How Many Ways Can We Skin this Cat Called Earth? Risks and Constraints to the Biobased Economy

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My objective is to assess risks and constraints to realizing the hopeful vision of a biobased economy in the twenty-first century — a future in which agriculture and other managed biobased production systems provide society with food, fiber, medicinals, energy, chemicals, and materials. I will evaluate whether the biobased economy is possible and whether it is sustainable, given constraints to the quantity and quality of land, water, nutrients, and energy to propel the system.

Human societies already use 50 percent of all solar energy assimilated by plants (Pimentel et al. 1999), which utilize less that 1 percent of the solar energy they intercept. With a biobased economy, we risk negative consequences of asking yet more from the earth.

To approach this assessment, I created a very simple needs-based, bottom-up model, using the world as the unit of analysis and the twenty-first century as the time frame. The model develops four scenarios, projecting supply and demand in a biobased society. Absolute precision is not an objective of these simulations. And the projections of the model are not predictions. They are a wake-up call.

An underlying assumption of the model is that energy drives all enterprise and is the ultimate constraint. Energy relations — energetics — is the input-output accounting system of life. It underlies and orchestrates evolutionary as well as day-to-day processes. In using energy analysis, a tool of systems ecology, to assess human society and systems, I am applying simple arithmetic to illustrate the calculus of my mentors David Pimentel and Charles A. S. Hall, as well as others to whom I owe an intellectual debt, principally Howard Odum, Fred Cottrell, Lester Brown, Herman Daly, Jay Forrester, the Steinharts, and Earl Cook.

ENERGETICS: the total energy relations and transformations of a physical, chemical or biological system. 1855. (Merriam Webster's Collegiate Dictionary)

Energy analysis is a means of quantifying "sustainability," so that "sustainability" is the outcome of a positive or neutral energy balance, rather than only a lofty ideal motivating the search for alternatives to the fossil-energy-based economy of the industrial and post-industrial eras.

SUSTAINABLE: of, relating to, or being a method of using a resource so that the resource is not depleted or permanently damaged. (Merriam-Webster's Collegiate Dictionary)

Clearly, a fossil-energy-dependent economy is not sustainable over time: it is estimated that global supplies of oil and natural gas will last 50 years, and coal reserves at most several hundred, based on current population and production. Because of the pollution generated, an economy dependent on fossil fuel is not sustainable within a finite space — even a space as large as our earth and its atmosphere. Global pollution from the current use of fossil energy is shrinking the ozone shield, causing climate change, polluting air and waterways, and killing coral reefs.

Although fossil fuels will not suddenly "run out" — there are massive supplies of coal in China, for example — they are becoming more difficult and more energy-intensive to extract as high quality fuels are used up and lower quality fuels remain. These lower-quality fuels contain more impurities and thus will increase the pollution load. As an analogy, copper ores mined in the United States early in the twentieth century contained 2.5 percent metal, whereas by 1980 they contained only 0.5 percent metal, a trend typical for other extractable metals and fossil resources (Gever et al. 1985).

BIOBASED ECONOMIES

Although it is clear that a fossil-energy-dependent economy is not sustainable, the more interesting question is whether an information-rich and technologically sophisticated biobased economy — the "new biobased economy" envisioned in the NABC *Vision Statement* (NABC 1999) — is sustainable. The presumption might be that a biobased system would be in equilibrium because it runs on contemporary infusions of energy, rather than depending upon fossil resources that have been concentrated and stored over millennia.

History provides many examples, however, of pre-industrial human societies in which biobased resources were degraded or depleted at an unsustainable rate. These societies could be maintained for a significant length of time only because in a world with many fewer people, groups could move on to new areas — the impacts of their resource overuse temporarily ignored. This overuse, however, led to erosion, desertification, and to the loss of major food species.

Despite the limitations observed from history, “contemporary” solar energy almost certainly *must* be the engine of a sustainable society. The solar radiation that reaches the earth (at $3.6x10^{18}$ kcal/day) is the source of the heat and energy that move earth and mountains by way of weather patterns that cause wind and rain, and thus, indirectly, erosion, sedimentation, and soil formation. Only a small fraction (about 0.1 percent) of the solar energy reaching earth is converted by photosynthesis into plant growth to directly fuel the biobased economy. This energy is concentrated as it moves through the ecosystem, and matter is consumed by higher trophic levels of living organisms, including humans (Cook 1976).

“World Food-Needs” Model

Human demands for food and other goods are driven by the size of the world population and by its level of consumption. To assess the potential for success of a biobased economy driven by “contemporary” energy input, I calculate the area of land and other inputs needed to feed a growing world population, and compare this demand with the amount of arable land. For the purpose of this exercise, the needs and demands of all people are considered to be equal.

The “World Food Needs” model assumes a 100-percent rice diet[1] of 2,700 Calories/person/day, the current world-average caloric intake.[2] Converting from kilocalories (= Calories) to kilograms, we calculate that 1.65 billion metric tons of edible grain are needed to feed the 6 billion people on earth in the year 2000, with each person consuming about one-quarter ton of rice.

Production requirements, however, are greater than the demand for consumable grain. It has been estimated that about 45 percent of production is used for seed, wasted, or lost to pests or diseases (Buringh and van Heemst 1977).[3] Thus, 3 billion metric tons of grain must be produced in order to supply adequate food to the current population of 6 billion.

Calculating World Food Needs

- 2,700 Calories/person/day x 365 days/year = 985,500 Calories/person/year
- Round up to 1 million Calories/person/year
- Assume rice is the worldwide staple, 100 percent of food Calories
- 1 kg rice = 3,640 Calories
- $1x10^6$ Calories/person/year ÷ 3,640 Calories/kg = about 275 kg “rice”/person/year
- 275 kg = 0.275 metric ton [= tonne (t)]
- 0.275 t “rice”/person /year x 6 billion people = 1.65 billion t of consumable grain needed to feed current world population
- 1.65×10^9 t = 55 percent of production need, accounting for seed, waste, loss to pests
- 1.65×10^9 t ÷ .55 = 3 billion t production needed to feed Year-2000 population

LAND NEEDED FOR FOOD PRODUCTION

The World Food Needs model is driven also by assumptions about yield (production per unit area of land), from which the total land area needed for production can be calculated. Table 1 shows a range of yields under various conditions and assumptions. Two of these yield levels are used as the basis for scenarios in the model:

- 2 t/ha — A "sustainable yield" with limited fossil-energy inputs. This yield level was selected based on results from two quite different methods of analysis. In one case, a theoretical world consumable grain production was calculated by looking at yields of crops grown in different soil types. Yield estimates in this model were 1.7 to 2.3 t/ha, assuming a "labor-oriented agriculture" (Buringh and van Heemst 1977).[4]

  In the other case, an agricultural ecologist looked at historical rice production in favorable areas under animal-powered agriculture. Historical yields were as high as 3.5 t/ha in China at the beginning of the common era, but more typically were in the range of 2 to 2.5 t/ha (Mitchell 1984).
- 4.5 t/ha — An "optimistic" world-average yield, based on a projected 20 percent increase in rice productivity over 1999 as a result of genetically engineering high efficiency C_4 photosynthetic capability from maize. [This is based on the work of Drs. John Sheehy, Maurice Ku, and others (IRRI 2000b).]

The model projections are based on the calculation that 1.5 billion ha of arable land would be needed to feed the current world population at a "sustainable yield," and that 0.7 billion ha would be needed in 2000 if the world were fed by genetically engineered rice produced at the "optimistic" yield.[5]

WORLD POPULATION GROWTH

The global population passed the 6-billion mark in early 1999, increasing at an annual rate of 1.4 percent (PRB 1999). The World Food Needs model reflects the fact that, at this growth rate, the population will double in 49 years. Table 2 shows population doubling times at higher rates of growth, because in many parts of the developing world growth rates of 2.5 percent are common. In the mid-1960s, the world population was increasing at 2 percent, leading to projections then that there would be 7 billion people by 2000. Projections were brought closer to 6 billion as growth rates declined to 1.7 percent in the mid-1980s (Drosdoff 1984).

Table 2 shows that the growth rate must decline below 0.75 percent in order to delay the doubling of the current population to beyond the twenty-first century. However most futurists predict a leveling of world population mid-century at 10 to 12 billion.

TABLE 1. LAND NEEDED FOR FOOD UNDER VARIOUS PRODUCTIVITY SCENARIOS

Land ($x10^9$ ha)	Yield (t/ha)	Situation and assumptions
2.0	1.5	Marginal conditions, minimal inputs.
1.5	2	Sustainable productivity level for labor-intensive/ animal-powered agriculture.
1.2	2.5	Average yield in Costa Rica for the years 1970–84, with significant fertilizer input (33 kg N/ha) (Levitan 1988).
0.8	3.8	World average, 1999, with significant fossil-energy-derived inputs, as well as significant variability (FAOSTAT 1999). Also 1996 average in Asia, with yields in China = 6.1 t/ha (Dawe and Doberman 1998).
0.7	4.5	Optimistic world-average yield, reflecting a projected 20 percent increase in rice yield over 1999 as a result of genetically engineering high-efficiency C_4 photosynthetic capability from maize into rice. (IRRI 2000b). Also, this was the average yield for unmilled rice in Indonesia in 1996 (Dawe and Doberman 1998).

TABLE 2. DOUBLING OF WORLD POPULATION AT VARIOUS RATES OF INCREASE

Annual rate of population increase (percent)	When year-2000 population will be doubled
3	2023
2.5	2028
2	2035
1.4	2049
1	2069
0.75	2092
0.5	2139

AGRICULTURAL LAND

To assess sustainability from the supply side, we accept a frequently cited current estimate of 1.5 billion ha of arable land (Table 3), which is 11 percent of total world land area (Buringh 1989; WRI 1994). “Arable,” from the Latin *arare*, to plow, means “fit for or used for the growing of crops.” In other words, the area of arable land that may be put to the service of meeting world food needs is not fixed, but rather depends upon social and political factors, as well as on agronomic considerations. With greater demand and scarcity, land previously considered marginal or uneconomical to use is put into production and thus becomes “arable.” History shows that yields from marginal lands are either lower than yields from more productive land or are more highly subsidized by inputs — in the forms of nutrients, water, pest controls, labor, etc. Use of marginal land for crop production also extracts a higher toll from the environment, with typically higher rates of soil erosion.

TABLE 3. WORLD LAND QUALITY AND USE (PIMENTEL ET AL. 1999)

Land use	Fraction of total (percent)	Billion ha
Arable	11	1.5
Pasture	26	3.5
Forest	30	4.0
Urban	9	1.2
Other	23	3.1
Total	100	13.3

We base our estimate of an upper limit on arable land on the area that Buringh and van Heemst (1977) deemed suitable for labor-oriented agriculture: 2.5 billion ha (approximately 18 percent of world land area).

The World Food Needs model factors in the loss of an estimated 10 million ha/year: land so severely degraded that it is abandoned for agriculture. At this rate, one-third of the arable land will have been lost by mid-twenty-first century due to erosion, nutrient depletion and salinization (Pimentel et al. 1995, 1999).

SIMULATION-MODEL PROJECTIONS FOR THE TWENTY-FIRST CENTURY

Results of the simulation show the year when demand for land to grow food will exceed the supply of arable land on earth (Figure 1, Table 4). Four scenarios are projected: two at the 2 t/ha “sustainable” yield, and two at the 4.5 t/ha “optimistic” yield. Each yield level is paired with both of the estimates of arable land area just described. The model incorporates population growth at 1.4 percent, and annual loss of arable land of 10 million ha.

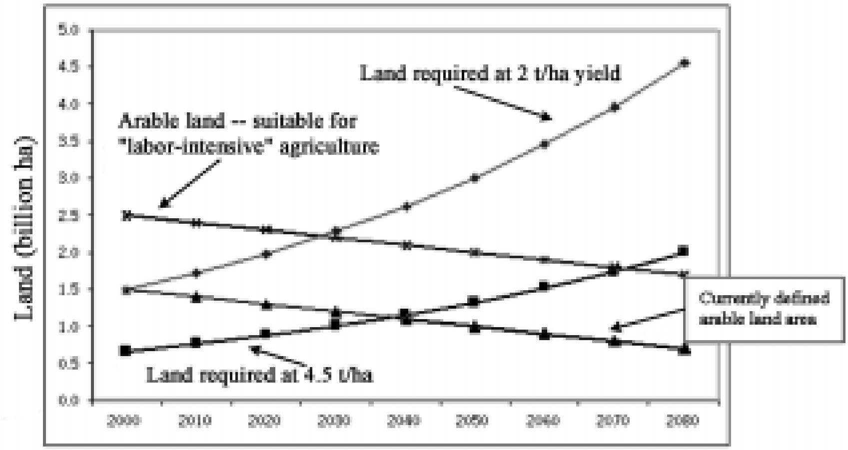

Figure 1. Land needed to grow food — a simulation assuming a 1.4-percent population growth and loss of arable land at 10 million ha/year. Two scenarios: "sustainable" yield = 2 t/ha, "optimistic" yield = 4.5 t/ha of rice genetically engineered with capacity for C_4 photosynthesis. Two estimates of arable land in year 2000: 1.5 billion ha and 2.5 billion ha.

Table 4. Land needed for food production compared with arable land available

Year	Land needed (billion ha) at yields of		Arable land (billion ha)		Global population ($x10^9$)
	2 t/ha	4.5 t/ha	Current	High est.	
2000	1.5	0.7	1.5	2.5	6.0
2010	1.7	0.8	1.4	2.4	6.9
2020	2.0	0.9	1.3	2.3	7.9
2030	2.3	1.0	1.2	2.2	9.1
2040	2.6	1.2	1.1	2.1	10.5
2050	3.0	1.3	1.0	2.0	12.0
2060	3.5	1.5	0.9	1.9	13.8
2070	4.0	1.8	0.8	1.8	15.9

- At the 2 t/ha “sustainable” yield and the current typical estimate of arable land, theoretical basic food demand exceeds the supply of land in the year 2000.
- At the 2 t/ha “sustainable” yield and the higher estimate of arable land, demand exceeds supply in 2030.
- If genetically engineered rice attains the photosynthetic efficiency of corn, and if this product is successfully integrated into production strategies worldwide, demand will exceed supply of arable land (as currently defined) by 2040. However, with higher yields, demand for water and nutrient inputs will also certainly increase, very likely to levels beyond what is sustainable or available.
- The last scenario treads into territory that is probably foolishly optimistic: projecting yields on marginal lands that are greater than yields known today on more productive land. But, even if average yields of 4.5 t/ha can be maintained, demand will exceed supply by 2070.

In sum, we project that sometime between 2000 and 2070, land availability will be less than that needed to provide an adequate, but very basic, diet for the global population. Is this too pessimistic? We think not: already the World Health Organization has estimated that 3 billion people — one-half the world population — are malnourished in terms of micronutrients (WHO 1996). Moreover, the United Nations standard caloric requirement for the average person, 2,600 Calories, is just 100 fewer than the current world average intake used in these projections (Collins 1982).

INPUTS, OUTPUTS AND ENERGY RELATIONS IN AGRICULTURE AND OTHER SECTORS

Agricultural yield depends on soil quality, genetic potential of the crop, and external inputs to production. As availability of suitable land becomes constrained, energy-intensive inputs are more important and production practices shift from extensive to intensive. As Steinhart and Steinhart illustrated in their classic paper (1974), agricultural output correlates closely with energy-based inputs. While the Steinharts’ data are from 1920 to 1980, others have focused on a broader array of technologies and societies, all pointing toward the same conclusion. Pimentel et al. (1973), for example, calculated that high-yielding corn genotypes use sixteen times as much nitrogen as their low-yielding counterparts.

Nitrogen fertilizer is perhaps the most energy-intensive input to production. Manufacture of sufficient nitrogen to replace that taken up by rice, requires the equivalent of 7 percent of the food-energy value of the rice.[6]

Water use also closely correlates with agriculture productivity. Worldwide, demand for freshwater quadrupled between 1940 and 1990, with 69 percent of water usage for agriculture, 23 percent for industry and only 8 percent domestic

(PRB 1999). In India, this use-rate is twice the sustainable yield for the country's aquifers (Worldwatch Institute 2000) and 95 percent of water in developing countries is polluted (WHO 1992). Clearly, there is very little additional water available to support increased biobased production.

Yet, thus far, our model has addressed only the input costs for food production, whereas in a biobased economy, land and energy inputs would also be needed to generate fuels for cooking and heating, as well as for clothing, materials, and medicinals. Technological societies such as ours use more than 98 percent of energy for these non-food purposes. Note that the 3,500 Calories used for food in a technological society is less than 2 percent of the total 230,000 Calories used per person per day (Table 5). In a biobased society, this non-food energy demand would ostensibly have to be met by agricultural and natural-resource-based production.

TABLE 5. ENERGY USE (CALORIES/PERSON/DAY) IN VARIOUS SOCIETIES (PIMENTEL AND PIMENTEL 1996)

Society	Food	Industry agriculture	Commercial & residential	Transport	Total
Primitive	2,000	—	—	—	2,000
Hunting	3,000	—	2,000	—	5,000
Primitive agriculture	4,000	4,000	4,000	1,000	13,000
Advanced agriculture	3,500	7,000	12,000	1,000	26,000
Industrial	3,500	24,000	32,000	14,000	77,000
Technological	3,500	91,000	66,000	63,000	230,000

RENEWABLE ENERGY

To make an admittedly rough estimate of the level of energy consumption that could be maintained into the future, we could perhaps look at the percentage of energy now derived from renewable sources (Table 6). Renewable, solar-powered energy sources — biomass, biofuels, hydro, wind and geothermal — now provide about 21 percent of the energy used.

We can also get a sense of what *type* of society could be maintained into the future by looking at past societies that were maintained on 21 percent of our current per capita energy consumption level — the portion of energy from renewable sources (Table 6). From Table 5, we find that the amount of renewable energy now generated is sufficient to sustain an advanced agricultural/low-input industrial society at our current population level.[7] Of course as population increases, available energy per capita will decrease.

TABLE 6. WORLD ENERGY SOURCES

Energy source	Fraction of Total (%)	Renewable?
Petroleum	34	No
Natural gas	19	No
Coal	22	No
Nuclear fission	6	No
Biomass	7	Yes
Hydroelectricity	6	Yes
Geothermal + wind	6	Yes
Biofuels (e.g. ethanol)	<2	Yes
(Total renewable)	(21)	

Increased production of biofuels, which now provide less than 2 percent of energy worldwide, is seen as key to increasing the availability of renewable energy while reducing environmental pollution. In the United States, corn has been the primary biofuel feedstock. Growing the crop is the most energy-expensive part of producing the ethanol fuel. Nearly 80 percent of the energy value of the ethanol made from fermented corn is put into the production of the crop in the forms of fertilizer and mechanization (Pimentel 1991).[8]

Thus, although corn-based ethanol production does result in a net energy advantage, its production remains highly dependent on fossil-derived energy. Moreover, corn grown for fuel faces the same environmental constraints as does corn grown for food: adequate arable land, soil degradation and pest problems. Corn is also the crop that uses the greatest total quantity of pesticides in the United States, and is responsible for much of the pesticide residue found in groundwater in the Midwest.

If corn-based ethanol were to meet the fuel needs of this country, it would require more than four times as much cropland as is actually and potentially available for all crops in the United States (Pimentel 1991). If corn is grown on less-productive land in order to meet this demand, it will require still greater inputs and lead to more erosion than when it is grown on higher-quality soil. Thus, unless alternative biofuel feedstocks are successfully developed and marketed (e.g. cellulosic biomass), the vision of biobased production meeting energy demand may be a mirage.

The potential for increasing the utility of biomass, especially waste products from agriculture and forestry, also provides a ray of hope for the success of a biobased economy. Now developing are biomass industries that make an array of commercial products, including fuels, electricity, chemicals, adhesives, lubricants and building materials, as well as new clothing fibers and plastics (polylactic acid polymer) (DOE 2000). Optimism is justified to the extent that biomass-based products can be derived from waste materials, thus reducing the waste stream. However, any increase in demand for biomass from the world's managed and natural forests will put greater stress on that diminishing resource. The forest-land base — now approximately 30 percent of the earth's land area — is declining at a rate of 1 percent every three years due to degradation of cropland and expansion of human settlements.

Biodiversity

Forests are a key repository, not only of biomass but also of biodiversity. While there are many compelling ecological and ethical reasons for maintaining biodiversity, the issue is perhaps particularly relevant to this consideration of a biobased economy because of the importance of biodiversity in developing medicinals. It can be expected that, in a biobased economy, the preservation of organisms will become even more critical as sources of genetic material for developing new means of alleviating and curing human diseases. However, this pool of genetic material is reduced as biodiversity declines.

The maintenance of biodiversity requires the preservation of diverse and productive habitats. However, as productive habitats are increasingly used for agriculture, biodiversity declines. The well-known report of the Brundtland Commission (World Commission 1987) recommended that 12 percent of ecologically productive land be left to non-human biota, but it is estimated that more than 90 percent of land area is already managed for agricultural or forestry production or occupied by human settlements (Western 1989).

Table 7. Threats to biodiversity in the United States. Percent of imperiled species affected by various factors; a single species may be affected by more than one factor. (The Nature Conservancy 2000)

Habitat destruction	85 percent
Alien species	49 percent
Pollution	~25 percent*
Overexploitation	17 percent
Disease	3 percent

*Primarily aquatic species

Biodiversity is affected also by run-off containing nitrogen and other pollutants from agricultural land to natural habitats. At a symposium at the February 2000 AAAS meetings, David Tilman noted that these imbalances give competitive advantage to invasive species. Experts at that symposium estimated that 50 to 70 percent of the decline and disappearance of species might be linked to invasive species that out-compete, infect or devour native species.[9] Thus, if high-input agriculture increases with greater use of nitrogen fertilizer, biodiversity is likely to decline.

Perhaps one statement can sum up the underlying threat to biodiversity: more human individuals are born each day than there are individuals in all the great ape species combined (Cincotta and Engelman 2000).

SUMMARY AND CONCLUSIONS

I want to summarize my conclusions by adding *redistribution* and *serious reassessment* to the three Rs of environmental protection: reduce, re-use and recycle. This reassessment should consider that:

- Human society is teetering close to the brink of an absolute limit to growth.
- While access to fossil energy and the inequitable distribution of the world's resources have masked the problem for some of us, it has neither been masked nor obfuscated for the malnourished half of the world's population (who also have access to few additional energy resources).
- While the transformation to a "new" biobased economy is essential, it is also likely in the short term to increase demand on stressed "renewable resources."
- In the long term, success of a biobased economy may be predicated on reducing the size, and level of consumption, of the human population.
- Land, energy and resource constraints must be factored into any creative envisioning of a "*new*" biobased economy in order to ground the proposals in the biophysical reality. Otherwise they are fantasy.
- "Recharting the course" will take tremendous political will, as well as creativity and intellectual resources.

In sum, because of resource constraints, I am skeptical that a sustainable biobased economy is possible if it is expected to continue at the pace and consumption level of the fossil-based economy that industrial and post-industrial societies have come to know in this recent snatch of human history.

The world economy will not suddenly run out of land to produce food and materials for the biobased economy. Rather, progression toward the ultimate limit to growth will be incremental, marked by increased pollution of air and water, declines in productivity of degraded soils, and reduced availability and access to fossil-fuel-derived inputs to production.

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1 In fact, rice accounts for 23 percent of world caloric intake (IRRI 2000a).

2 Data from 1992: 2,698 Calories/person/day world average; 3,732 Calories daily per capita consumption in US (IRRI 2000a).

3 In our basic grain model, we ignore the 38 percent of grain now fed to cattle.

4 The Buringh and van Heemst (1977) model assumes that two-thirds of cultivable land is cropped, that cropland is left fallow one-third of the time, and that only half of production is used for human nutrition — the rest is lost, used for seed or used as fodder. From this, they estimate the global carrying capacity for human beings at 3.5 billion, 58 percent of the current population.

5 If 3 billion tons of "rice" are needed to feed a population of 6 billion, and 0.5 tons of grain is required per person per year, four people can be fed per hectare at yield = 2 t/year and total land requirement = 1.5 billion ha (6 billion people ÷ four people/ha). At the optimistic 4.5 t/ha yield, 9 persons can be fed per ha (4.5 t/ha ÷ 0.5 t/person) and total land requirement is 0.7 billion ha (6 billion people ÷ 9 people/ha = 0.67 = 0.7).

6 Chemical synthesis of nitrogen requires about 14,700 kcal energy input per kilogram of nitrogen produced (Mudahar and Hignett 1982; Pimentel 1984). Production of a metric ton of rice removes 17 kg nitrogen from the soil. Thus 0.25 million kcal are used to manufacture nitrogen for 1 ton of edible rice (assuming for the purpose of these calculations that all nitrogen removed from soil is from chemical manufacture). The energy for nitrogen manufacture is thus about 7 percent of the 3.64 million kcal food energy value per ton of rice.

7 Twenty-one percent of the 230,000 kcal consumed daily per capita in a technological society = 48,000 kcal/person/day from renewable sources. This was the level of energy consumption in advanced agricultural/early industrial societies (Table 5).

8 One bushel of corn produces 2.5 gallons ethanol. At average United States output of 110 bushels corn/acre, 275 gallons of ethanol are produced per acre. Ethanol has only two-thirds the energy value of corn, however, so the 275 gallons has the energy equivalent of 174 gallons gasoline. The production of this ethanol has required an input equivalent of 137 gallons of gasoline for fertilizer, mechanization, etc. (an amount that will increase as corn production moves to less fertile land). Net gain is 37 gallons/acre/year (174-137=37). Fourteen acres of corn would be needed to fuel a typical car for a year, as compared with 1.5 acres cropland now used to feed each American — a nine-fold difference (Pimentel 1991).

9 This estimate is consistent with results from a recent Nature Conservancy study of threats to biodiversity in the United States, which found that habitat destruction affects 85 percent of imperiled or endangered species, and presence of alien species affects 49 percent (The Nature Conservancy 2000).