Feasibility of Large-Scale Biofuel Production

Mario Giampietro; Sergio Ulgiati; David Pimentel


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Does an enlargement of scale change the picture?

Mario Giampietro, Sergio Ulgiati, and David Pimentel

Biofuels are widely seen as a feasible alternative to oil. Indeed, in 1995 the Clinton Administration proposed amendments to the Clean Air Act that would require gasoline sold in the nine most polluted US cities to contain additives from renewable sources, such as grain alcohol. This move, even if blocked by a three-judge panel of the US Court of Appeals in Washington, DC (Southerland 1995), has helped to focus attention on the question of whether research and development in biofuel production from agricultural crops should be increased (e.g., Abelson 1995). In Europe, similar fiscal and regulatory provisions have already been introduced (Chartier and Savanne 1992, Sourie et al. 1992). These policies assume that biofuels have the potential to reduce current dependence of industrialized societies on rapidly disappearing fossil energy stocks and that biofuels are desirable from an ecological point of view. But are these assumptions correct?

Although abundant scientific literature is available on various biofuel production techniques, attempts to provide a comprehensive evaluation of large-scale biofuel production as an alternative to fossil energy depletion are few and controversial. The complexity of the assessments involved and ideological biases in the research of both opponents and proponents of biofuel production make it difficult to weigh the contrasting information found in the literature. Moreover, the validity of extrapolating results obtained at the level of the individual biofuel plant or farm to entire societies or ecosystems has rarely been explicitly addressed in the literature. In this article, we attempt to provide such a comprehensive assessment of the feasibility of large-scale biofuel production by critically reviewing the existing biofuel literature from a broad perspective.

What are biofuels?

A biofuel is any type of liquid or gaseous fuel that can be produced from biomass substrates and that can be used as a (partial) substitute for fossil fuels. Common examples are ethanol, methanol, and biodiesel. Ethanol alcohol can be obtained by yeast- or bacteria-mediated fermentation of sugar crops, such as sugar-cane, sugarbeet, and sweet sorghum, or of starchy crops, such as corn and cassava. It can also be obtained, albeit at lower yields, from cellulose, a sugar polymer from woody crops, through acid or enzymatic hydrolysis followed by fermentation. Methanol can be obtained from wood or woody crops by means of a wood gasification process followed by compression and methanol synthesis (Ellington et al. 1993, Wyman et al. 1993). Finally, biodiesel fuels can be obtained from oil crops, such as soybean, rapeseed, sunflowers, and palms, by extracting the oil with suitable solvents or through mechanical pressing and then converting the oil into diesel fuel by a transesterification process (Shay 1993).

Ethanol is a good substitute for gasoline in spark-ignition engines (Marrow et al. 1987, Parisi 1983); methanol can also be used as a substitute for gasoline. Of course, existing vehicles cannot run on 100% ethanol or methanol fuel unless engines are modified substantially. However, gasoline and biofuel mixtures in a proportion of 85% and 15%, respectively, can be used with only minor adjustments to the engine. Performance tests indicate that biodiesel can be a good substitute for diesel oil in compression-ignition engines (Shay 1993).

Research is still in progress to improve the chemical and industrial...
Table 1. Typical biofuel production systems from agricultural crops.

<table>
<thead>
<tr>
<th>Indicators of performance</th>
<th>Biodiesel†</th>
<th>Ethanol in temperate areas</th>
<th>Ethanol in (sub)tropical areas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross energy yield (GJ · ha⁻¹ · yr⁻¹)</td>
<td>20–40</td>
<td>40–80</td>
<td>800–1300</td>
</tr>
<tr>
<td>Net energy yield (GJ · ha⁻¹ · yr⁻¹)</td>
<td>&lt;0–10</td>
<td>&lt;0–30</td>
<td>500–700</td>
</tr>
<tr>
<td>Output-input energy ratio</td>
<td>0.6–1.3</td>
<td>0.5–1.7</td>
<td>3.0–2.5</td>
</tr>
<tr>
<td>Net to gross ratio (F₁/F₁)</td>
<td>&lt;0–0.2</td>
<td>&lt;0–0.4</td>
<td>0.66–0.60</td>
</tr>
<tr>
<td>Water requirement (t · ha⁻² · yr⁻¹)</td>
<td>4000–7000</td>
<td>4000–8000</td>
<td>10,000–15,000</td>
</tr>
<tr>
<td>Energy throughput (net MJ/h)</td>
<td>&lt;0–250</td>
<td>&lt;0–1000</td>
<td>250–1600</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Best-performing system</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Oilseed rape</td>
<td></td>
<td>corn-sorghum</td>
<td>sugarcane</td>
</tr>
<tr>
<td>Land requirement (ha/net GJ)</td>
<td>0.100</td>
<td>0.033</td>
<td>0.020–0.014</td>
</tr>
<tr>
<td>Water requirement (t/net GJ)</td>
<td>500</td>
<td>170</td>
<td>200–200</td>
</tr>
<tr>
<td>Labor requirement (h/net GJ)</td>
<td>4</td>
<td>1</td>
<td>4–0.6</td>
</tr>
</tbody>
</table>

†Trans-methylester from oil seeds (sunflower, rapeseed, or soybeans). Sunflower and soybean systems have net energies close to or less than zero.

Low-input production, as in the Brazilian ProAlcohol Project (Giampietro et al. 1997a).

High-input production, as reported in Pimentel et al. (1997b).

- The ratio between net and gross biofuel production. Large-scale biofuel production must fulfill the obvious condition that the energy-yield ratio (or output-input ratio) of the entire process be higher than unity; otherwise, biofuel will not be a feasible alternative to oil. In Figure 1, this condition means that F₁ > (F₂ + F₃ + F₄), where F₁ is the amount of biofuel output generated in the production process and F₂, F₃, and F₄ are the various energy inputs required by the process in the form of fuel energy. In addition, the ratio between the gross output of biofuel (F₁) and the fuel consumed in the process (F₂ + F₃ + F₄) must be sufficiently high to prevent an excessive demand of land and labor per unit of net fuel delivered to society. What is considered sufficiently high depends on land and labor constraints. For example, when the output-input energy ratio (F₁/ [F₂ + F₃ + F₄]) equals 1.5, the ratio between net (F*) and gross output (F₁) of biofuel (F*/F₁) is 0.33. That is, the net supply of 1 L of biofuel to society requires a gross production of 3 L of biofuel. When the output-input energy ratio is only 1.2, the ratio between net and gross output of biofuel (F*/F₁) is 0.16, and consequently, the net supply (F*) of 1 L of biofuel requires a gross biofuel production (F₁) of 6 L. Therefore, a reduction of 20% in the output-input energy ratio, from 1.5 to 1.2, doubles the land, water, and labor demand per unit of fuel delivered to society.

- Difference in quality of energy outputs. In most biofuel production systems, the residues (e.g., the straw that is left after harvesting grain crops) and/or byproducts (e.g., the soybean cakes left after pressing oil)
of the energy crop can be recovered and used in some fashion. The gross energy content of these residues or byproducts (H in Figure 1) is frequently accounted for as an output in the energy balance of the biofuel production process and then simply added to the biofuel energy produced (e.g., Da Silva et al. 1978, Stout 1990, TRW 1980). This accounting method obviously increases the calculated overall energy efficiency of the process, but it is misleading because ethanol, residues, and byproducts differ in quality.

Differences in energy quality of fuels relate to one or more of the following characteristics of the fuels: their thermodynamic properties, such as the characteristics defined by exergy analysis (Ahern 1980, Pillet et al. 1987); their technical convenience, such as transportability, homogeneity for handling, and available devices for energy conversion; and the types of emission (especially of particulates) after combustion. For example, the quality of a fuel delivered to society in the form of straw residues is much lower than that of liquid biofuel endproducts, such as ethanol, because of a lower score on all three characteristics.

A similar problem exists with the accounting of byproducts, such as soybean and sunflower cakes, that have other, nonfuel uses, such as animal feed. It is misleading to add the energy content of these byproducts, or the fossil energy that would have been required to produce an equivalent amount of animal feed, to the liquid biofuel energy output because liquid biofuels and animal feed are simply different things.

Indeed, in large-scale biofuel production, byproducts should be considered a serious waste disposal problem (and, most probably, an energy cost) rather than a positive event in terms of energy output. For example, to supply 10% of the energy consumption of the United States (325 GJ per capita per year), large-scale production of ethanol fuel would generate approximately 3.7 t of distiller’s dark grains, the byproduct of ethanol production from corn and sorghum (0.83 kg/L ethanol), per capita per year (TRW 1980). This quantity of byproduct is more than 37 times the 98.5 kg of commercial livestock feed that is used per capita per year in the United States (USDA 1992).

Finally, certain energy inputs in the process of biofuel production, such as the energy needed for the construction of the machinery and plant (F2 in Figure 1), require high-quality liquid fuel; low-quality fuels, in the form of residues or byproducts, cannot be used. These energy inputs must therefore be subtracted from the gross flow of liquid fuel (F1) that is produced for society.

- The energy costs of using byproducts. Although the energy content of byproducts is readily accounted for in the gains of the biofuel production process, the costs involved in recovering and using the byproducts (F3 in Figure 1), such as labor and energy requirements to harvest, dry, bale, transport, store, and prepare agricultural byproducts for the burner (e.g., briquetting), are generally ignored. Similarly, losses in energy value of byproducts due to changes in moisture content and their decay during storage are neglected. These costs and losses deserve more attention because they can seriously affect the convenience of large-scale use of biomass in terms of energy, economics, and labor.
- Accounting for inputs in energy crop production. The assessment of energy demand in the agricultural production of the energy crop used to generate biofuel (F4 in Figure 1) is another source of controversy. Nitrogen fertilizer or other inputs with large embodied energy costs are sometimes omitted or underestimated in the assessment of agricultural energy consumption in biofuel production systems. Clearly, however, overlooking the high energy demand of nitrogen fertilizer input increases the apparent efficiency of biofuel production. Even when no nitrogen fertilizer is applied, energy crop production depends on crop rotation or leaving land fallow, or it depletes nutrient stocks in the soil. In these cases, one must either account for the area used in rotation or left fallow in terms of an increased land requirement or somehow directly account for the difference between the nitrogen taken out with the harvested biomass and the naturally occurring nitrogen fixation in the soil during the period of the crop cycle. For example, nitrogen in the amount of approximately 180 kg/ha is removed from the soil when harvesting sugarcane (Helsel 1992), only approximately one-sixth of the quantity of nitrogen fixed by natural processes.
- Yields and conversions used in the assessment. Yields and conversion factors used to evaluate large-scale biofuel production should refer to real research or commercial data and, as is often found, to theoretical conversions, maximum achievable yields, or exceptional results obtained in experimental plots. Certainly, assumptions and models about possible future improvements in biofuel production technology deserve attention. However, starting with an overall assessment of the process in

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**Figure 1. Biofuel production cycle.** See text for details. B = biomass processed for fuel production; Q = energy content of biomass feedstock processed for fuel (Q = B × e, where e = energy content per unit of biomass); R = crop residues; R* = harvested crop residues used as energy source in the conversion process; H = energy input from residues (H = R* × heat content of residues); F1 = gross biofuel production; F2 = biofuel equivalent for energy inputs other than residues used in the conversion process; F3 = biofuel equivalent for energy inputs used in harvesting and processing residues; F4 = biofuel equivalent for energy inputs used in agricultural production; and F* = net biofuel output accessible to society (F* = F1 – F2 – F3 – F4).
real terms helps to place such assumptions in a more realistic context. For example, the maximum yield in the literature for sugar from sugarcane is 15.7 t/ha (Buringh 1987). As noted by Buringh, such a value has little to do with the average yield of sugar from sugarcane currently obtained worldwide, which is less than 6 t/ha. Moreover, large-scale production of energy crops will undoubtedly result in an expansion of energy crop monocultures, which could ultimately reduce yields because of increased pest problems, diseases, and soil degradation. The approach followed by many biofuel proponents—that is, starting with maximum achievable crop yields multiplied by theoretical conversions that are assumed to be achievable in the near future—is unlikely to provide sound data for policy decisions.

* Accounting for labor in the assessment. In contrast to most studies, we consider labor not as an energy input but rather as another crucial parameter that is needed to examine whether the proposed biofuel system is compatible with the present socioeconomic structure of society. On the basis of data for the labor requirement in the energy sector per unit of net energy delivered to society, we assess the aggregate labor requirement of a hypothetical energy sector based on biofuel and compare this value to the labor that is available for the energy sector, given the present socioeconomic characteristics of society (Giampietro et al. 1993, 1996b). We assume that the energy cost of supporting humans in society is already accounted for by the requirement of energy consumption per capita at the societal level.

From small- to large-scale assessments

The performances of three of the most common types of biofuel systems from agricultural crops are summarized in Table 1. These three systems are biodiesel production from oilseed crops, ethanol production from crops grown in temperate areas, and ethanol production from crops grown in tropical and subtropical areas. The ranges of values listed for these systems are based on biophysical inputs and outputs reported in the literature for variants of these three biofuel systems. Values found in the literature have been standardized by using a single set of energy equivalents for the biophysical inputs and outputs instead of the original conversion factors, which differed among the various studies. A critical appraisal of the assessments found in the literature is provided elsewhere (Giampietro et al. 1997a). The performances in Table 1 do not include energy costs for pollution control nor long-term energy costs to offset soil erosion because the relevant data are not available. We address these factors in a subsequent section.

The performances of the biofuel systems are evaluated on the basis of the ratio of net to gross energy yield (F*IF1 in Figure 1) and the requirements of arable land, fresh water, and labor per unit of net energy delivered. The assessments are derived from data at the individual farm or biofuel production plant level. To extrapolate to a larger scale, we need to consider the impact of the production system on the larger ecosystem and the compatibility of the production system with the socioeconomic system in which the biofuel production takes place. Both aspects of the production system can be evaluated on the basis of the demand for environmental services (environmental loading) and labor requirement per unit of energy delivered.

Including the ecosystem. On a small scale, it is virtually impossible to define an environmental loading for a biofuel production system per unit of net energy delivered. Environmental loading is, by definition, scale dependent: How many plants are operating in a particular area? How big are the production plants? What are the thresholds for economies of scale and decreasing returns of a biofuel energy system? Moreover, when the scale of biofuel production is enlarged, pollution, soil erosion, and other adverse environmental impacts can exhibit nonlinear behavior. So far, studies on the environmental impacts of biofuel production have focused on immediate environmental effects, such as the effluents of ethanol plants as potential sources of pollution (e.g., Bevilacqua et al. 1981, Hunsaker et al. 1989).

Pollution by effluents. Distillery waste, the principal component of effluent from ethanol plants, has a biological oxygen demand (a standard measure of pollution) after five days (BOD) of 1000–78,000 mg/L and hence poses a serious waste disposal problem (de Bazúa et al. 1991, Frings et al. 1992, Hunsaker et al. 1989, Mishra 1993). Approximately 10–14 L of stillage waste (distillery waste) are generated per liter of gross production of ethanol (F1). This value is not affected by the type of biomass used in the fermentation because it relates to the amount of liquid removed during the distillation from the fermented broth, and the level of alcohol cannot be raised due to physiological limits: a higher concentration of alcohol will inhibit the yeast (Coble et al. 1985).

In tropical Brazil, the effluent problem is already evident. A Brazilian distillery producing ethanol from sugarcane in the amount of 300,000 L/d (actually 261,000 L/d, given that F*/F1 = 0.84), which is the equivalent of the energy consumed by approximately 40,000 Brazilians (Table 2), releases a pollution load that is equivalent to the domestic sewage of a city of 2 million people (assuming a sewage load of approximately 70,000 mg BOD5 per person per day; Rosillo-Calle 1987).

Things are much worse when ethanol fuel is produced in temperate areas, where the F*/F1 ratio is lower (Table 1). For example, if F*/F1 = 0.34, the delivery of one net liter of ethanol (F*) implies the production of 2.94 L ethanol at the plant (F1) and hence a production of approximately 38 L stillage. Under these conditions, the 325 GJ of commercial energy used per US citizen per year (Table 2), which is equivalent to more than 15,000 L ethanol (F*), would imply the generation of approximately 1500 kg of stillage per US citizen per day. In this way, each American would daily generate the pollution equivalent of the sewage of more than 800 people, assuming the same sewage load of 70,000 mg BOD5 per capita per day.

The energetic cost of treating this pollutant is significant and should be included in the assessment of energy inputs in the biofuel production process. However, none of the stud-
the demand for land and water that
Japan
Table

<table>
<thead>
<tr>
<th>Country</th>
<th>Commercial energy consumption (GJ/yr)*</th>
<th>Arable land available (ha)</th>
<th>Fresh water withdrawal (t/yr)*</th>
<th>Land demand for biofuel (ha)</th>
<th>Water demand for biofuel (t/yr)</th>
<th>Total arable land demand/ supply ratio</th>
<th>Biofuel water demand/current withdrawal ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burundi</td>
<td>8</td>
<td>0.20</td>
<td>20</td>
<td>0.16</td>
<td>1600</td>
<td>1.8</td>
<td>80</td>
</tr>
<tr>
<td>Egypt</td>
<td>21</td>
<td>0.05</td>
<td>1028</td>
<td>0.42</td>
<td>4200</td>
<td>9.4</td>
<td>4</td>
</tr>
<tr>
<td>Ghana</td>
<td>6</td>
<td>0.08</td>
<td>35</td>
<td>0.12</td>
<td>1200</td>
<td>2.5</td>
<td>34</td>
</tr>
<tr>
<td>Uganda</td>
<td>8</td>
<td>0.28</td>
<td>20</td>
<td>0.16</td>
<td>1600</td>
<td>1.4</td>
<td>80</td>
</tr>
<tr>
<td>Zimbabwe</td>
<td>31</td>
<td>0.29</td>
<td>136</td>
<td>0.62</td>
<td>6200</td>
<td>2.9</td>
<td>46</td>
</tr>
<tr>
<td>Argentina</td>
<td>66</td>
<td>0.81</td>
<td>1042</td>
<td>1.32</td>
<td>13,200</td>
<td>2.1</td>
<td>13</td>
</tr>
<tr>
<td>Brazil</td>
<td>49</td>
<td>0.40</td>
<td>245</td>
<td>0.98</td>
<td>9800</td>
<td>3.0</td>
<td>40</td>
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<tr>
<td>Canada</td>
<td>437</td>
<td>1.75</td>
<td>1688</td>
<td>14.42</td>
<td>74,300</td>
<td>8.7</td>
<td>44</td>
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<td>Costa Rica</td>
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<td>780</td>
<td>0.70</td>
<td>7000</td>
<td>8.0</td>
<td>9</td>
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<tr>
<td>Mexico</td>
<td>54</td>
<td>0.27</td>
<td>921</td>
<td>1.78</td>
<td>9200</td>
<td>7.6</td>
<td>10</td>
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<tr>
<td>United States</td>
<td>325</td>
<td>0.76</td>
<td>1868</td>
<td>10.72</td>
<td>55,200</td>
<td>14.6</td>
<td>30</td>
</tr>
<tr>
<td>Bangladesh</td>
<td>3</td>
<td>0.08</td>
<td>212</td>
<td>0.06</td>
<td>600</td>
<td>1.8</td>
<td>3</td>
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<tr>
<td>China</td>
<td>25</td>
<td>0.08</td>
<td>462</td>
<td>0.50</td>
<td>5000</td>
<td>7.2</td>
<td>11</td>
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<tr>
<td>India</td>
<td>12</td>
<td>0.20</td>
<td>612</td>
<td>0.24</td>
<td>2400</td>
<td>2.2</td>
<td>4</td>
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<tr>
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<td>134</td>
<td>0.03</td>
<td>732</td>
<td>4.42</td>
<td>22,800</td>
<td>148.3</td>
<td>31</td>
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<tr>
<td>France</td>
<td>163</td>
<td>0.32</td>
<td>778</td>
<td>5.38</td>
<td>27,700</td>
<td>17.6</td>
<td>36</td>
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<tr>
<td>Italy</td>
<td>113</td>
<td>0.16</td>
<td>996</td>
<td>3.73</td>
<td>19,200</td>
<td>24.3</td>
<td>19</td>
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<tr>
<td>Netherlands</td>
<td>202</td>
<td>0.06</td>
<td>994</td>
<td>6.66</td>
<td>34,300</td>
<td>112.0</td>
<td>34</td>
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<td>6.5</td>
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<tr>
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<td>0.12</td>
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<td>5.11</td>
<td>26,300</td>
<td>43.6</td>
<td>104</td>
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<tr>
<td>Australia</td>
<td>216</td>
<td>2.90</td>
<td>1306</td>
<td>3.02</td>
<td>43,200</td>
<td>1.5</td>
<td>33</td>
</tr>
</tbody>
</table>

*Data from UN (1991).
*Data from WRI (1992).
*Referring to low-input sugarcane system (Table 1).
*Referring to corn—sweet sorghum system (Table 1).
*Referring to high-input sugarcane system (Table 1).

The total arable land demand equals the biofuel land demand plus the arable land for food security. The demand for arable land for biofuel production was obtained by dividing the energy consumption per capita (GJ/yr) by the land demand (ha/GJ) of the biofuel energy system under consideration. For countries that depend heavily on food imports (all countries with less than 0.5 ha arable land per capita), the arable land demand for food production is assumed to be equal to the entire arable land in the country. For net food-exporting countries, we estimated the demand for arable land for food production on the basis of the ratio between food exports and internal consumption: 80% of total arable land in France, Uganda, and Zimbabwe, and 50% in Argentina, Australia, Brazil, Canada, and the United States.

ies we examined provided data on this energy cost and it is, therefore, not included in the performances listed in Table 1. Nevertheless, some idea of the magnitude of the energy costs can be obtained. Assuming a BOD₅ of approximately 30,000 mg/L (typical of distillery waste), 1 kg of BOD₅ must be removed per liter of net biofuel produced. With an approximate cost of 1 kWh per kg of BOD₅, removed (Troshib 1992), the cost of controlling the pollution generated by one net liter of ethanol produced would be 10.5 MJ (1 megajoule = 10⁶ joules) of fuel equivalent, or approximately 50% of the energy supplied per liter of ethanol.

Including this cost among the inputs in the biofuel production process significantly decreases the estimated F₁/F₀ ratio and dramatically increases the demand for land and water that is reported in Table 1.

Because none of the known ethanol systems can afford to spend 50% of their net output in pollution control, intensive wastewater treatment is never considered in the literature as a method for dealing with the stillage waste that is generated by the biofuel production process. Instead, environmentally friendly alternatives are usually proposed, such as concentrating stillage for use as animal feed, using stillage as fertilizer, or recovering methane from anaerobic fermentation of stillage. However, little or no reliable information exists on the feasibility of these alternative solutions on a large scale (e.g., their energy costs and labor demand). As noted earlier, the supply of byproducts for use as animal feed from large-scale biofuel production would far outweigh demand. As for using stillage as fertilizer or recovering methane from it, any handling of wastewater from stillage will increase the demand for both high-quality energy and human labor, ultimately lowering the F₁/F₀ ratio. That is, it will increase the demand for land, fresh water, and labor per unit of energy delivered by such a biofuel system.

**Energy crop production.** Long-term implications for the agroecosystem cultivated for fuel crops are seldomly addressed in assessments of the performance of biofuel systems, even though a rough idea of the size of the problem can easily be obtained. The commercial energy consumed per US citizen is approximately 325 GJ/yr. The best-performing biofuel system for temperate areas, ethanol produced from corn and sorghum (Table 1) would require 11.7 ha of fuel cropland per capita to generate sufficient ethanol fuel to meet annual commercial energy demand. This amount is more than 15 times the arable land currently available per US citizen. Assuming an average pesticide consumption of 3.5 kg/ha (for corn) and 2 kg/ha (for sweet sorghum), such a biofuel production system would result in the use of approximately 31 kg of pesti—
I-, 1, round water— all of which are al-
ure 2) of the energy throughput con-
including its costs in any analysis of
process may dramatically increase the
energy input in the biofuel production
is among the highest in the world, and
erosion rate (La1 1995). Soil erosion
ethanol system that is considered in
favorable performance of the tropical
biofuel production would reduce the
increase in energy demand of approxi-
ately 6000 MJ/ha to produce the
soil eroded, which represents an in-
crease in the primary sectors of the economy
in 21 countries

Indeed, a correlation analysis (Fig-
ure 2) of the energy throughput con-
sumed by society per hour of labor in the
primary sectors of the economy and 24 classic indicators of socio-
economic development for a sample
of more than 100 countries has con-
firmed this trend (Pastore et al. 1996).

The western standard of living is
based on a throughput (at the level of society) of more than 500 MJ
of commercial energy per hour of labor in the primary sectors of the
economy. Given that the work sup-
ply in the energy sector of industrial-
ized countries is generally less than
5% of the work force in the primary
economic sectors, it is evident that
the energy sector needs to achieve an
energy throughput in the order of
10,000 MJ per hour of labor. For
example, in Italy, with a population
of 57 million, only 7.3% of the total
499 billion hours of human time
available were spent doing paid work
in 1991. Of this yearly labor supply,
60% was absorbed by the service
sector, 30% by the industrial sector,
and 9% by agriculture, fishery, and
forestry, leaving a tiny 1%, or 360
million labor-hours, to run the en-
tire energy sector (ISTAT 1992).

Total energy consumption in Italy
that year was 6,500,000 TJ (1
terajoule = 10^12 joules), implying that
in 1991 the Italian energy sector de-
ivered almost 18,000 MJ of energy
throughput per hour of labor in that
sector. This throughput was achieved
with the almost exclusive use (more
than 90%) of fossil energy sources.

Thus, a developed society requires
that the energy throughput per hour
of labor in the energy sector range
to 10,000 to 20,000 MJ/h. These
levels are well beyond the range of
values achievable with biofuel, that
is, 250-1600 MJ/h (Table 1). This
mismatch is the primary reason why
processes of biofuel generation, so
optimistically assessed in feasibility
studies, do not pass the economic
test in the real world.

Large-scale biofuel production
in 21 countries

An evaluation of large-scale biofuel
production, including both socioeco-
nomic and ecological constraints,
requires that the characteristics of the
biofuel system be checked against

Figure 2. Correla-
tions between Bio-
Economic Pressure
(BEP) and several
indicators of socioeco-
nomic development.
BEP is defined as the
ratio between the to-
tal energy consumed
by a society in a year
(in megajoules) di-
vided by the total
amount of working
time in the same year
(in hours). BEP should
be considered a con-
straint derived from
the socioeconomic characteristics of a society on the feasibility of production

(cide per capita per year, or a total of
more than 8 million metric tons. This
amount is almost 20 times the current
use of pesticide in the United States.

Moreover, the expansion of mono-
cultures that would be required to
obtain the high yields necessary for
economic viability of the biofuel sys-
tem is likely to aggravate problems
of soil erosion, pollution from nutrient
leaching, and overdraft of under-
ground water—all of which are al-
ready threatening current food
supplies (Ehrlich et al. 1993, Kendall
and Pimentel 1994, Pimentel et al.
1995). For instance, soil erosion rates
for corn and sunflower, both row
crops grown on 2-5% sloping land,
are approximately 20 t·ha^-1·yr^-1,
assuming that the corn residues stay
on the land. Approximately 4 kg of
nitrogen are lost per ton of fertile
soil eroded, which represents an in-
crease in energy demand of approxi-
ately 6000 MJ/ha to produce the
equivalent amount of fertilizer. In ad-
dition, at least 2 kg of phosphates and
410 kg of potassium are lost with this
soil. The removal of crop residues
(e.g., straw) from the fields for use as
energy input in the biofuel production
process may dramatically increase the
erosion rate (Lal 1995). Soil erosion
associated with sugarcane production
is among the highest in the world, and
including its costs in any analysis of
biofuel production would reduce the
favorable performance of the tropical
ethanol system that is considered in
Table 1. For instance, Edwards
(1993) reports erosion rates of 380 t·
ha^-1·yr^-1 on cane fields in Australia,
and rates of 150 t·ha^-1·yr^-1 are not
uncommon.

Yet another agronomic implica-
tion of fuel crop monocultures is an
adverse impact on biodiversity. Clearly,
hypothesizing a smaller fraction
of energy coverage by biofuel
(e.g., 15% of total energy consump-
tion) would reduce this and other
effects on agroecosystems, but the
picture would still be gloomy.

Including the socioeconomic system.
To analyze the compatibility of a
biofuel energy system with the charac-
teristics of the society, we examined
energy consumption at the societal
level per unit of labor in the primary
sectors of the economy—in particular,
the energy sector. The energy sector is
defined as that part of the economy
that performs all activities involved in
supplying energy to society—that is,
procuring, processing, and distrib-
uting energy (Holdren 1982).

Technological development of a
society accelerates energy through-
put in the primary sectors of the
economy because it increases the
average per capita consumption of
energy (from less than 1 GJ/yr in de-
veloping countries to approximately
305 GJ/yr in the United States) and
decreases the percentage of total
human time that is allocated to work
in the primary sectors of the economy
(from 10% in poor developing coun-
tries to 4% in developed countries;
Giampietro et al. 1997b, Pastore et
al. 1996). The latter change results
from an absorption of labor by the
expanding service sector and a re-
duction in the labor supply due to
progressive aging of the population,
a longer education period, and a
lighter work load for the labor force.

Indeed, a correlation analysis (Fig-
ure 2) of the energy throughput con-
sumed by society per hour of labor in the
primary sectors of the economy and 24 classic indicators of socio-
3

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Table 3. Labor demand in large-scale biofuel production compared to potential labor supply.

<table>
<thead>
<tr>
<th>Country</th>
<th>Commercial energy consumption (10^6 GJ/yr)*</th>
<th>Total population (10^6)</th>
<th>Total labor force (as percentage of population)*</th>
<th>Potential labor supply (10^6 h/yr)*</th>
<th>Biofuel labor demand (10^6 h/yr)</th>
<th>Biofuel labor demand (as percentage of supply)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burundi</td>
<td>42</td>
<td>5.3</td>
<td>55.5</td>
<td>5916</td>
<td>200*</td>
<td>3</td>
</tr>
<tr>
<td>Egypt</td>
<td>1075</td>
<td>51.2</td>
<td>31.6</td>
<td>32,358</td>
<td>4300*</td>
<td>13</td>
</tr>
<tr>
<td>Ghana</td>
<td>88</td>
<td>14.6</td>
<td>45.4</td>
<td>13,230</td>
<td>400*</td>
<td>3</td>
</tr>
<tr>
<td>Uganda</td>
<td>137</td>
<td>17.1</td>
<td>45.6</td>
<td>15,613</td>
<td>550*</td>
<td>3</td>
</tr>
<tr>
<td>Zimbabwe</td>
<td>301</td>
<td>9.7</td>
<td>37.3</td>
<td>7199</td>
<td>1200*</td>
<td>16</td>
</tr>
<tr>
<td>Argentina</td>
<td>2105</td>
<td>31.9</td>
<td>38.0</td>
<td>24,267</td>
<td>8400*</td>
<td>35</td>
</tr>
<tr>
<td>Brazil</td>
<td>7178</td>
<td>146.5</td>
<td>41.9</td>
<td>122,775</td>
<td>28,700*</td>
<td>23</td>
</tr>
<tr>
<td>Canada</td>
<td>11,493</td>
<td>26.3</td>
<td>51.7</td>
<td>27,184</td>
<td>11,500*</td>
<td>42</td>
</tr>
<tr>
<td>Costa Rica</td>
<td>105</td>
<td>3.0</td>
<td>37.7</td>
<td>2232</td>
<td>400*</td>
<td>18</td>
</tr>
<tr>
<td>Mexico</td>
<td>4460</td>
<td>82.6</td>
<td>38.4</td>
<td>63,460</td>
<td>4500*</td>
<td>7</td>
</tr>
<tr>
<td>United States</td>
<td>80,405</td>
<td>247.4</td>
<td>50.9</td>
<td>251,853</td>
<td>80,400*</td>
<td>32</td>
</tr>
<tr>
<td>Bangladesh</td>
<td>332</td>
<td>110.8</td>
<td>30.2</td>
<td>66,923</td>
<td>1350*</td>
<td>2</td>
</tr>
<tr>
<td>China</td>
<td>28,432</td>
<td>1137.3</td>
<td>60.5</td>
<td>1,376,133</td>
<td>113,700*</td>
<td>8</td>
</tr>
<tr>
<td>India</td>
<td>10,032</td>
<td>836.0</td>
<td>39.1</td>
<td>652,947</td>
<td>40,100*</td>
<td>6</td>
</tr>
<tr>
<td>Japan</td>
<td>16,495</td>
<td>123.1</td>
<td>49.8</td>
<td>122,558</td>
<td>16,500*</td>
<td>13</td>
</tr>
<tr>
<td>France</td>
<td>9209</td>
<td>56.5</td>
<td>44.3</td>
<td>50,059</td>
<td>9200*</td>
<td>18</td>
</tr>
<tr>
<td>Italy</td>
<td>6309</td>
<td>57.6</td>
<td>41.7</td>
<td>48,038</td>
<td>6500*</td>
<td>14</td>
</tr>
<tr>
<td>The Netherlands</td>
<td>2990</td>
<td>14.8</td>
<td>55.0</td>
<td>16,280</td>
<td>3000*</td>
<td>18</td>
</tr>
<tr>
<td>Spain</td>
<td>3332</td>
<td>38.3</td>
<td>36.8</td>
<td>28,189</td>
<td>3300*</td>
<td>12</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>8881</td>
<td>57.3</td>
<td>48.3</td>
<td>55,352</td>
<td>9000*</td>
<td>16</td>
</tr>
<tr>
<td>Australia</td>
<td>3650</td>
<td>16.9</td>
<td>47.4</td>
<td>15,974</td>
<td>2200*</td>
<td>14</td>
</tr>
</tbody>
</table>

*Data from UN (1991).
*Data from WRI (1992).
*Data from ILO (1992).
*Assuming a common workload of 2000 h/yr.

the following data: availability of arable land, fresh water, or other limiting natural resources (e.g., nutrient supply) as far as they are used in the biofuel production system; average per capita energy consumption in society; and available supply of labor time and its distribution over the various economic sectors.

We used readily available data for the national level to assess compatibility with large-scale biofuel production, although any other level (e.g., regional or global) for which data are available could also be used for such an evaluation. We chose for the evaluation the best-performing biofuel production system, given climatic conditions, from those presented in Table 1. We also made the assumption that biofuel will be the only energy source in society. The ecological part of the analysis focused on arable land and fresh water constraints, and the socioeconomic part focused on the labor supply for the energy sector.

We evaluated a total of 21 countries; these include both developed and developing countries and both densely and sparsely populated countries. We defined the level of development of a country based on the average per capita consumption of commercial energy: Developed countries have a per capita consumption of more than 100 GJ/yr, and developing countries have a per capita consumption of less than 20 GJ/yr. Densely populated countries were defined as having less than 0.1 ha of arable land per capita, and sparsely populated countries were defined as having more than 0.5 ha of arable land per capita. We further distinguished among countries that are net exporters of food (i.e., Argentina, Australia, Brazil, Canada, France, Uganda, United States, and Zimbabwe) and those that are net food importers (the other 13 countries).

For those developed countries in the sample whose climate is temperate and whose energy throughput per hour of labor is high, we considered the highly mechanized ethanol biofuel system based on corn and sweet sorghum (see the upper value of the performance range listed for ethanol in temperate regions in Table 1). For developing countries, where tropical or subtropical climatic conditions exist and more labor-intensive production is common, we considered ethanol biofuel production based on sugarcane, similar to that developed in Brazil in the ProAlcohol project (Pereira 1983, Rosillo-Calle 1987). We assumed that sweet sorghum, processed in a similar way as sugarcane, can be used in areas where sugarcane cannot be produced.

For biofuel production systems in both developed and developing countries, we used the technical parameters listed in Table 1 for the ethanol biofuel system based on corn and sweet sorghum. These parameters are based on the following optimistic (indeed, unrealistic) assumptions: no soil erosion for the yields of 7500 kg/ha of corn grain and 80,000 kg/ha of sweet sorghum (wet weight of the total biomass; 80% of the weight is water), no major losses of byproducts during storage and transportation, and no energy charge for pollutants generated by this biofuel system.

Ecological side of the analysis. The demand and supply of arable land and fresh water are provided in Table 2 for the 21 selected countries. The data in this table indicate that none of the biofuel technologies considered in our analysis appears even close to being feasible on a large scale due to shortages of both arable land and water for fuel crop production. This conclusion is true for both developed and developing countries.

*The corn grain yield of 7500 kg/ha is dry weight. The corn stover dry weight equals 7500 kg/ha. Thus, the total biomass of corn is 15,000 kg/ha dry weight.
Moreover, the conclusion would be even gloomier if pollution control measures (which would decrease the output-input energy ratio of the production process) or trends in population growth and loss of arable land (which would reduce the available arable land per capita and endanger food security) were included in the analysis.

In addition, the proposed use of arable land to farm for fuel is implicitly based on the hypothesis that sufficient arable land can be spared from food production. Our analysis shows that this hypothesis is unrealistic for large-scale biofuel production. Indeed, many densely populated countries are unable to supply their internal demand for food without relying heavily on fossil energy stocks for the production of fertilizers and pesticides.

**Socioeconomic side.** Table 3 compares the labor demand of the biofueled energy sector and the labor supply available. We estimated the labor supply as the economically active population, as described by the International Labour Office (ILO 1992), but we also included the unemployed. This assumption takes into account the potential positive effect of biofuel production on employment, although it ignores the potential problem that many unemployed people in developed countries may not want to live in rural areas and work in the agricultural activity of producing feedstock for ethanol distillation. In fact, many European countries are currently experiencing both high unemployment (more than 10%) and, at the same time, a shortage of labor supply in the agricultural sector. To express the labor supply in hours, we applied a common workload per worker of 2000 h/yr.

Socioeconomic constraints on large-scale biofuel production are less severe in developing countries than in developed countries (Table 3). For example, if Burundi, Ghana, Uganda, Bangladesh, China, and India only had more arable land, they could fuel the activities of their society with biofuel, because up to 10% of their labor force could be allocated to the energy sector without disturbing the economic process. However, biofuel is a realistic source of energy in these poor countries only because commercial energy demand is low (less than 15 GJ/yr per capita). Given the characteristics of biofuel production (Table 3), however, these countries would have to resort to fossil fuels if they were to undergo rapid economic and technological development. Indeed, an energy system that would improve the socioeconomic condition of developing countries would be one that enables these societies to decrease the percentage of total time allocated to labor (by increasing life expectancy at birth and education), to decrease the labor force in the primary sectors in favor of the service sector, and to increase per capita energy consumption. Conversely, basing the energy sector of a developing country on biofuel means locking that society into a low standard of living (Gianpietro et al. 1993, 1997b). The low density of energy flows, both per hectare and per hour of labor, that can be achieved with biofuel makes a 100% supply of energy by biofuel impossible even in Australia, a developed country with a large amount of arable land per capita, or in Brazil, a sparsely populated country with a relatively low energy consumption per capita.

**Nonlinear behavior of biophysical requirements.** Thus far in this article, we have examined the theoretical feasibility of large-scale biofuel production by multiplying the crop, land, water, and labor demand per unit of net energy delivered in small-scale biofuel systems with the total energy that is consumed in society. We thus arrived at the total requirements for land, water, and labor for a biofueled society.

However, in practice, assessments of requirements for biofuel production turn out to be more complex. The fact that the biofuel production process is an autocatalytic loop—in the sense that a fraction of the biofuel generated by the system must be used to run the biofuel production system itself—implies a nonlinear behavior of land, water, and labor requirements in response to changes in technical coefficients of the production process. Land and water requirements refer to energy consumed in the production of biofuel rather than to energy delivered to society; therefore, these requirements are amplified by an increase of the internal loop of energy use.

Indeed, at a fixed level of energy consumption in society, small fluctuations in the overall output-input energy ratio of the biofuel production process can generate large fluctuations in total biophysical requirements. Such fluctuations are especially likely when the output-input ratio is close to 1.0, as is the case for the vast majority of current biofuel systems. In this situation, any assessment of requirements of land, water, and labor for the biofuel system are unreliable. Small fluctuations in the efficiency of the production process may easily result in the production system running into biophysical constraints (that is, requirements surpass availability). This situation typically occurs when new activities aimed at pollution control are added to the biofuel production system, thus lowering the output-input energy ratio of the overall production process.

**Putting things in perspective.** The country analyses presented in Tables 2 and 3 are not intended to represent an actual scenario of a world that is powered entirely by biofuel, but rather to put the process of large-scale biofuel production in a realistic perspective. Even if we were to adopt different assumptions—for instance, that biofuels will be used to meet only 15% or 30% of the total commercial energy requirement—the nature of the problems indicated by our evaluation of biofuel production requirements would remain more or less the same for developed and developing countries, and for densely and sparsely populated countries.

**Can technological progress change the picture?**

Extensive research has been conducted in the last few decades to improve technological processes to produce biofuels. Excellent reviews have been provided by, among others, the International Energy Agency (IEA 1994), Johansson et al. (1993), Klass (1993), and Wright and Hohenstein (1994). In general, innovations appear to aim at two main
goals: improving the efficiency and speed of the bioconversion process, most notably by direct production of hydrocarbon fuels from biomass, and enabling the use of biomass, such as wood and herbaceous crops, as raw material for biofuel to overcome shortages of arable land. As far as the first goal goes, thermochemical biomass liquefaction is still far from the commercial stage (Stevens 1992). The second goal may be closer to hand. Two potential noncrop candidates appear to be feasible in the medium term (OTA 1993, Wright and Hohenstein 1994): herbaceous energy crops, which are perennial grasses such as switchgrass, and short-rotation woody crops, which typically consist of a plantation of closely spaced (from 2 to 3 m apart on a grid) trees that are harvested on a cycle of 3–10 years. Both herbaceous energy crops and short-rotation woody crops produce large quantities of biomass—straw, wood, bark, and leaves—without the need for intensive human management: The former regrow from the remaining stubble, the latter from the remaining stumps. The produced biomass is composed principally of cellulose and lignin, which can be used as feedstock (raw material) to generate electricity directly or can be converted to liquid fuels or combustible gases (OTA 1993).

Although valuable information on the expected performance of these new biofuel production technologies is available (IEA 1994, Johansson et al. 1993), values for the entire set of parameters required for a comprehensive assessment, such as we have carried out for more established biofuels, are not yet available. In general, published studies do not assess the labor demand and/or all of the biophysical inputs required for the entire production process for these new biofuels. Our analysis of these new technologies is, therefore, limited to general features.

Can woody biomass escape arable land constraints? Methanol production from wood is a relatively new biofuel production system for which data are rapidly becoming available. This system is considered to be promising because methanol production from wood may avoid the dilemma of whether to grow food or energy crops when arable land is a limiting factor. The (nonarable) land requirement for a methanol/wood biofuel system depends on the yield of wood biomass per hectare of land and on the efficiency of the process by which wood biomass is converted into methanol (F1/Q). At present, wood biomass production systems can be classified into conventional wood production, with low yields per hectare, and short-rotation woody crops, with high yields per hectare.

In conventional wood production, a harvest of 2500 kg·ha⁻¹·yr⁻¹ (considering the entire area in rotation) would be ecologically compatible and achievable without external inputs where water is not a limiting factor. Based on data for the conversion of wood into methanol (Ellington et al. 1993), conventional wood production delivers a net density of methanol to society (F* in Figure 1) of 12.2 GJ·yr⁻¹·ha⁻¹ (Table 4). To put this number in perspective, if the 325 GJ of energy required per US citizen per year were to be produced exclusively by this biofuel system, approximately 27 ha of wood-producing area would be needed per capita—an area of wood cultivation of almost 7000 million ha, or more than 20 times the entire area of forest and woodland present in the United States (WRI 1994). Thus, even if all US forest and woodland were harvested for biofuel production, not even 5% of the current US energy demand would be covered.

In biomass production from short-rotation woody crops, yields are reported to be much higher than in conventional forestry, ranging from approximately 10,000 kg/ha at present to a projected 12,500 kg/ha in the near future (IEA 1994). However, these higher yields imply higher energy costs because of the necessity of using fertilizers. The reported yields are based on nitrogen inputs of 50–100 kg·ha⁻¹·yr⁻¹, along with phosphate and potassium fertilizers (IEA 1994). Moreover, yields of 10,000–12,500 kg/ha on marginal land and without ample nutrients and water use are probably unrealistic. If these woody crops are cultivated on marginal land to avoid competition with food production on arable land, the estimated nitrogen demand of 100 kg/ha seems too low for the expected yields.

<table>
<thead>
<tr>
<th>Characteristics of the process</th>
<th>Conventional wood production</th>
<th>Short-rotation woody crops</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fertilizer input (as N, P₂O₅, K₂O) (kg·ha⁻¹·yr⁻¹)</td>
<td>none</td>
<td>100, 20, 60⁸</td>
</tr>
<tr>
<td>Pesticide application (kg·ha⁻¹·yr⁻¹)</td>
<td>none</td>
<td>0.39²</td>
</tr>
<tr>
<td>Energy input in wood production (MJ/ha gross methanol produced)</td>
<td>0</td>
<td>2054⁴</td>
</tr>
<tr>
<td>Energy input in wood production (MJ/ha)</td>
<td>0</td>
<td>914³</td>
</tr>
<tr>
<td>Energy inputs for wood harvesting and handling (MJ/ha gross methanol produced)</td>
<td>data not available</td>
<td>1712⁴</td>
</tr>
<tr>
<td>Energy inputs at the plant (F2) (MJ/ha gross methanol produced)</td>
<td>8726⁶</td>
<td>8726⁶</td>
</tr>
<tr>
<td>Wood yield (kg·ha⁻¹·yr⁻¹)</td>
<td>2500</td>
<td>10,000</td>
</tr>
<tr>
<td>Heat equivalent of wood (MJ/kg)</td>
<td>16.73</td>
<td>16.73</td>
</tr>
<tr>
<td>Energy density of wood biomass production for fuel (Q) (MJ·ha⁻¹·yr⁻¹)</td>
<td>41,820</td>
<td>167,300</td>
</tr>
<tr>
<td>Conversion efficiency of wood biomass into methanol (F1/Q)</td>
<td>0.53⁵</td>
<td>0.53³</td>
</tr>
<tr>
<td>Net/gross methanol supply (F*/F1)</td>
<td>0.55⁷</td>
<td>0.37⁷</td>
</tr>
<tr>
<td>Net methanol supply (F* (GJ/ha))</td>
<td>12.2</td>
<td>32.8</td>
</tr>
</tbody>
</table>

¹IEA (1994); equivalent to 22.5 kg N, 4.5 kg P₂O₅, and 13.5 kg K₂O per ton of methanol produced.
²Typical value for US equivalent to 0.09 kg pesticide per ton of methanol produced (Hohenstein and Wright 1994).
³Based on 2247 kg of wood per ton of methanol (Ellington et al. 1993) and energy conversion factors for fertilizer and pesticide inputs reported in Helsel (1992).
⁴F3 = F4/1.2, after IEA (1994).
⁵Ellington et al. (1993).
⁶Estimated after Ellington et al. (1993) considering a smaller F3 than in intensive tree farming.
⁷Based on 2247 kg of wood per ton of methanol produced (Ellington et al. 1993) and listed assessments of energy inputs.
⁸F* (GJ/ha) = Q × F1/Q × F*/F1.

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Nevertheless, for our assessment of methanol production from short-
rotation woody crops we used the optimistic values for biomass pro-
duction found in literature (Table 4). Accounting for the fertilizer and
pesticide inputs and using the wood demand of 2247 kg per ton of gross
methanol reported by Ellington et al. (1993), we find that 2.7 L methanol
have to be produced per liter of net methanol delivered to society (an F*/F1
ratio of 0.37).

Therefore, using energy inputs in the form of fertilizers and pesticides
in short-rotation woody crops increases the yield per hectare but de-
creases the efficiency of the process. The F*/F1 ratio is much lower in
short-rotation woody crops (0.37) than in conventional wood produc-
tion (0.53; Table 4). The idea behind the cultivation of short-rotation
woody crops is the same as for high-
input agriculture: saving land by us-
ing more energy inputs, such as fer-
tilizers and pesticides. Indeed, the
F*/F1 ratio for methanol production
from short-rotation woody crops
(0.37) is close to that for ethanol
production from corn and sweet sor-
ghum (0.34).

As a result, the fourfold increase
in wood biomass yield per hectare
for short-rotation woody crops com-
pared with conventional forestry re-
sults in only a 2.5-fold decrease in
land requirement per unit of net
methanol biofuel produced. The higher requirement for inputs in
short-rotation woody crops offsets the potential gain of this biomass
production system by lowering the F*/F1 ratio. If control measures for
the environmental problems that in-
tensive, large-scale production of
short-rotation woody crops are likely
to cause are included, the resulting
increase in the internal energy de-
mand would probably translate into
even more severe increases in land
and labor demand, because the out-
put-input energy ratio of this pro-
cess is already 1.58 (determined by
the value F*/F1 = 0.37).

Methanol production from short-
rotation woody crops thus does not
appear to represent a major break-
through in terms of avoiding arable
land constraints. A net supply of
32.8 GJ of methanol per hectare
would imply a land demand of 10 ha

of short-rotation woody crops per
US citizen, assuming that methanol
is the only energy source in the United
States. This land demand is equiva-
 lent to more than 2500 million ha of
short-rotation woody crop mono-
culture, or eight times the size of all
present US forests combined, and an
annual release of approximately
970,000 t of pesticide, which is more
than three times the current pesti-
cide application in the United States.
Even assuming a less important role
for methanol in the US energy sector
(e.g., 30% of the total energy de-
mand) would not significantly change
the overall picture.

Labor demand in methanol biofuel
production: Data on labor input in
the production of short-rotation
woody crops are not available in the
literature, so we cannot determine
whether the energy throughput
achieved per hour of labor in this
system of methanol production meets
the expectation of an energy sector
of a modern society (i.e., more than
10,000 MJ/h). Compared with con-
ventional forestry, short-rotation
woody crops are more labor inten-
sive (Betters et al. 1991). A reduction
of labor input would require intensive
mechanization, but mechanization
would have adverse environmental
impacts and would further increase
the energy requirements for harvest-
ing operations (causing a decrease in
the F*/F1 ratio through higher en-
ergy investment in the internal loop).

When considering large-scale
methanol biofuel production, pollu-
tion control and recycling within the
production system are necessary to
keep the process environmentally
friendly. As a general trend, adding
pollution control measures to a pro-
duction process increases the labor
requirement per unit of net energy
supply, even in the case of fossil
energy power plants. For example,
installing antipollution devices
(scrubbers) required an increase in
the number of workers of 27 units
out of a total of 194 workers in a
675-MW coal-fired plant in New
York State. Limiting environmental
impacts through recycling of natural
flows can also dramatically increase
the labor requirements of an energy
system. When the energetic return of
recycling—that is, the energy gain
obtained by recycling divided by the
extra labor required—is lower than
the minimum labor requirement per
net gigajoule imposed by socioeconomic
constraints, recycling should
be considered a service and, there-
fore, a cost (Giampietro et al. 1997b).
Indeed, it has been shown repeatedly
that when economic development
provides access to fossil energy
through the market, time-demand-
ing activities with a low energy re-
turn are abolished. For example,
approximately half of the 7 million
digesters for biogas (gas produced at
the home and farm level through fer-
citation of organic wastes) in China
have reportedly been abandoned as
commercial energy has become increas-
ingly available in rural areas (Stuckey
1986). Similar economic problems due
to the low density of biogas are expe-
rienced in the United States (Frank

Obstacles to improving biofuel pro-
duction from woody and herbaceous
biomass. An energy input made of
woody and/or herbaceous biomass,
because of its physical nature, is of
much lower quality than a fossil en-
ergy input. Moreover, because bio-
mass is generated by biophysical pro-
cesses operating at a large scale (e.g.,
at the ecosystem level), it is very
difficult to change the overall char-
acteristics of such production.

Power intrinsic reliability of biofuel
supply. To remain viable, any biofuel
system operating at an output-input
energy ratio close to 1.0 must be able
to maximize energy crop yields and
optimize the use of every single byproduct. Consequently, perfor-
mance of such a biofuel system is
susceptible to natural perturbations,
such as climatic fluctuations and
outbreaks of pests or diseases, and to
socioeconomic perturbations, such
as price fluctuations and strikes.

For instance, the moisture con-
tent of herbaceous energy crops
can dramatically affect their caloric
value and the possibility of storing
them for use as an energy source later
on in the year (Belletti 1987, Bludau
1989). Complete drying of straw and
other herbaceous crops consumes

J. I. Fiala, 1993, personal communica-
tion. New York State Electric & Gas Corporation,
Binghamton, NY.
high-quality fuel, which would further lower the energetic performance of the system. Therefore, these crops are normally dried naturally in the field or elsewhere in the open air (Apfelbeck et al. 1989). This approach is successful only when the entire drying period is free of rain and low in humidity (Bludau 1989). Such climatic conditions are rare in temperate areas, making this solution unreliable in northern Europe, Canada, and the northern United States. In warm tropical areas, conversely, intense biological activity induced by high temperature may reduce the quantity and quality of herbaceous crops that are left too long in the field.

**Improving energy efficiency through genetic research.** Some research on trees and alternative energy crops aims to improve the density and reliability of the supply of biomass by genetic improvement of cultivated trees and by specific changes obtained through biotechnology. We believe that the potential improvements through this approach are limited. Major advances in agricultural production were obtained during the Green Revolution by reallocating energy use within plants (i.e., by increasing that part of the plant structure or function that is useful to humans), but the goal of increasing tree biomass produced per hectare would require an increase in the efficiency of photosynthesis at the ecosystem level—that is, a rearrangement of the flows of nutrients and water in entire ecosystems on a large scale (Giampietro 1994, Hansen 1991). This objective is overambitious given the present state-of-the-art in biotechnology. Technological improvements achieved in the Green Revolution that increased yields per hectare induced, as a side effect, a drastic reduction in the energy output-input ratio of crops (i.e., they decreased marginal return of input application). Such a solution has been accepted for food crop production by modern society because increasing supplies of food was seen as worth an increase in expenditures of fossil energy. However, such a tradeoff would be unacceptable for energy crop cultivation.

**Environmental obstacles to the production of woody energy crops.** Little research has been done on the long-term environmental impacts of woody energy crops, even though these energy crops are likely to generate environmental problems that are similar to or worse than those experienced with conventional food and cash crops. The few studies available have been short-term, small scale, and of limited scope (OTA 1993).

One possible long-term problem is loss of biodiversity and the disappearance of entire natural communities when energy crop monocultures spread onto adjacent nonarable land. Intensive production of trees and other sources of cellulose poses the same risks to biodiversity as cultivation of conventional energy crops. Assessments of the potential biofuel yield of short-rotation woody crops seldom pay attention to the potential long-term environmental effects of such a strategy (Ferm et al. 1989, Verma and Misra 1989). Indeed, the potentially serious environmental impact of intensive harvesting for energy production have, in general, been overlooked in the research agenda of most countries (Dyck and Bow 1992).

**Outlook for new biofuel production systems.** In light of general trends in technological development of agriculture, fisheries, and forestry, it appears that the density of flows of natural resources harvested by humans can be augmented, both per hectare and per hour of labor, only by a more than proportional increase in the density of inputs used in the process (Hall et al. 1986)—that is, the higher the intensity of the throughput, the lower the output-input ratio of the process. Similarly, the more the pattern of matter and energy flows in a managed ecosystem differs from natural patterns that occurred in the ecosystem that was replaced, the higher the expected environmental impact of human management (Giampietro 1997, Giampietro et al. 1992). Finally, the need for a high throughput per hour of labor in biomass production calls for mechanization, which calls, in turn, for an expansion of monocultures to synchronize the activities in the biomass production process.

The combination of these factors suggests that technological improvements aimed at intensifying biomass flows to overcome biophysical constraints will, sooner or later, decrease the marginal return in the use of energy inputs, decrease the $F^*/F_1$ ratio, and increase environmental impacts. Because, as we have shown, large-scale biofuel production will be feasible only if the energy throughput per hectare and per hour of labor of current biofuel energy systems increases severalfold, it is unlikely that a massive adoption of short-rotation woody crops or herbaceous energy crops will represent a viable solution for biofuel production in the future.

Biophysical limits to large-scale production of biofuel, such as limited supplies of land and water, endangered natural equilibria, and unsustainable rates of deforestation and soil erosion, are difficult to detect at the pilot plant scale. Therefore, technological optimists, by considering only their own small scale of analysis, will continue to claim to have dramatically increased the efficiency of the single step of the process that they are studying. By contrast, socioeconomic constraints to large-scale production of biofuel are harder to ignore: No one can reasonably expect that biofuels will achieve anything like the energy throughputs (on the order of 10,000 MJ) per hour of labor that are currently obtained by mining of fossil energy stocks. A shift to biofuel systems with much smaller energy throughputs per hour of labor would require a dramatic setback in the standard of living, the population size, or both. All of these issues must be addressed in discussions of future scenarios of large-scale biofuel production.

Humans already appropriate, directly or indirectly, 40% of the productivity of the biosphere (Vitousek et al. 1986). To put the issue of large-scale production of biofuel in perspective, the following questions need to be answered. Are humans already overdisturbing the environment just to produce food and forest products and to maintain a certain lifestyle? Many indicators, including deforestation, soil erosion, loss of biodiversity, ozone layer depletion, accumulation of carbon dioxide in the atmosphere, shortages of fresh water, and pollution, suggest caution in using further resources (Brown 1980–1994). Is it conceivable to augment our current

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level of appropriation by severalfold to produce, via biological conversion, the huge quantity of fuel that is currently being consumed? We strongly believe that, from an ecological perspective, large-scale production of biofuel from herbaceous grass or short-rotation trees would further destroy natural habitats without improving the current unsustainable solution in which fossil energy stocks are depleted and greenhouse gases are accumulating.

**Biofuel production in perspective**

Despite the need for more reliable data on large-scale biofuel systems operating without fossil energy subsidies, we believe that some conclusions are warranted based on current data on biofuel production:

- Large-scale biofuel production is not an alternative to the current use of oil and is not even an advisable option to cover a significant fraction of it. Biofuel systems appear to be unable to match the demand for net useful energy or the high-energy throughput per hour of labor typical of the energy sector of a developed society. First, none of the countries that we analyzed has sufficient land or water to rely exclusively on biofuel for energy security. The ratio of the demand for land to available land ranges from 1.4 to 148 for the countries in our sample, and the ratio between fresh water demand and current fresh water withdrawal ranges from 3 to 104. Second, in developed countries an energy sector based entirely on biofuel would absorb from 20% to 40% of the working force, including the unemployed, which is not compatible with the current labor distribution over the various economic sectors. Third, the data on which the first and second conclusions are based do not even account for ecological costs. If the energy requirement for reducing the BOD of effluents from ethanol plants to acceptable levels (10 MJ per liter of net ethanol delivered) were included, then land, water, and labor demand would increase dramatically. In addition, in the long term, the energy cost of soil erosion would further increase land, fresh water, and labor demand per gigajoule delivered through a reduction of biomass yields. Meeting the current demand for energy in the United States with ethanol from crops would necessitate a 20-fold increase in current pesticide use. And destroying all existing forest and increasing pesticide use threefold to produce methanol from short-rotation woody crops would not cover even 15% of current US energy demand.

- Food and environmental security should be of greater concern to society than energy security for a world population that is projected to reach a plateau of approximately 8–12 billion. At present, less than 0.27 ha of arable land is available per capita for food production, and humankind is already using fossil energy to reduce land demand for food security. Thus, using arable land for saving fossil energy is impractical. Heavy reliance of the world economy on biofuel would make it impossible to guarantee food security because of the competition for arable land and water. Moreover, biofuel production would result in more serious environmental impacts than are currently experienced with the use of fossil energy.

- Biomass does have a role to play in the energy security of modern society, both in developed and developing countries, in terms of better energy efficiency of agriculture. Despite their importance for soil conservation and the high direct and indirect costs involved in their harvest, agricultural residues and byproducts can contribute to a more efficient and sustainable agricultural system. They can be used as energy inputs in all cases where their use is compatible with existing constraints (e.g., the direct firing of biomass with cogeneration). However, the recognition that there is room for a more rational and efficient use of biomass at the rural level has nothing to do with the idea of farming on large scale for fuel per se. Research into new processes of biofuel production other than ethanol should avoid repeating the mistake with ethanol, in which declared yields and expectations seem to have been inversely related to the quantity of real data used in the assessment.

- The economic cost of biofuel, especially in developed countries, derives mostly from the labor demand per unit of energy throughput delivered. This cost is related to the opportunity cost of labor in the rest of society. In developed countries, this cost is proportional to the ability to produce and consume goods and services by using a large amount of useful energy and a small fraction of human time. Massive adoption of biofuel, with its much lower energy throughput per unit of labor than fossil energy, would reverse a basic trend conferred by technological progress—namely, reducing the fraction of human time that can be allocated to the service sector, retirement, and leisure.

- The nonsubstitutability of oil with biofuel is a major cause of concern because it does not provide an escape from the current unsustainability of a civilization that is based on depletion of fossil fuels. While fossil energy still lasts, alternative energy sources other than biofuel will need to be developed, along with technologies that improve the efficiency of energy use and lifestyles that are more consistent with sustainable natural cycles.

- If a major increase in energy efficiency, a dramatic change in lifestyle, and implementation of energy resources other than oil will enable humankind to soon curb the energy requirement of a world population that will eventually stabilize at a size of approximately 8–12 billion, biomass will be essential for other purposes. Specifically, the biomass of natural ecosystems will be needed to provide life support to the human species by stabilizing the structure and functions of the biosphere. The diversity and health of natural communities existing in different types of ecosystem all over the planet will be the most important “capital” available to humankind to achieve sustainability, because technology will never be able to substitute for it.

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