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Feasibility of Large-Scale Biofuel Production

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.

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

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 sugarcane, 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

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Table 1. Typical biofuel production systems from agricultural crops.

Indicators of performance	Biodiesel[a]	Ethanol in temperate areas	Ethanol in (sub)tropical areas
Gross energy yield ($\mathrm{GJ \cdot ha^{-1} \cdot yr^{-1}}$)	20–40	40–80	80[b]–130[c]
Net energy yield ($\mathrm{GJ \cdot ha^{-1} \cdot yr^{-1}}$)	<0–10	<0–30	50[b]–70[c]
Output–input energy ratio	0.6–1.3	0.5–1.7	3.0[b]–2.5[c]
Net to gross ratio (F*/F1)	<0–0.2	<0–0.4	0.66[b]–0.60[c]
Water requirement ($\mathrm{t \cdot ha^{-1} \cdot yr^{-1}}$)	4000–7000	4000–8000	10,000[b]–15,000[c]
Energy throughput (net MJ/h)	<0–250	<0–1000	250[b]–1600[c]
Best-performing system	oilseed rape	corn–sorghum	sugarcane
Land requirement (ha/net GJ)	0.100	0.033	0.020[b]–0.014[c]
Water requirement (t/net GJ)	500	170	200[b]–200[c]
Labor requirement (h/net GJ)	4	1	4[b]–0.6[c]

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

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

[c]High-input production, as reported in Pimentel et al. (1988).

aspects of biofuel production processes in attempts to reduce energy inputs and increase the overall fuel yield. Typical yields and output–input ratios have been discussed in detail elsewhere (Giampietro et al. 1996a)[1] and are summarized in Table 1. Other assessments are available (CCPCS 1991, CNR-PFE 1979, ERL 1990, IEA 1994), as are general studies on evaluation procedures for energy from biomass (Herendeen and Brown 1987, Lyons et al. 1985, Pellizzi 1986).

Evaluating biofuel production

We propose that the feasibility of biofuel production as an alternative to oil be analyzed by relating the performance of the biofuel energy system to the characteristics of both the socioeconomic and environmental system in which the biofuel production and consumption take place. Specifically, biofuel can substitute for fossil energy only if the large-scale production of biofuel is biophysically feasible (i.e., not constrained by the availability of land and fresh water sources for energy crop production); environmentally sound (i.e., does not cause significant soil degradation, air and water pollution, or biodiversity loss); and compatible with the socioeconomic structure of society (i.e., requires labor productivity that is consistent with the existing labor supply and per capita energy consumption in society). The latter two conditions imply that the biofuel system must deliver a sufficiently large amount of net energy to society per hour of labor employed in the cycle of biofuel production to make the process economically convenient for society while generating a sufficiently low environmental loading per unit of net energy supplied to keep the process environmentally sound.

Data in the literature on modern biofuel systems can be used to estimate the biophysical requirements per unit of net energy supply to society. Depending on the production system, these requirements, per gigajoule (1 gigajoule = 10^9 joules) of net energy, are 0.015–0.100 ha of arable land, 200–400 t of fresh water, and 0.6–5.5 hours of labor. A comparison of these values with actual land and fresh water availability and existing socioeconomic constraints—such as the energy consumed by society per hour of labor in the primary sectors of the economy—for several different countries indicates whether biofuel production on a large scale is feasible. As we show in this article, this approach indicates that biofuels are unlikely to alleviate to any significant extent the current dependence on fossil energy. Moreover, with current technologies, biofuels do not decrease the environmental impact per unit of net fuel delivered to society. Available analyses of biofuel production tend to overlook these biophysical constraints because they are invisible at the small scale of the laboratory, individual farm, or plant that is used in most assessments.

In this article, we analyze the net energy requirements of the process of biofuel production, as shown in Figure 1. This analysis is based on the net-energy approach proposed by Odum (1971) and Slesser (1978), and used by Cleveland et al. (1984) and Hall et al. (1986), among others. Several aspects of the analysis deserve special attention:

- 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)

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[1] S. Ulgiati, unpublished manuscript.

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).

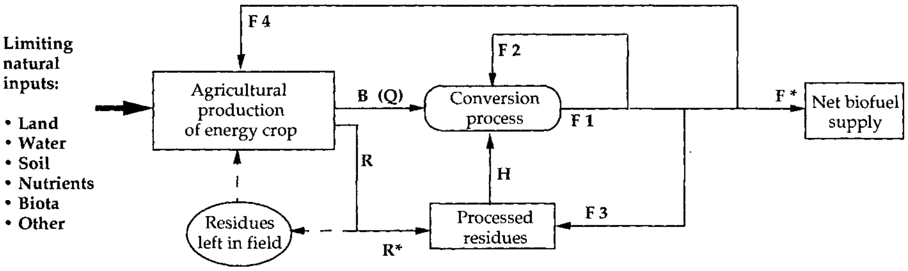

Figure 1. Biofuel production cycle. See text for details. B = biomass processed for fuel production; Q = energy content of biomass feedstock processed for fuel ($Q = B \times e$, where e = energy content per unit of biomass); R = crop residues; R^* = harvested crop residues used as energy source in the conversion process; H = energy input from residues ($H = R^* \times$ 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 ($F^* = F1 - F2 - F3 - F4$).

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 not, 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

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*/F1 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_5) 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 BOD_5 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 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 BOD_5 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-

Table 2. Land and water demand in large-scale biofuel production compared to availability (expressed on a per capita basis).

Country	Commercial energy consumption (GJ/yr)[a]	Arable land available (ha)[b]	Fresh water withdrawal (t/yr)[b]	Land demand for biofuel (ha)	Water demand for biofuel (t/yr)	Total arable land demand[f]/supply ratio	Biofuel water demand/current withdrawal ratio
Burundi	8	0.20	20	0.16[c]	1600[c]	1.8	80
Egypt	21	0.05	1028	0.42[c]	4200[c]	9.4	4
Ghana	6	0.08	35	0.12[c]	1200[c]	2.5	34
Uganda	8	0.28	20	0.16[c]	1600[c]	1.4	80
Zimbabwe	31	0.29	136	0.62[c]	6200[c]	2.9	46
Argentina	66	0.81	1042	1.32[c]	13,200[c]	2.1	13
Brazil	49	0.40	245	0.98[c]	9800[c]	3.0	40
Canada	437	1.75	1688	14.42[d]	74,300[d]	8.7	44
Costa Rica	35	0.10	780	0.70[c]	7000[c]	8.0	9
Mexico	54	0.27	921	1.78[d]	9200[d]	7.6	10
United States	325	0.76	1868	10.72[d]	55,200[d]	14.6	30
Bangladesh	3	0.08	212	0.06[c]	600[c]	1.8	3
China	25	0.08	462	0.50[c]	5000[c]	7.2	11
India	12	0.20	612	0.24[c]	2400[c]	2.2	4
Japan	134	0.03	732	4.42[d]	22,800[d]	148.3	31
France	163	0.32	778	5.38[d]	27,700[d]	17.6	36
Italy	113	0.16	996	3.73[d]	19,200[d]	24.3	19
Netherlands	202	0.06	994	6.66[d]	34,300[d]	112.0	34
Spain	87	0.52	1188	2.87[d]	14,800[d]	6.5	12
United Kingdom	155	0.12	253	5.11[d]	26,300[d]	43.6	104
Australia	216	2.90	1306	3.02[e]	43,200[e]	1.5	33

[a] Data from UN (1991).
[b] Data from WRI (1992).
[c] Referring to low-input sugarcane system (Table 1).
[d] Referring to corn–sweet sorghum system (Table 1).
[e] Referring to high-input sugarcane system (Table 1).
[f] 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 cost can be obtained. Assuming a BOD_5 of approximately 30,000 mg/L (typical of distillery waste), 1 kg of BOD_5 must be removed per liter of net biofuel produced (30 g/L × 38 L for ethanol in temperate areas). With an approximate cost of 1 kWh per kg of BOD_5 removed (Trobish 1992), the cost of controlling the pollution generated by one net liter of ethanol produced would be 10.5 MJ (1 megajoule = 10^6 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 F*/F1 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 F*/F1 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),[2] such a biofuel production system would result in the use of approximately 31 kg of pesti-

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[2] Estimated on the basis of an insecticide application rate in the United States for corn of 1.12 kg/ha and a herbicide (predominantly atrazine) application rate of 3.83 kg/ha. For sorghum, the average treatment with insecticides is 0.96 kg/ha, and the average herbicide treatment is 1.29 kg/ha (Pimentel et al. 1992).

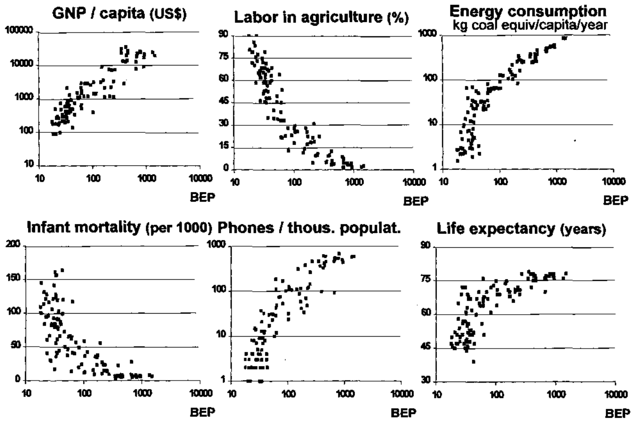

Figure 2. Correlations between Bio-Economic Pressure (BEP) and several indicators of socioeconomic development. BEP is defined as the ratio between the total energy consumed by a society in a year (in megajoules) divided by the total amount of working time in the same year (in hours). BEP should be considered a constraint derived from the socioeconomic characteristics of a society on the feasibility of production techniques in the primary sectors.

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 monocultures that would be required to obtain the high yields necessary for economic viability of the biofuel system is likely to aggravate problems of soil erosion, pollution from nutrient leaching, and overdraft of underground water—all of which are already 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 increase in energy demand of approximately 6000 MJ/ha to produce the equivalent amount of fertilizer. In addition, 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 implication 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 consumption) 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 characteristics 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 distributing energy (Holdren 1982).

Technological development of a society accelerates energy throughput in the primary sectors of the economy because it increases the average per capita consumption of energy (from less than 1 GJ/yr in developing countries to approximately 325 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 countries 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 reduction 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 (Figure 2) of the energy throughput consumed by society per hour of labor in the primary sectors of the economy and 24 classic indicators of socioeconomic development for a sample of more than 100 countries has confirmed 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 supply in the energy sector of industrialized 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 of 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 entire 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 delivered 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 from 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 socioeconomic and ecological constraints, requires that the characteristics of the biofuel system be checked against

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

Country	Commercial energy consumption (10^6 GJ/yr)[a]	Total population (10^6)[b]	Total labor force (as percentage of population)[c]	Potential labor supply (10^6 h/yr)[d]	Biofuel labor demand (10^6 h/yr)	Biofuel labor demand (as percentage of supply)
Burundi	42	5.3	55.5	5916	200[e]	3
Egypt	1075	51.2	31.6	32,358	4300[e]	13
Ghana	88	14.6	45.4	13,230	400[e]	3
Uganda	137	17.1	45.6	15,613	550[e]	3
Zimbabwe	301	9.7	37.3	7199	1200[e]	16
Argentina	2105	31.9	38.0	24,267	8400[e]	35
Brazil	7178	146.5	41.9	122,775	28,700[e]	23
Canada	11,493	26.3	51.7	27,184	11,500[f]	42
Costa Rica	105	3.0	37.7	2232	400[e]	18
Mexico	4460	82.6	38.4	63,460	4500[f]	7
United States	80,405	247.4	50.9	251,853	80,400[e]	32
Bangladesh	332	110.8	30.2	66,923	1350[e]	2
China	28,432	1137.3	60.5	1,376,133	113,700[e]	8
India	10,032	836.0	39.1	652,947	40,100[e]	6
Japan	16,495	123.1	49.8	122,558	16,500[f]	13
France	9209	56.5	44.3	50,059	9200[f]	18
Italy	6509	57.6	41.7	48,038	6500[f]	14
The Netherlands	2990	14.8	55.0	16,280	3000[f]	18
Spain	3332	38.3	36.8	28,189	3300[f]	12
United Kingdom	8881	57.3	48.3	55,352	9000[f]	16
Australia	3650	16.9	47.4	15,974	2200[g]	14

[a] Data from UN (1991).
[b] Data from WRI (1992).
[c] Data from ILO (1992).
[d] Assuming a common workload of 2000 h/yr.
[e] Referring to low-input sugarcane system (Table 1).
[f] Referring to corn–sweet sorghum system (Table 1).
[g] Referring to high-input sugarcane system (Table 1).

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[3] 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.

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[3] 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, then 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 (Giampietro 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 cropland, 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

Table 4. Methanol production from wood biomass.

Characteristics of the process	Conventional wood production	Short-rotation woody crops
Fertilizer input (as N, P_2O_5, K_2O) (kg · ha^{-1} · yr^{-1})	none	100, 20, 60[a]
Pesticide application (kg · ha^{-1} · yr^{-1})	none	0.39[b]
Energy input in wood production (MJ/t gross methanol produced)	0	2054[c]
Energy input in wood production (MJ/ha)	0	9143[c]
Energy inputs for wood harvesting and handling (MJ/t gross methanol produced)	data not available	1712[d]
Energy inputs at the plant (F2) (MJ/t gross methanol produced)	8726[e]	8726[e]
Wood yield (kg · ha^{-1} · yr^{-1})	2500	10,000
Heat equivalent of wood (MJ/kg)	16.73	16.73
Energy density of wood biomass production for fuel (Q) (MJ · ha^{-1} · yr^{-1})	41,820	167,300
Conversion efficiency of wood biomass into methanol (F1/Q)	0.53[e]	0.53[e]
Net/gross methanol supply (F*/F1)	0.55[f]	0.37[g]
Net methanol supply (F*)[h] (GJ/ha)	12.2	32.8

[a] IEA (1994); equivalent to 22.5 kg N, 4.5 kg P_2O_5, and 13.5 kg K_2O per ton of methanol produced.

[b] Typical value for US equivalent to 0.09 kg pesticide per ton of methanol produced (Hohenstein and Wright 1994).

[c] Based 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).

[d] F3 = F4/1.2, after IEA (1994).

[e] Ellington et al. (1993).

[f] Estimated after Ellington et al. (1993) considering a smaller F3 than in intensive tree farming.

[g] Based on 2247 kg of wood per ton of methanol produced (Ellington et al. 1993) and listed assessments of energy inputs.

[h] F* (GJ/ha) = Q × F1/Q × F*/F1.

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.

Nevertheless, for our assessment of methanol production from short-rotation woody crops we used the optimistic values for biomass production 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 decreases the efficiency of the process. The F*/F1 ratio is much lower in short-rotation woody crops (0.37) than in conventional wood production (0.55; Table 4). The idea behind the cultivation of short-rotation woody crops is the same as for high-input agriculture: saving land by using more energy inputs, such as fertilizers 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 sorghum (0.34).

As a result, the fourfold increase in wood biomass yield per hectare for short-rotation woody crops compared with conventional forestry results 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 intensive, large-scale production of short-rotation woody crops are likely to cause are included, the resulting increase in the internal energy demand would probably translate into even more severe increases in land and labor demand, because the output–input energy ratio of this process 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 breakthrough 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 equivalent to more than 2500 million ha of short-rotation woody crop monoculture, 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 pesticide 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 demand) 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 conventional forestry, short-rotation woody crops are more labor intensive (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 harvesting operations (causing a decrease in the F*/F1 ratio through higher energy investment in the internal loop).

When considering large-scale methanol biofuel production, pollution 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 production 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.[4] 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, therefore, 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-demanding activities with a low energy return are abolished. For example, approximately half of the 7 million digesters for biogas (gas produced at the home and farm level through fermentation of organic wastes) in China have reportedly been abandoned as commercial energy has become increasingly available in rural areas (Stuckey 1986). Similar economic problems due to the low density of biogas are experienced in the United States (Frank and Smith 1987, Schiefelbein 1989).

Obstacles to improving biofuel production 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 energy input. Moreover, because biomass is generated by biophysical processes operating at a large scale (e.g., at the ecosystem level), it is very difficult to change the overall characteristics of such production.

Poor 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, performance 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 content 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

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[4] J. I. Fiala, 1993, personal communication. 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 dramatic 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*/F1 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 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_5 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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References cited

Abelson PH. 1995. Renewable liquid fuels. Science 268: 955.

Ahern JI. 1980. The energy method of energy systems analysis. New York: John Wiley & Sons.

Apfelbeck R, Bludau D, Krämer U. 1989. Technical improvement of systems for harvest, transport, storage and dehydration of wood and straw for energy under consideration of economical aspects. Pages 267–273 in Grassi G, Gosse G, dos Santos G, eds. Biomass for energy and industry, 5th E.C. Conference. Vol. 1. Policy, environment, production, and harvesting. London: Elsevier Applied Science.

Belletti A. 1987. Sweet sorghum: from harvesting to storage. Pages 129–135 in Ferrero GL, Grassi G, Williams HE, eds. Biomass energy from harvesting to storage. London: Elsevier Applied Science.

Betters DR, Wright LL, Couto L. 1991. Short rotation woody crop plantations in Brazil and the United States. Biomass and Bioenergy 1: 305–316.

Bevilacqua OM, Bernard MJ III, Maxfield DP. 1981. The environmental implications of the large scale utilization of alcohol/fuels in the United States. Pages 719–726 in Proceedings of the IV International Symposium on Alcohol Fuels Technology. Vol. II, C-1. 5–8 October 1980; Guarujá, Brazil. São Paulo (Brazil): Istituto de Pesquisas Tecnológicas do Estado de São Paulo S.A., Brazil.

Bludau DA. 1989. Harvest and storage of sweet sorghum. Pages 260–266 in Grassi G, Gosse G, dos Santos G, eds. Biomass for energy and industry, 5th E.C. Conference. Vol. 1. Policy, environment, production and harvesting. London: Elsevier Applied Science.

Brown L. 1980–1994. The state of the world. Washington (DC): Worldwatch Institute.

Buringh P. 1987. Bioproductivity and land potential. Pages 27–46 in Hall DO, Overend RP, eds. Biomass. New York: John Wiley & Sons.

[CCPCS] Commission Consultative pour la Production de Carburant de Substitution. 1991. Rapport des Travaux du Groupe Numero 1. Paris: Commission Consultative pour la Production de Carburant de Substitution.

Chartier PL, Savanne D. 1992. Medium-term outlook for biofuels. Comptes Rendus de l'Académie d'Agriculture de France 78: 35–50.

Cleveland CJ, Costanza C, Hall C, Kaufmann R. 1984. Energy and the US economy: a biophysical perspective. Science 225: 890–897.

[CNR-PFE] Consiglio Nazionale delle Ricerche, Progetto Finalizzato Energetica. 1979. Etanolo per Via Fermentativa. Rome: Consiglio Nazionale delle Ricerche.

Coble CG, Sweeten JM, Egg RP, Soltes EJ, Aldred WH, Givens DA. 1985. Biological conversion and fuel utilization: fermentation for ethanol production. Pages 113–173 in Hiler EA, Stout BA, eds. Biomass energy: a monograph. College Station (TX): Texas A&M University Press.

Da Silva JG, Moreira JR, Conçalves JC, Goldemberg J. 1978. Energy balance for ethyl alcohol production from crops. Science 201: 903–906.

de Bazúa CD, Cabrero MA, Poggi HM. 1991. Vinasse biological treatment by anaerobic and aerobic processes: laboratory and pilot-plant tests. Bioresource Technology 35: 87–93.

Dyck WJ, Bow CA. 1992. Environmental impacts of harvesting. Biomass and Bioenergy 2: 173–191.

Edwards K. 1993. Soil erosion and conservation in Australia. Pages 147–170 in Pimentel D, ed. World soil erosion and conservation. Cambridge (UK): Cambridge University Press.

Ehrlich PR, Ehrlich AH, Daily GC. 1993. Food security, population, and environment. Population and Development Review 19: 1–32.

Ellington RT, Meo M, El-Sayed DA. 1993. The net greenhouse warming forcing of methanol produced from biomass. Biomass and Bioenergy 4: 405–418.

[ERL] Environmental Resources Limited. 1990. Study of the environmental impacts of large scale bio-ethanol production in Europe: final report. London: Environmental Resources Limited.

Ferm A, Hytönen J, Vuori J. 1989. Effect of spacing and nitrogen fertilization on the establishment and biomass production of short rotation poplar in Finland. Biomass 18: 95–108.

Frank JR, Smith WH. 1987. Perspective on biomass research. Pages 455–464 in Smith WH, Frank JR, eds. Methane from biomass: a systems approach. New York: Elsevier Applied Science.

Frings RM, Hunter IR, Mackie KL. 1992. Environmental requirements in thermochemical and biochemical conversion of biomass. Biomass and Bioenergy 2 : 263–278.

Giampietro M. 1994. Sustainability and technological development in agriculture. BioScience 44: 677–689.

______. 1997. Socioeconomic constraints to farming with biodiversity. Agriculture, Ecosystems, and Environment 62: 145–167.

Giampietro M, Cerretelli G, Pimentel D. 1992. Assessment of different agricultural production practices. Ambio 21: 451–459.

Giampietro M, Bukkens SGF, Pimentel D. 1993. Labor productivity: a biophysical definition and assessment. Human Ecology 21: 229–260.

Giampietro M, Ulgiati S, Pimentel D. 1997a. A critical appraisal of energetic assessments of biofuel production systems. Environmental Biology. Cornell University Technical Report nr 97-1.

Giampietro M, Bukkens SGF, Pimentel D. 1997b. Linking technology, natural resources and socioeconomic structure of human society: examples and applications. Pages 129–199 in Freese L, ed. Advances in human ecology. Vol. 6. Greenwich (CT): JAI Press.

Hall CAS, Cleveland CJ, Kaufmann R. 1986. Energy and resource quality. New York: John Wiley & Sons.

Hansen EA. 1991. Poplar woody biomass yields: a look to the future. Biomass and Bioenergy 1: 1–7.

Helsel Z. 1992. Energy and alternatives for fertilizer and pesticide use. Pages 177–201 in Fluck RC, ed. Energy in farm production. Vol. 6. Amsterdam: Elsevier.

Herendeen R, Brown S. 1987. A comparative analysis of net energy from woody biomass. Energy 12: 75–84.

Hohenstein WG, Wright LL. 1994. Biomass energy production in the United States: an overview. Biomass and Bioenergy 6: 161–173.

Holdren JP. 1982. Energy hazards: what to measure, what to compare. Technology Review 85: 32–38, 74–75.

Hunsaker DB, McBrayer JF, Elmore JL. 1989. Ethanol production and the environment. Energy 14: 451–468.

[IEA] International Energy Agency. 1994. Biofuels. Policy Analysis Series: Energy and Environment. International Energy Agency. Paris: Organization for Economic Cooperation and Development.

[ILO] International Labour Office. 1992. Economically active population, estimates and projections 1950–2025. Geneva: International Labour Office.

[ISTAT] Istituto Centrale di Statistica. 1992. Annuario statistico Italiano. Rome: Istituto Centrale di Statistica.

Johansson TB, Kelly H, Reddy AKN, Williams RH, eds. 1993. Renewable energy: sources for fuels and electricity. Washington (DC): Island Press.

Kendall H, Pimentel D. 1994. Constraints to the world food supply. Ambio 23: 198–205.

Klass DL, ed. 1993. Energy from biomass and wastes XVI. Chicago: Institute of Gas Technology.

Lal R. 1995. The role of residues management in sustainable agricultural systems. Journal of Sustainable Agriculture 5: 51–78.

Lyons GJ, Lunny F, Pollock HP. 1985. A procedure for estimating the value of forest fuels. Biomass 8: 283–300.

Marrow JE, Coombs J, Lees EW. 1987. An assessment of bio-ethanol as a transport fuel in the UK. Vol. 1. ETSU-R-44. London: Department of Energy/HMSO.

Mishra K. 1993. Cytotoxic effects of distillery waste on *Allium cepa* L. Bulletin of Environmental Contamination Toxicology 50: 199–204.

Odum HT. 1971. Environment, power, and society. New York: Wiley-Interscience.

[OTA] Office of Technology Assessment, US Congress. 1993. Potential environmental impacts of bioenergy crop production. Washington (DC): US Government Printing Office. Paper nr OTA-BP-E-118.

Parisi F. 1983. Energy balances for ethanol as a fuel. Advances in Biochemical Engineering and Biotechnology 28: 41–68.

Pastore G, Giampietro M, Mayumi K. 1996. Bio-economic pressure as indicator of material standard of living. Paper presented at the Fourth Biennial Meeting of the International Society of Ecological Economics (ISEE) on Designing Sustainability; 4–7 Aug 1996; Boston, MA.

Pellizzi G. 1986. A procedure to evaluate energy contribution of biomass. Energy in Agriculture 5: 317–324.

Pereira A. 1983. Employment implications of ethanol production in Brazil. International Labour Review 122: 111–127.

Pillet G, Baranzini A, Villet M, Collaud G. 1987. Exergy, emergy, and entropy. Pages 277–302 in Pillet G, Murota T, eds. Environmental economics: the analysis of a major interface. Geneva: Roland Leimgruber.

Pimentel D, Warneke AF, Teel WS, Schwab KA, Simcox NJ, Ebert DM, Baenisch KD, Aaron MR. 1988. Food versus biomass fuel: socioeconomic and environmental impacts in the United States, Brazil, India, and Kenya. Advances in Food Research 32: 185–238.

Pimentel D, Acquay H, Biltonen M, Rice P, Silva M, Nelson J, Lipner V, Giordano S, Horowitz A, D'Amore M. 1992. Environmental and economic costs of pesticide use. BioScience 42: 750–760.

Pimentel D, Harvey C, Resosudarmo P, Sinclair K, Kurz D, McNair M, Crist S, Shpritz L, Fitton L, Saffouri R, Blair R. 1995. Environmental and economic costs of soil erosion and conservation benefits. Science 267: 1117–1123.

Rosillo-Calle F. 1987. Brazil: a biomass society. Pages 329–348 in Hall DO, Overend RP, eds. Biomass: regenerable energy. Chichester (UK): John Wiley & Sons.

Schiefelbein GF. 1989. Biomass thermal gasification research: recent results from the United States DOE's Research Program. Biomass 19: 145–159.

Shay EG. 1993. Diesel fuel from vegetable oils: status and opportunities. Biomass and Bioenergy 4: 227–242.

Slesser M. 1978. Energy in the economy. New York: St. Martin's Press.

Sourie JC, Hautcolas J, Blanchet J. 1992. Which opportunities for the short term development of biofuels as a result of the new fiscal and regulatory provisions in France and within EEC. Comptes rendus de l'Académie d'Agriculture de France 78: 19–29.

Southerland D. 1995. Clinton mandate on cleaner gas was rejected. The Washington Post, 29 April 1995, sec. C, pp. 1–2.

Stevens DJ. 1992. Biomass conversion: an overview of the IEA bioenergy agreement task VII. Biomass and Bioenergy 2: 213–227.

Stout BA. 1990. Handbook of energy for world agriculture. London: Elsevier Applied Science.

Stuckey DC. 1986. Biogas: a global perspective. Page 18 in El-Halwagi MM, ed. Biogas technology, transfer and diffusion. Amsterdam: Elsevier.

Trobish KH. 1992. Recent developments in the treatment of chemical waste water in Europe. Water Science and Technology 26: 319–322.

[TRW] TRW Energy Systems Planning Division. 1980. Energy balances in the production and end-use of alcohols derived from biomass, a fuels-specific comparative analysis of alternate ethanol production cycles. Report prepared for the US National Alcohol Fuels Commission and the Office of Advanced Technology R&D Assistant Secretary for Policy and Evaluation. Washington (DC): US Department of Energy. Document nr 97611-E002-UX-00.

[UN] United Nations. 1991. Energy statistics yearbook. New York: United Nations.

[USDA] US Department of Agriculture. 1992. Agricultural statistics. Washington (DC): US Department of Agriculture.

Verma SC, Misra PN. 1989. Biomass and energy production in coppice stands of *Vitex negundo L.* in high density plantations on marginal lands. Biomass 19: 189–194.

Vitousek PM, Ehrlich PR, Ehrlich AH, Matson PA. 1986. Human appropriation of the products of photosynthesis. BioScience 36: 368–373.

[WRI] World Resources Institute. 1992. World resources 1992–93. New York: Oxford University Press.

______. 1994. World resources 1994–95. New York: Oxford University Press.

Wright LL, Hohenstein WG, eds. 1994. Dedicated feedstock supply systems: their current status in the USA. Biomass and Bioenergy 6 (special issue): 159–241.

Wyman CE, Bain RL, Hinman ND, Stevens DJ. 1993. Ethanol and methanol from cellulosic biomass. Pages 865–923 in Johansson TB, Kelly H, Reddy AKN, Williams RH, eds. Renewable energy sources for fuels and electricity. Washington (DC): Island Press.

LINKED CITATIONS

- Page 1 of 2 -

Feasibility of Large-Scale Biofuel Production

Mario Giampietro; Sergio Ulgiati; David Pimentel

BioScience, Vol. 47, No. 9. (Oct., 1997), pp. 587-600.

Stable URL:

http://links.jstor.org/sici?sici=0006-3568%28199710%2947%3A9%3C587%3AFOLBP%3E2.0.CO%3B2-F

[Footnotes]

[3] **Environmental and Economic Costs of Pesticide Use**

David Pimentel; H. Acquay; M. Biltonen; P. Rice; M. Silva; J. Nelson; V. Lipner; S. Giordano; A. Horowitz; M. D'Amore

BioScience, Vol. 42, No. 10. (Nov., 1992), pp. 750-760.

Stable URL:

http://links.jstor.org/sici?sici=0006-3568%28199211%2942%3A10%3C750%3AEAECOP%3E2.0.CO%3B2-Z

References cited

Editorial: Renewable Liquid Fuels

Philip H. Abelson

Science, New Series, Vol. 268, No. 5213. (May 19, 1995), p. 955.

Stable URL:

http://links.jstor.org/sici?sici=0036-8075%2819950519%293%3A268%3A5213%3C955%3AERLF%3E2.0.CO%3B2-B

Energy and the U.S. Economy: A Biophysical Perspective

Cutler J. Cleveland; Robert Costanza; Charles A. S. Hall; Robert Kaufmann

Science, New Series, Vol. 225, No. 4665. (Aug. 31, 1984), pp. 890-897.

Stable URL:

http://links.jstor.org/sici?sici=0036-8075%2819840831%293%3A225%3A4665%3C890%3AEATUEA%3E2.0.CO%3B2-8

LINKED CITATIONS

Energy Balance for Ethyl Alcohol Production from Crops
José Gomes da Silva; Gil Eduardo Serra; José Roberto Moreira; José Carlos Conçalves; José Goldemberg
Science, New Series, Vol. 201, No. 4359. (Sep. 8, 1978), pp. 903-906.
Stable URL:
http://links.jstor.org/sici?sici=0036-8075%2819780908%293%3A201%3A4359%3C903%3AEBFEAP%3E2.0.CO%3B2-X

Food Security, Population and Environment
Paul R. Ehrlich; Anne H. Ehrlich; Gretchen C. Daily
Population and Development Review, Vol. 19, No. 1. (Mar., 1993), pp. 1-32.
Stable URL:
http://links.jstor.org/sici?sici=0098-7921%28199303%2919%3A1%3C1%3AFSPAE%3E2.0.CO%3B2-5

Sustainability and Technological Development in Agriculture
Mario Giampietro
BioScience, Vol. 44, No. 10. (Nov., 1994), pp. 677-689.
Stable URL:
http://links.jstor.org/sici?sici=0006-3568%28199411%2944%3A10%3C677%3ASATDIA%3E2.0.CO%3B2-Y

Environmental and Economic Costs of Pesticide Use
David Pimentel; H. Acquay; M. Biltonen; P. Rice; M. Silva; J. Nelson; V. Lipner; S. Giordano; A. Horowitz; M. D'Amore
BioScience, Vol. 42, No. 10. (Nov., 1992), pp. 750-760.
Stable URL:
http://links.jstor.org/sici?sici=0006-3568%28199211%2942%3A10%3C750%3AEAECOP%3E2.0.CO%3B2-Z

Environmental and Economic Costs of Soil Erosion and Conservation Benefits
David Pimentel; C. Harvey; P. Resosudarmo; K. Sinclair; D. Kurz; M. McNair; S. Crist; L. Shpritz; L. Fitton; R. Saffouri; R. Blair
Science, New Series, Vol. 267, No. 5201. (Feb. 24, 1995), pp. 1117-1123.
Stable URL:
http://links.jstor.org/sici?sici=0036-8075%2819950224%293%3A267%3A5201%3C1117%3AEAECOS%3E2.0.CO%3B2-4

Human Appropriation of the Products of Photosynthesis
Peter M. Vitousek; Paul R. Ehrlich; Anne H. Ehrlich; Pamela A. Matson
BioScience, Vol. 36, No. 6. (Jun., 1986), pp. 368-373.
Stable URL:
http://links.jstor.org/sici?sici=0006-3568%28198606%2936%3A6%3C368%3AHAOTPO%3E2.0.CO%3B2-1

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