Rep.	15981	14	1371
Chad	55005	7	5087
Comoros x	89	617	0
Congo	8330	10	742
Cote d'Ivoire	17193	43	972
Djibouti x	2312	∞	231
Egypt	54416	3	5244
Equat. Guinea	1280	15	108
Ethiopia	54750	52	2578
Gabon	3775	40	225
The Gambia	658	35	42
Ghana	12092	25	902
Guinea	9159	10	822
Guinea-Bissau	1407	15	119
Kenya	41433	6	3890
Lesotho	582	69	17
Liberia	6332	10	568
Libya	107887	12	9448
Madagascar	38752	9	3517
Malawi	2809	99	0
Mali	57545	3	5535
Mauritania	29606	1	2912
Mauritius x	21	7355	0
Morocco	27730	16	2323
Mozambique	55862	22	4355
Namibia	46198	2	4516
Niger	56449	6	5263
Nigeria	46035	62	1737
Rwanda x	758	236	0
Senegal	7170	84	112
Sierra Leone	3288	86	45
Somalia	43695	5	4145
South Africa	104417	2	10157
Sudan	116307	14	9984
Swaziland	1450	10	129
Tanzania	38615	15	3259
Togo	2381	76	55
Tunisia	8423	70	249
Uganda	7286	94	43
Zaire	41578	33	2753
Zambia	31360	15	2637
Zimbabwe	16581	10	1490
Africa Total	1374857	19	111348

† This is the 1990 area that is neither cropland, wilderness, nor forest (from equation 7).

* From equation 8.

x These countries rely heavily on imported food or a large proportion of the country is currently cropland..

Table A.5. Production of biomass energy in Africa by country in 2025, assuming 10% of available non-crop, non-forest, non-wilderness area is planted with biomass, and assuming biomass production as a function of precipitation as given in Fig. 4. National average annual precipitation is used for each country.

Country	Energy Crop Area† (thousand ha)	Assumed* Precipitation (mm/yr)	Eucalyptus Yield^x (tonnes/ha-yr.)	Primary Energy# (PJ)
Algeria	6062	250	2.9	355
Angola	3878	713	10.3	799
Benin	276	1320	20.0	110
Botswana	1634	397	5.3	172
Burkina Faso	1354	1028	15.3	415
Burundi	0	254	3.0	0
Cameroon	529	1498	22.8	241
Cape Verde	12	1524	23.2	5
Cent. Afr. Rep.	1371	1485	22.6	619
Chad	5087	567	8.0	811
Comoros	0	1524	23.2	0
Congo	742	1397	21.2	314
Cote d'Ivoire	972	1562	23.8	462
Djibouti	231	1168	17.5	81
Egypt	5244	101	0.6	59
Equat. Guinea	108	2032	30.0	64
Ethiopia	2578	889	13.1	675
Gabon	225	2044	30.0	135
The Gambia	42	1295	19.6	16
Ghana	902	1054	15.7	283
Guinea	822	2984	30.0	493
Guinea-Bissau	119	2184	30.0	71
Kenya	3890	1079	16.1	1254
Lesotho	17	762	11.1	3
Liberia	568	4445	30.0	341
Libya	9448	158	1.5	278
Madagascar	3517	889	13.1	921
Malawi	0	1155	17.3	0
Mali	5535	482	6.6	733
Mauritania	2912	177	1.8	103
Mauritius	0	1524	23.2	0
Morocco	2323	501	6.9	322
Mozambique	4355	990	14.7	1281
Namibia	4516	241	2.8	251
Niger	5263	245	2.8	300
Nigeria	1737	1384	20.9	728
Rwanda	0	762	11.0	0
Senegal	112	647	9.2	20
Sierra Leone	45	3479	30.0	27
Somalia	4145	241	2.8	231
South Africa	10157	482	6.6	1346
Sudan	9984	330	4.2	839
Swaziland	129	762	11.0	28
Tanzania	3259	905	13.3	871
Togo	55	787	11.4	12
Tunisia	249	292	3.6	17
Uganda	43	1358	20.5	17
Zaire	2753	1441	21.8	1205
Zambia	2637	1024	15.2	804
Zimbabwe	1490	698	10.0	300
Africa Total	111348	-	8.5	18432

† From equation 10.
* Mean of values reported by Van der Leeden [1990].
^x From equation 9.
Assuming 20 GJ/dry-metric-tonne of biomass.

Appendix B

Detailed Tables Associated with Calculation of Bioenergy Potential in

LATIN AMERICA

Notes:

- Table B.5 assumes that 10% of available non-crop, non-forest, non-wilderness land is used for biomass energy production (including 10% of "spare" cropland--see text discussion). Figure 9 shows results assuming 5, 10, 15, or 20% of available land is used.

Table B.1. Food needs for Latin America by country.

Country	Population in 1990 (thousands)	Population in 2025 (thousands)	Calories Needed / Calories Available	Multiplication of Food Supply
Barbados	257	307	1.00	1.19
Belize	190	310	1.00	1.63
Costa Rica	3035	5608	1.00	1.85
Cuba	10608	12993	1.00	1.22
Dominican Rep	7170	11447	1.00	1.60
El Salvador	5172	9735	1.00	1.88
Guatemala	9197	21668	1.00	2.36
Haiti	6486	13128	1.12	2.27
Honduras	5138	11510	1.01	2.26
Jamaica	2420	3509	1.00	1.45
Mexico	84486	137483	1.00	1.63
Nicaragua	3676	9079	1.00	2.47
Panama	2418	3862	1.00	1.60
Trinidad/Tobago	1236	1779	1.00	1.44
Argentina	32322	45505	1.00	1.41
Bolivia	7171	14096	1.22	2.40
Brazil	149042	219673	1.00	1.47
Chile	13173	19774	1.00	1.50
Colombia	32300	49359	1.00	1.53
Ecuador	10547	18643	1.00	1.77
Guyana	796	1141	1.00	1.43
Paraguay	4277	9182	1.00	2.15
Peru	21550	37350	1.04	1.81
Suriname	422	668	1.00	1.58
Uruguay	3094	3691	1.00	1.19
Venezuela	19321	32665	1.00	1.69
Total	435504	694165	1.01	1.61

Table B.2. Required increase in cropland, 2025 versus 1990, for Latin America by country.

Country	Multiplication of Production	Cropland in 1990 (thousand ha)	Cropland Needed in 2025 (thousand ha)	Increase in Cropland (thousand ha)
Barbados	7.61	33	150	117
Belize	1.94	56	65	9
Costa Rica	2.95	527	931	404
Cuba	9.47	3332	18930	15598
Dominican Rep	3.02	1440	2607	1167
El Salvador	2.31	733	1015	282
Guatemala	2.80	1868	3135	1267
Haiti	3.26	904	1766	862
Honduras	2.79	1793	3001	1208
Jamaica	102.85	296	18265	17969
Mexico	1.79	24708	26500	1792
Nicaragua	3.17	1270	2416	1146
Panama	1.78	576	614	38
Trinidad/Tobago	10.46	120	753	633
Argentina	1.23	35750	28316	-7433
Bolivia	3.25	3461	7272	3811
Brazil	1.50	78233	75926	-2306
Chile	1.54	4415	4399	-16
Colombia	1.64	5348	5658	310
Ecuador	2.07	2683	3593	910
Guyana	1.53	495	490	-5
Paraguay	2.15	2203	3057	854
Peru	2.42	3727	5817	2090
Suriname	1.50	68	65	-2
Uruguay	1.16	1307	975	-331
Venezuela	2.45	3883	6144	2261
Total	2.60	179229	221872	42644

Table B.3. Non-agricultural land areas in 1990 in Latin America by country.

Country	Pastureland in 1990 (thousand ha)	Forest in 1990 (thousand ha)	'Other' Land in 1990 (thousand ha)	Wilderness in 1990 (thousand ha)
Barbados	4	0	6	0
Belize	48	1012	1164	0
Costa Rica	2310	1640	629	0
Cuba	2992	2750	1908	0
Dominican Rep	2092	619	687	0
El Salvador	610	104	625	0
Guatemala	1380	3910	3685	0
Haiti	499	42	1311	0
Honduras	2235	3010	3024	1126
Jamaica	193	187	434	0
Mexico	73131	42740	47238	3050
Nicaragua	4539	3083	1460	1521
Panama	1537	3407	2079	0
Trinidad/Tobago	11	222	160	0
Argentina	133436	55661	33845	14976
Bolivia	22170	46258	18739	17810
Brazil	124502	409281	31573	202061
Chile	9009	5916	32452	23086
Colombia	34010	43075	6278	15156
Ecuador	5050	11500	8451	0
Guyana	447	5959	579	12204
Paraguay	16215	11885	1699	7726
Peru	19119	48574	19918	36660
Suriname	5	4257	188	11080
Uruguay	13520	669	1988	0
Venezuela	11392	19907	23280	29742
Total	480463	725674	243405	376198

Table B.4. Non-forest, non-wilderness, non-cropland (i.e., pasture and 'other' lands) in Latin America in 1990 by country, percentage of this land required for new cropland in 2025, 10% of remaining pasture plus 'other' lands, and 1990 cropland not needed for crops in 2025 ("spare cropland").

Country	Pasture+Other 1990 (thousand ha)	Percent of PO to go to New Crop Land	10% of Remaining Pasture+Other Land in 2025	Spare Crop Land (thousand ha)
Barbados	10	1177	0	0
Belize	1212	1	120	0
Costa Rica	2939	14	253	0
Cuba	4900	318	0	0
Dominican Rep	2779	42	161	0
El Salvador	1235	23	95	0
Guatemala	5065	25	379	0
Haiti	1810	48	94	0
Honduras	5259	23	405	0
Jamaica	627	2865	0	0
Mexico	120370	1	11857	0
Nicaragua	6000	19	485	0
Panama	3616	1	357	0
Trinidad/Tobago	171	370	0	0
Argentina	167281	0	16728	7433
Bolivia	40909	9	3709	0
Brazil	156075	0	15607	2306
Chile	41462	0	4146	16
Colombia	40289	1	3997	0
Ecuador	13501	7	1259	0
Guyana	1026	0	102	5
Paraguay	17915	5	1706	0
Peru	39038	5	3694	0
Suriname	194	0	19	2
Uruguay	15508	0	1550	331
Venezuela	34672	6	3241	0
Total	723869	6	69964	10093

Table B.5. Production of biomass energy in Latin America by country in 2025, assuming 10% of available non-crop, non-forest, non-wilderness area (including "spare cropland") is planted with biomass, and assuming biomass production as a function of precipitation as given in Fig. 4. National average annual precipitation is used for each country.

Country	Energy Crop Area (thousand ha)	Assumed Precipitation (mm/yr)	Eucalyptus Yield (tonnes/ha-yr)	Primary Energy (PJ)
Barbados	0	1277	19.2	0
Belize	120	1889	29.0	69
Costa Rica	253	1798	27.5	139
Cuba	0	1224	18.4	0
Dominican Rep	161	1295	19.5	63
El Salvador	95	1778	27.2	51
Guatemala	380	1315	19.0	151
Haiti	95	1353	20.5	38
Honduras	405	2440	30.0	243
Jamaica	0	800	11.7	0
Mexico	11858	945	13.9	3317
Nicaragua	485	2032	30.0	291
Panama	358	2540	30.0	214
Trinidad/Tobago	0	1630	24.9	0
Argentina	17471	498	6.9	2405
Bolivia	3710	753	10.9	811
Brazil	15838	1537	23.4	7418
Chile	4148	1258	19.0	1573
Colombia	3998	2600	30.0	2398
Ecuador	1259	973	14.4	363
Guyana	103	1993	30.0	61
Paraguay	1706	1181	17.7	605
Peru	3695	723	10.5	773
Suriname	20	2311	30.0	11
Uruguay	1584	1079	16.1	510
Venezuela	3241	795	11.6	751
Total	70984	-	-	22267

Table B.6. Biomass energy production in 2025 in Latin America on 10% of pasture plus 'other' lands and on 10% of "spare cropland."

Country	Primary Energy from 10% P+O (PJ)	Primary Energy from 10% Spare Crop Land (PJ)	Primary Energy (PJ)
Barbados	0	0	0
Belize	69	0	69
Costa Rica	139	0	139
Cuba	0	0	0
Dominican Rep	63	0	63
El Salvador	51	0	51
Guatemala	151	0	151
Haiti	38	0	38
Honduras	243	0	243
Jamaica	0	0	0
Mexico	3317	0	3317
Nicaragua	291	0	291
Panama	214	0	214
Trinidad/Tobago	0	0	0
Argentina	2303	102	2405
Bolivia	811	0	811
Brazil	7310	108	7418
Chile	1573	6	1573
Colombia	2398	0	2398
Ecuador	363	0	363
Guyana	61.	3	61
Paraguay	605	0	605
Peru	773	0	773
Suriname	12	1	11
Uruguay	500	11	510
Venezuela	752	0	751
Total	22045	222	22267

Appendix C

Detailed Tables Associated with Calculation of Bioenergy Potential in

ASIA

Notes:

- Table C.5 assumes that 10% of available non-crop, non-forest, non-wilderness land is used for biomass energy production (including 10% of "spare" cropland--see text discussion). Figure 10 shows results assuming 5, 10, 15, or 20% of available land is used.

Table C.1. Food needs for Asia by country.

Country	Population in 1990 (thousands)	Population in 2025 (thousands)	Calories Needed / Calories Available	Multiplication of Food Supply
Afghanistan	16556	45832	1.20	3.34
Bahrain	503	1014	1.00	2.02
Bangladesh	113684	223252	1.16	2.28
Bhutan	1539	3395	1.00	2.21
Cambodia	8336	16716	1.03	2.07
China	1153470	1539758	1.00	1.33
Cyprus	702	904	1.00	1.29
India	846191	1393871	1.01	1.66
Indonesia	184283	283318	1.00	1.54
Iran	58267	144625	1.00	2.48
Iraq	18080	46260	1.00	2.56
Israel	4660	8146	1.00	1.75
Japan	123537	127034	1.00	1.03
Jordan	4009	10807	1.00	2.70
Korea, DPR	21771	33339	1.00	1.53
Korea, R	43377	50289	1.00	1.16
Kuwait	2143	2789	1.00	1.30
Lao	4202	9411	1.00	2.24
Lebanon	2740	4476	1.00	1.63
Malaysia	17891	31274	1.00	1.75
Mongolia	2190	4584	1.00	2.09
Myanmar	41825	75604	1.06	1.92
Nepal	19571	40055	1.00	2.05
Oman	1524	4705	1.05	3.25
Pakistan	118122	259562	1.00	2.20
Philippines	62437	105147	1.00	1.68
Qatar	427	731	1.00	1.71
Saudi Arabia	14870	40426	1.00	2.72
Singapore	2710	3309	1.00	1.22
Sri Lanka	17217	24738	1.00	1.44
Syria	12355	35250	1.00	2.85
Thailand	54677	72264	1.00	1.32
Turkey	55991	92881	1.00	1.66
UAE	1589	2792	1.19	2.09
Viet Nam	66688	116958	1.16	2.04
Yemen	11684	34237	1.16	3.41
Total	3109818	4889753	1.01	1.60

Table C.2. Required increase in cropland, 2025 versus 1990, for Asia by country.

Country	Multiplication of Production	Cropland in 1990 (thousand ha)	Cropland Needed in 2025 (thousand ha)	Increase in Cropland (thousand ha)
Afghanistan	3.64	8054	18915	10861
Bahrain	753.79	2	784	782
Bangladesh	2.46	9271	11851	2580
Bhutan	2.46	130	166	36
Cambodia	2.11	3056	3348	292
China	1.35	96615	67856	-28758
Cyprus	2.22	157	181	24
India	1.67	169357	146922	-22434
Indonesia	1.56	21233	17232	-4000
Iran	3.16	14830	24386	9556
Iraq	5.95	5450	16862	11412
Israel	8.04	433	1810	1377
Japan	1.08	4675	2630	-2044
Jordan	15.09	372	2920	2548
Korea, DPR	1.56	1990	1610	-379
Korea, R	1.33	2136	1480	-655
Kuwait	50.94	4	105	101
Lao	2.31	901	1082	181
Lebanon	6.36	301	995	694
Malaysia	2.70	4880	6865	1985
Mongolia	2.03	1359	1436	77
Myanmar	1.91	10035	9953	-81
Nepal	2.06	2600	2783	183
Oman	277.72	48	6934	6886
Pakistan	2.22	20770	24030	3260
Philippines	1.76	7957	7290	-666
Qatar	24.97	5	64	59
Saudi Arabia	4.86	1183	2990	1807
Singapore	1362.79	2	1417	1415
Sri Lanka	1.66	1898	1642	-255
Syria	3.59	5564	10403	4839
Thailand	1.24	21624	13929	-7694
Turkey	1.66	27858	23998	-3859
UAE	90.09	39	1827	1788
Viet Nam	2.03	6592	6975	383
Yemen	9.14	1480	7040	5560
Total	3.25	452861	450733	-2128

Table C.3. Non-agricultural land areas in 1990 in Asia by country.

Country	Pastureland in 1990 (thousand ha)	Forest in 1990 (thousand ha)	'Other' Land in 1990 (thousand ha)	Wilderness in 1990 (thousand ha)
Afghanistan	25412	1609	21393	8740
Bahrain	4	0	62	0
Bangladesh	600	1966	1181	0
Bhutan	200	1929	1261	1179
Cambodia	580	13372	644	0
China	238634	94867	291746	210776
Cyprus	5	123	639	0
India	11814	66176	48811	1161
Indonesia	10932	105091	32139	11761
Iran	39361	16120	77603	15685
Iraq	3323	1570	26916	6477
Israel	148	110	1342	0
Japan	637	25105	7235	0
Jordan	791	71	7660	0
Korea, DPR	50	8970	1031	0
Korea, R	88	6492	1157	0
Kuwait	134	2	1642	0
Lao	784	12645	8311	437
Lebanon	10	80	632	0
Malaysia	24	17380	7816	2844
Mongolia	104613	11751	14794	24131
Myanmar	345	30915	21912	2547
Nepal	1997	2480	6603	0
Oman	775	0	15653	4769
Pakistan	4757	3132	45691	2737
Philippines	1220	10750	9890	0
Qatar	50	0	1045	0
Saudi Arabia	58007	818	87070	67889
Singapore	0	3	56	0
Sri Lanka	439	1747	2379	0
Syria	8166	598	4078	0
Thailand	688	13002	12964	2809
Turkey	8633	20199	20182	0
UAE	153	2	6227	1938
Viet Nam	330	9356	16271	0
Yemen	12400	2408	24802	11706
Total	536109	480845	828846	377586

Table C.4. Non-forest, non-wilderness, non-cropland (i.e., pasture and 'other' lands) in Asia in 1990 by country, percentage of this land required for new cropland in 2025, 10% of remaining pasture plus 'other' lands, and 1990 cropland not needed for crops in 2025 ("spare cropland").

Country	Available Area (thousand ha)	Percent to go to New Crop Land	10% of Remaining Pasture+ OtherLand in 2025	Spare Crop Land (thousand ha)
Afghanistan	46805	15	3962	0
Bahrain	66	1185	0	0
Bangladesh	1781	144	0	0
Bhutan	1461	2	142	0
Cambodia	1224	23	93	0
China	530381	0	53038	28758
Cyprus	644	3	61	0
India	60625	0	6062	22434
Indonesia	43071	0	4307	4000
Iran	116964	8	10740	0
Iraq	30239	37	1882	0
Israel	1490	92	11	0
Japan	7872	0	787	2044
Jordan	8451	30	590	0
Korea, DPR	1081	0	108	379
Korea, R	1245	0	124	655
Kuwait	1776	6	167	0
Lao	9096	2	891	0
Lebanon	642	108	0	0
Malaysia	7840	25	585	0
Mongolia	119407	0	11932	0
Myanmar	22257	0	2225	81
Nepal	8600	2	84	0
Oman	16429	42	954	0
Pakistan	50448	6	4718	0
Philippines	11110	0	1111	666
Qatar	1095	5	103	0
Saudi Arabia	145078	1	14327	0
Singapore	56	2528	0	0
Sri Lanka	2818	0	281	255
Syria	12244	39	740	0
Thailand	13653	0	1365	7694
Turkey	28815	0	2881	3859
UAE	6380	28	459	0
Viet Nam	16601	2	1621	0
Yemen	37202	14	3164	0
Total	1364956	0	129515	70825

Table C.5. Production of biomass energy in Asia by country in 2025, assuming 10% of available non-crop, non-forest, non-wilderness area (including "spare cropland") is planted with biomass, and assuming biomass production as a function of precipitation as given in Fig. 4. National average annual precipitation is used for each country.

Country	Energy Crop Area (thousand ha)	Assumed Precipitation (mm/yr)	Eucalyptus Yield (tonnes/ha-yr)	Primary Energy (PJ)
Afghanistan	3962	248	2.9	230
Bahrain	0	76	0.2	0
Bangladesh	0	1879	28.8	0
Bhutan	142	2286	30.0	85
Cambodia	93	1397	21.2	39
China	55914	829	12.1	13587
Cyprus	62	381	5.0	6
India	8306	2325	30.0	4983
Indonesia	4707	2841	30.0	2824
Iran	10741	266	3.2	683
Iraq	1883	237	2.7	102
Israel	11	567	8.0	1
Japan	992	1498	22.8	452
Jordan	590	279	3.4	40
Korea, DPR	146	924	13.6	39
Korea, R	190	1305	19.7	74
Kuwait	167	129	1.0	3
Lao	891	1714	26.2	467
Lebanon	0	891	13.1	0
Malaysia	585	2440	30.0	351
Mongolia	11933	195	2.0	491
Myanmar	2234	2829	30.0	1340
Nepal	842	1427	21.7	364
Oman	954	99	0.5	9
Pakistan	4719	435	5.8	554
Philippines	1177	2026	30.0	706
Qatar	103	76	0.2	0
Saudi Arabia	14327	77	0.2	53
Singapore	0	3903	30.0	0
Sri Lanka	307	2344	30.0	184
Syria	740	256	3.0	44
Thailand	2134	1468	22.3	952
Turkey	3267	1546	23.6	1539
UAE	459	106	0.6	5
Viet Nam	1621	1873	28.7	932
Yemen	3164	74	0.1	8
Total	137369	-	-	31164

Table C.6. Biomass energy production in 2025 in Asia on 10% of pasture plus 'other' lands and on 10% of "spare cropland."

Country	Primary Energy from 10% P+O (PJ)	Primary Energy from 10% Spare Crop Land (PJ)	Primary Energy (PJ)
Afghanistan	230	0	230
Bahrain	0	0	0
Bangladesh	0	0	0
Bhutan	86	0	85
Cambodia	39	0	39
China	12888	699	13587
Cyprus	6	0	6
India	3637	1346	4983
Indonesia	2584	240	2824
Iran	684	0	683
Iraq	102	0	102
Israel	2	0	1
Japan	359	93	452
Jordan	40	0	40
Korea, DPR	29	10	39
Korea, R	49	26	74
Kuwait	3	0	3
Lao	468	0	467
Lebanon	0	0	0
Malaysia	351	0	351
Mongolia	491	0	491
Myanmar	1335	5	1340
Nepal	365	0	364
Oman	10	0	9
Pakistan	554	0	554
Philippines	666	40	706
Qatar	0	0	0
Saudi Arabia	53	0	53
Singapore	0	0	0
Sri Lanka	169	15	184
Syria	45	0	44
Thailand	609	343	952
Turkey	1358	182	1539
UAE	6	0	5
Viet Nam	932	0	932
Yemen	9	0	8
Total	28164	2999	31164