
The Eco-Footprint of Agriculture: A Far-from-(Thermodynamic)-Equilibrium Interpretation

WILLIAM E. REES

*University of British Columbia
Vancouver, BC*

Food is the most basic of all resources, and food production has effectively diverted more natural landscape to human purposes than any other ecologically significant human economic activity. Massive famines punctuate the history of human civilization—ironically, since civilization was made possible by agriculture—and, until relatively recently, fear of food shortages was a concern of most human groups.

The reason for fear of famine was most famously explained by the Reverend—and economist—Thomas Malthus in the eighteenth century, in his *Essay On the Principle of Population*. Malthus observed that “population, when unchecked, increases in a geometric ratio, subsistence increases only in an arithmetic ratio.” A modern Malthus might say that population increases exponentially (like compound interest) while food production increases only linearly (in constant increments). Regardless of how one expresses the relationship, “a slight acquaintance with numbers will show the immensity of the first power in comparison to the second...” In Malthus’s words (1798), “The race of plants and the race of animals shrink under this great restrictive law. And the race of man cannot, by any efforts of reason, escape from it.”

Most people in the developed world today believe that Reverend Malthus was wrong, that industrial “man” has indeed, “by efforts of reason, escaped from it.” Technology-based developments—from the spread of irrigation, extensive use of fertilizers, pesticides and high-yielding crop varieties, to field mechanization and expanding trade—succeeded in keeping global food production ahead of population increases through the last century, with the most spectacular results in the post-WW-II period. Meanwhile, of course, the human population has increased by 152% from 2.5 billion in 1950 to about 6.3 billion today.

But there is reason for pause. By some estimates, after three decades or more of steady increases, world grain production *per capita* has stabilized or declined since the late 1980s and we have just seen an unprecedented four sequential crop years in which global consumption has exceeded the harvest with each shortfall greater than the one before (Pimentel and Pimentel, 1999; Brown, 2004). According to Brown (2004):

The grain shortfall of 105 million tons in 2003 is easily the largest on record, amounting to five percent of annual world consumption of 1,930 million tons. The four harvest shortfalls have dropped world carryover stocks of grain to the lowest level in 30 years, amounting to only 59 days of consumption. Wheat and corn prices are at 7-year highs. Rice prices are at 5-year highs.

By some assessments, absolute levels of food production (cereals, pulses, roots and tubers) may have fallen over the past four or five years. Meanwhile, groundwater tables are falling in over half the world's agricultural areas, soil erosion is rampant, there is increasing evidence that the era of cheap energy—critical to modern agriculture—is ending and population growth continues at 1.3% per year. Are we waking Malthus's ghost?

In this context, the purpose of this paper is three-fold. First, I examine the prospects for soil/landscape conservation and maintaining adequate global food production through the lenses of ecological-footprint analysis and far-from-equilibrium thermodynamic theory. Can we keep the Malthusian spectre at bay using prevailing approaches to production? Second, I briefly examine the case for genetically modified (GM) crops, the latest “advance” in the so-called high-tech approach to food production. Third, I explain why the prevailing approach to production agriculture, including the introduction of GM crops, has proven so successful in displacing alternatives with arguably more desirable ecological and social characteristics.

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THE ECOLOGICAL FOOTPRINT OF AGRICULTURE

Ecological footprint analysis (EFA) estimates the “load” imposed on the ecosphere by any specified human population or production activity in terms of the land/water area effectively “appropriated” to sustain that population/activity (Rees,

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1992, 1996; Wackernagel and Rees, 1996). Thus, we define the ecological footprint of a study population as (Rees, 2001):

the area of productive land and water ecosystems required, on a continuous basis, to produce the resources that the population consumes and to assimilate the wastes that the population produces, wherever on Earth the relevant land/water may be located.

Agriculture contributes one of the largest components to a typical population eco-footprint (EF). This should be no surprise. Brower and Leon (1999) suggested that, next to transportation, food production (meat, poultry, fruits, vegetables and grains) causes the greatest level of environmental impact associated with the average household (Table 1) Transportation and food, together with household operations (heating of space and water, running appliances and lighting) comprise between 64% and 86% of the total ecological impact of household consumption in the several impact categories shown in Table 1.

TABLE 1. HOUSEHOLD ENVIRONMENTAL IMPACT CONTRIBUTED BY FOOD PRODUCTION/CONSUMPTION COMPARED TO TRANSPORTATION AND HOUSEHOLD OPERATIONS (FROM BROWER AND LEON, 1999)

Contribution from	Global warming	Air pollution		Water pollution		Habitat alteration	
	Greenhouse gases	Common	Toxic (%)	Common	Toxic	Water	Land
Transportation	32	28	51	7	23	2	15
Food	12	17	9	38	22	73	45
Household operations	35	32	20	21	14	11	4
Sub-total	80	77	80	67	59	86	64

A major component of the food production impact is landscape alteration. For example, about 60% of the US land area is dedicated to crop production or live-stock grazing and 45% of the nation's habitat loss or alteration is due to agriculture. (The US is the world's greatest agricultural powerhouse.)

Figure 1 shows the *per capita* cropland eco-footprints (demand) for a selection of countries, and compares these to available domestic cropland *per capita* (supply). To facilitate comparisons, estimates for each country are presented in terms of world average cropland equivalents using data from the World Wildlife Fund (WWF, 2002). Only land area actually used for growing crops is included in the calculations. Consumption by agriculture to maintain production—energy, fertilizers, pesticides, *etc.*—is accounted for in other components of the total EF. Nor does this figure include adjustments to reflect unsustainable use of cropland; such adjustments would significantly increase the agricultural eco-footprints of many countries.

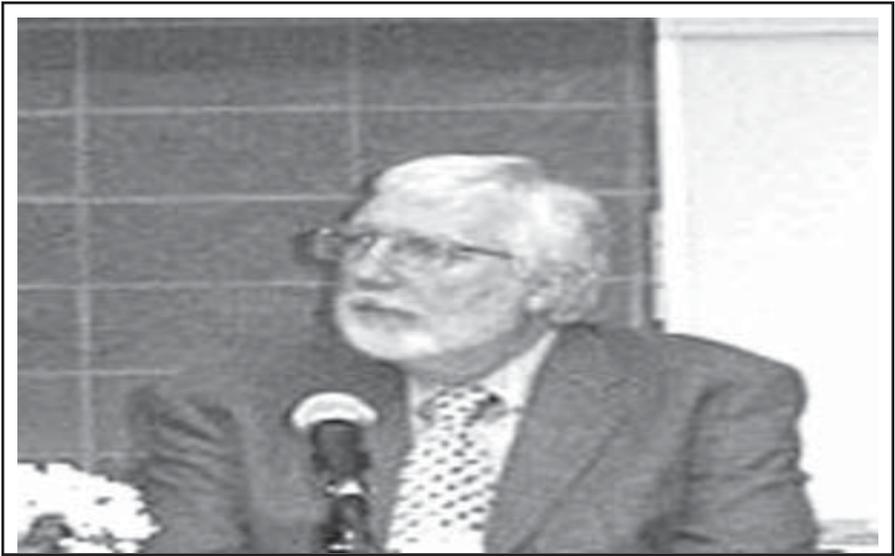


Figure 1. *Per-capita* cropland ecofootprints and domestic cropland for selected countries (1999).

Note that the area of world-average cropland used to produce the diets of today's high-income consumers can be as high as 1.5 hectares (3.7 acres) *per capita*, typically four to eight times the cropland required by the poorest of the world's poor. Canada's *per capita* demand for cropland at about 1 hectare is about twelve times that of a typical Bangladeshi or Mozambican.

With prevailing practices, it actually needn't take more than 0.5 hectares (1.2 acres) to provide a diverse high-protein diet like that enjoyed by western Europeans and North Americans (Pimentel and Pimentel, 1999). The fact that there are only 0.25 hectares of cropland available *per capita* on Earth is a measure of the difficulty in bringing the entire world population up to "northern" dietary stan-

dards. To complicate matters, the domestic cropland available in many poor countries is barely equivalent to national aggregate demand, and in some cases is considerably less (e.g., Peru and Pakistan) (Figure 1). Many densely populated countries have far less than 0.25 hectares of cropland, the area that might be considered their “fair share” of the global total. These countries have no hope of reaching a European-style diet without massive imports of food, a highly unlikely prospect given their chronic poverty and increasing competition on world food markets.

Not only poor countries are net importers of food. Wealthy countries such as Spain, the Netherlands and the United Kingdom have agricultural eco-footprints up to several times larger than their domestic agricultural land bases. Unlike the poorer developing countries, these wealthy nations have, so far, financed their considerable food-based “ecological deficits” with the rest of the world.

Actually, countries that are net food importers are more the rule than the exception. Most of the world’s 183 nations are partially dependent on food imports. Just five countries—the United States, Canada, Australia, France and Argentina—account for 80% of cereal exports and most of the safety net in global food markets (Pimentel and Pimentel, 1999). These countries have exceptionally high cropland-to-population ratios and relatively few soil constraints, and use intensively mechanized, fossil-energy dependent production methods.

It should be clear from even this brief discussion of cropland eco-footprints relative to land supply that land constraints represent a major barrier to increased food production in the future, particularly for those countries that need it the most. Increasing the total area of cropland is possible in some cases, but would require expansion of agriculture into inferior land and massive damage to remaining wildlife natural habitat. Moreover, the following section shows that cropland scarcity is only one of the problems confronting prospects for large-scale increases in food production.

THE BIOPHYSICAL CONTEXT:

FAR-FROM-EQUILIBRIUM THERMODYNAMICS

[Production] agriculture is the use of land to convert oil into food.

—Albert Bartlett

Why is thermodynamic theory relevant to the future of agriculture? Think for a moment of verdant forests, natural grasslands, thriving estuaries, salt marshes, and coral reefs, and of mineral and coal deposits, petroleum, aquifers and arable soils. These are all forms of “natural capital” that represent *highly-ordered* self-producing ecosystems or rich accumulations of energy/matter with high use potential (low entropy). Now contemplate despoiled landscapes, eroding croplands, depleted fisheries, toxic mine tailings, anthropogenic greenhouse gases, acid rain and anoxic/polluted waters. These all represent *disordered* systems or degraded forms of energy and matter with little use potential (high entropy). The

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main process connecting these two system states is human economic activity, particularly industrial activity, including production agriculture (Rees, 2003). Far-from-equilibrium thermodynamics explains why contemporary growth-bound fossil-energy subsidized development of all kinds must ultimately *necessarily* destroy the very ecosystems that support it.

The starting point for this interpretation is the second law of thermodynamics. In its simplest form, the second law states that any spontaneous change in an isolated system, one that can exchange neither energy nor matter with its environment, produces an increase in entropy. This means that when a change occurs in an isolated complex system it becomes less structured, more disordered, and there is less potential for further activity. In short, isolated systems always tend toward a state of maximum entropy, a state in which nothing further can happen.

For purposes of this discussion, imagine a homogenized, totally disordered world in which everything is evenly dispersed—there are no distinguishable forms or structures, no gradients of energy or matter. In effect, no finite point in the ecosphere would be distinguishable from any other. We can take this hypothetical randomized distribution of all naturally occurring elements and stable compounds to represent a state of maximum global entropy. It is also, by definition, a state of thermodynamic equilibrium. This is the state toward which the ecosphere would spontaneously gradually descend over time in the absence of sunlight and life. (Entropy can be likened to a relentless form of biophysical gravity.)

Of course, the real world could hardly be more different from this randomized primordial soup. The ecosphere is a highly ordered system of mind-boggling complexity, of many-layered structures and steep gradients represented by accumulated energy and differentiated matter. In the course of several billion years, the trend in the ecosphere has been one of increasing order and complexity, even after allowing for occasional catastrophic setbacks. Millions of emergent organisms have adapted to the many physical environments on Earth, co-evolved in response to each other and their physical environments, and self-organized into differentiated communities and ecosystems. In short, the ecosphere—life—has clearly been moving ever further from thermodynamic equilibrium. So fundamental is this process that, according to Prigogine (1997), “distance from equilibrium becomes an essential parameter in describing nature, much like temperature [is] in [standard] equilibrium thermodynamics.”

How is it that the ecosphere can apparently exist and evolve greater complexity apparently in conflict with the second law? The key is in recognizing that all living systems, from cellular organelles through individual organisms to entire ecosystems are complex, dynamic, *open* systems that can exchange energy and matter with their host “environments.” As Erwin Schrödinger (1945) observed, organisms are able to maintain themselves and grow “...by eating, drinking, breathing and (in the case of plants) assimilating...” Schrödinger recognized that, like any isolated system, a living organism tends continually to “produce[s] positive entropy—and thus tends to approach the dangerous state of maximum entropy, which is of death. It can only keep aloof from it, *i.e.* alive, by continually drawing from its environment negative entropy...” (“Negative entropy”—also called “negentropy” or “essergy”—is free energy available for work.) In short, rather than tending toward equilibrium, living systems, from individual foetuses to entire ecosystems, consume “extra-somatic” resources to gain in mass and organizational complexity over time.

In the case of green plants, the extra-somatic energy is actually extra-planetary. Photosynthesis is the chemical process by which plants “fix” as chemical energy a small portion of the incident solar energy reaching Earth. The plants use the resultant products—carbohydrates, fats and proteins—to produce themselves and in the process provide the fuel for most other life-forms, including humans. Indeed, photosynthesis provides the free energy and the organic material building blocks of virtually the entire ecosphere.

Appearances to the contrary, none of this violates the second law. Despite the “negentropy” represented by living, growing systems, production in the ecosphere actually increases the net entropy of the universe as expected. All living systems maintain their local level of organization at the expense of increasing global entropy, particularly the entropy of their immediate host (Schneider and Kay, 1994, 1995). As noted, the ecosphere develops and evolves—maintains itself far-from-equilibrium—by permanently dissipating solar energy. However, since photosynthesis and evapotranspiration degrade a much larger quantity of solar energy than is incorporated in the products, the entropy of the total system increases. Because individual plants, ecosystems and other self-organizing systems develop and grow by continuously degrading and dissipating available energy, they are called “dissipative structures” (Prigogine, 1997).

Like ecosystems, humans and their economies are self-organizing, far-from-equilibrium dissipative structures. However, the human enterprise is but a single sub-system, or “holon,” fully contained within the loose overlapping hierarchy of living, self-organizing, holarchic open (SOHO) systems that comprise the ecosphere (Kay and Regier, 2000). This means that the growth and development of the human enterprise are fuelled all but entirely by the products of photosynthesis, both ancient and contemporary. Human economic activity necessarily feeds on and destroys gradients of usable energy and material first produced by nature. In effect, the human enterprise is thermodynamically positioned to consume the ecosphere from the inside out (Rees, 1999).

Herein lies the proximate cause of the (un)sustainability conundrum in general and the potential crisis in agriculture in particular. Uniquely among sub-systems of the ecosphere (*i.e.*, other consumer organisms), the human enterprise is dominated by positive feedback and auto-catalytic processes. Therefore, it grows continuously, disordering the ecosphere in the process. A critic might argue that every increment of human population growth, each new factory, every addition to the world's expanding fleet of SUVs, the daily additions to the population of high-tech electronic devices, *etc.*, *etc.*, adds to the scale and complexity of the human enterprise, thus increasing internal order and seemingly moving us ever further from equilibrium. Again, however, beware the illusion—the continuous growth of the human subsystem simultaneously degrades and dissipates the very resources and ecosystems that sustain it. The increasing negentropy of the human sub-system is greatly outweighed by the increased disordering of the ecosphere: global net entropy rises with the erosion of our earthly habitat.

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THE KEYSTONE GRADIENTS—SOIL AND OIL

Arguably, the two most important gradients feeding the human enterprise are soils and fossil fuels. Arable lands and productive soils represent concentrated stocks of the nutrients and organic matter essential for food production. The vital components in soil have accumulated over thousands of years of negentropic interaction among parent soil material, climate and thousands of species of bacteria, fungi, plants and animals, both below and above ground. However, since the dawn of farming 8,000 to 10,000 years ago, agricultural practices have tended to degrade soils and even entire landscapes. This entropic process has tended to accelerate the more allegedly “sophisticated” and productive our agricultural technology becomes. Agriculture-induced erosion, water-logging, acidification, and salination of soils, combined with the dissipation of nutrients (removed with the harvest) and organic matter (the oxidation of agricultural soils is a major source of anthropogenic atmospheric carbon dioxide), have seriously compromised the productivity of large areas of cropland around the world. Since virtually all the readily cultivable land on Earth is already under the plough, more land is coming out of production today because of degradation than is being brought into production.

In recent decades, high-yielding crop varieties, abetted by fossil-energy subsidized irrigation and mechanization and agricultural chemicals (the latter also partly derived from fossil hydrocarbons) have more than compensated for losses of land and natural soil fertility while actually accelerating these losses. Global food production continued to outpace population growth. But, as noted at the outset, ebullience over the so-called “Green Revolution” has been somewhat muted lately

. . . challenges to agriculture in the twenty-first century:

as the growth of food production stalls and there is increasing evidence that the era of cheap, accessible fossil fuel is coming to an end; accessible reserves are rapidly being dissipated. In this light, consider the following challenges to agriculture in the twenty-first century:

- To keep pace with UN medium population-growth projections, food production will have to increase by 57% by 2050. Improving the diets of billions of people could push the increase toward 100%.
- By 1990, 562 million hectares (38%) of the roughly 1.5 billion hectares in cropland had become eroded or otherwise degraded, some so severely as to be taken out of production. Since then, 5 to 7 million hectares have been lost to production annually (SDIS, 2004). According to the UN Food and Agriculture Organization (FAO, 2000), a cumulative 300 million hectares (21%) of cultivated land—enough to feed almost all of Europe—has been so severely degraded “as to destroy its productive functions.” Only 35% of global arable land is free from degradation.
- Depending on climate and agricultural practice, topsoil is being “dissipated” sixteen to 300 times as fast as it is regenerated.
- Fifty-eight countries, including twenty-one in Europe have no undegraded cropland. More than 60% of the croplands of fifteen European, and twenty-five Asian, African and Latin American nations are severely or very severely degraded (FAO, 2000).
- Since 1967, intensification of agriculture—double-cropping, irrigation, mechanization and chemicals—has accounted for 79 to 96% of the increased yields of wheat, rice and maize (Cassman, 1999). Fossil energy is a major factor, both as a feedstock in fertilizer and pesticide production and as a direct energy source. Primary level (farm level) agriculture in Canada, for example, now represents 5% of the national energy budget and energy accounts for 20% of annual farm expenses (CAEEDAC, 1998).
- While sparing natural ecosystems from conversion to agriculture, this intensification of crop production has accelerated the degradation/dissipation of natural soils, disrupted nutrient cycles, lowered groundwater tables, and contributed to ground and surface water pollution (Cassman, 1999; FAO, 2000; Gregory *et al.*, 2002; Matson *et al.*, 1997).
- Consistent with the above, growing populations and increasing land constraints suggest that any future increase in agricultural output on the current path will depend largely on further intensification of irrigation, chemical inputs and mechanization, *i.e.*, ever-greater reliance on fossil energy stocks. This, in turn, implies increased ecological damage (Conforti and Giampetro, 1997).

- Fossil energy supplies may be problematic. Petroleum reserves are finite and global consumption of oil has exceeded discovery for at least 20 years. North American petroleum reserves and production have been in decline even longer and natural gas is now also declining. In response to rising demand, North American domestic natural gas prices have risen steeply and are now 300% or more above those of just a few years ago. Several fertilizer plants have closed or moved operations to Eurasia for reasons of rising costs and diminishing feedstocks. According to various industry experts, global conventional petroleum output is likely to peak within this decade (Campbell, 1999; Duncan and Youngquist, 1999; Laherrere, 2003; Longwell, 2002). Other analysts argue that we still don't know enough to choose among different energy-supply scenarios or among feasible renewable energy technologies (Hall *et al.*, 2003). Given the uncertainty over suitable substitutes for many uses of liquid, portable fossil fuel, still others are speculating on the implosion of industrial civilization (*e.g.*, Duncan, 1993). Manning (2004) provided an engaging popular account of the crisis.
- Because of market conditions, land degradation, and diminishing returns from inputs, the area of irrigated cropland has declined by 12% and the use of fertilizers by 23% from peak levels. Grain production *per capita* has been in decline for almost a decade and aggregate food production has fallen for the past 4 years (Pimentel and Pimentel, 1999; Brown, 2004; EarthTrends Data tables compiled from UN-FAO statistics).
- Partially as a result, millions are plagued by hunger. As many as 800 million people remain chronically malnourished and up to 3 billion have inadequate diets. (Contributing to this are patterns of land-ownership and trade that deny impoverished people access to either land for subsistence agriculture or commercially produced food. The poor often cannot participate in food markets for want of cash. Thus, some countries with serious food shortages and nutritional problems are net exporters of luxury cash crops for first world markets.)

The foregoing makes clear that the Green Revolution has by no means been an unqualified success. Food production has increased dramatically in the past 50 years, but this has allowed a 156% increase in the human population. The result is that we now have over 6 billion people, on the way to perhaps 9 billion by the middle of the century, all with rising expectations and all dependent on a bio-physical resource base that has been severely eroded by the same agricultural revolution that made their existence possible. Ominously, various important crops in all categories seem to be approaching production plateaus in many parts of the world.

ARE TRANSGENIC CROPS THE SOLUTION?

How has mainstream agricultural science responded to this complexity of problems? Probably the major development in recent years has been the development and rapid introduction of transgenic or genetically modified crops. The most frequently cited potential benefits of transgenic crop varieties include:

- use of fewer, less-toxic or less-persistent pesticides,
- potential for increased crop yields, thus reducing the pressure to convert pasture, woodlands, and other habitats and land-types to agricultural production,
- decreased water use, thus conserving water and providing a buffer against climate change,
- reduced soil tillage and an attendant reduction in mineralization and erosion.

Ostensibly to take advantage of these benefits, transgenic crops (TCs) have become an increasingly dominant feature of the agricultural landscapes of the United States and other countries such as China, Argentina, Mexico and Canada. Between 1986 and 1997, an estimated 25,000 field trials were conducted on more than sixty crops using ten traits in forty-five countries. Worldwide, the areas planted to transgenic crops increased dramatically from 1996 to 1999, from 3 million hectares in 1996 to nearly 40 million hectares in 1999 (Altieri, 2000, 2004). This is no small incursion into the agricultural landscape. According to Altieri (2000): “In the USA, Argentina and Canada, over half of the acreage for major crops such as soybean, corn and canola are planted in transgenic varieties. Herbicide-resistant crops and insect-resistant crops (*Bt* crops) accounted respectively for 54 and 31% of the total global area of all crops in 1997.”

Is this significant commitment paying off? Regrettably, the jury is still out. Despite their own extensive survey, Ervin *et al.* (2000) stated that: “Most studies of the environmental effects of transgenic crops have been confined to laboratories or small fields. The lack of detailed environmental impact data required for commercial approval and releases has hindered risk and benefit assessment efforts.” Nevertheless, some trends do seem to be emerging in two of the key areas pertaining to pesticide use and yield.

As noted, the initial expectation was that farmers who planted TCs would use fewer or less-toxic pesticides, thus reducing the negative ecological effects of intensive agriculture. The rapid spread of these crops suggests that some farmers are benefiting economically, perhaps mainly from simplified weed control. However, various analysts have concluded that, with the possible exception of *Bt* cotton, there is little evidence that pesticidal and herbicide-resistant TCs require less pesticide. Roundup Ready® soybeans actually require up to 30% more herbicide than the conventional counterpart, despite claims to the contrary (Benbrook, 2001a).

More generally, herbicide-tolerant varieties seem to have modestly reduced the average number of active ingredients applied per acre but have modestly increased the average pounds applied per acre. Depending on the measure used, these crops have either reduced or increased pesticide requirements—either measure alone gives an incomplete picture of the overall impact of herbicide-tolerant varieties on pesticide use and the sustainability of weed-management systems (Benbrook, 2001b). The bottom line is that it is too early to know the long-term impact of transgenic plants on pesticide use—TCs may induce entirely new patterns and volumes of total pesticide use. “Unfortunately, at this stage in crop biotechnology, the cumulative shifts in use of many pesticide compounds are mostly uncertain” (Ervin *et al.*, 2000).

The effect of transgenic varieties on yield is no less ambiguous. Proponents of TCs argue that increased yield would reduce the need for further land conversions for agriculture. However, this simplistic view ignores the multiple possible interactions of different kinds of genetic modification with pest conditions, weather factors, soil types, *etc.* (Ervin *et al.*, 2000). Keep in mind, too, that the most widely accepted transgenic varieties, such as Roundup Ready® soybeans, were not intended to achieve yield increases. Even in the case of *Bt* cotton and corn, increased yield projections were based only on improved pest control and results have been variable (Ervin *et al.*, 2000). On the negative side, there is solid evidence that Roundup Ready® soybean cultivars produce 5 to 10% fewer bushels per acre in contrast to otherwise identical varieties grown under comparable field conditions (Benbrook, 2001a). In the longer term, it is possible that transgenes involving the manipulation of basic physiological processes such as photosynthesis will improve yields dramatically, but this will likely be accompanied by complications such as increased demand for water and nutrients. At present, there is no empirical evidence that TCs change water use or tillage requirements.

While the promise of TCs has yet to be unambiguously realized, numerous authors have speculated on the potential for serious ecological damage. Emergent and anticipated problems include (Rissler and Mellon, 1996; Altieri, 2000, 2004):

- spread of TCs threatens crop genetic diversity by simplifying cropping systems and promoting genetic erosion,
- potential transfer of genes from herbicide-resistant varieties to wild or semi-domesticated relatives thus, creating super weeds (a form of genetic pollution),
- herbicide-resistant volunteers become weeds in subsequent crops,
- use of herbicide-resistant crops undermines possibilities for crop diversification, thus reducing agrobiodiversity in time and space,
- vector-mediated horizontal gene transfer and recombination could create new pathogenic bacteria,
- vector recombination could generate new virulent strains of virus, especially in transgenic plants engineered for viral resistance with viral genes,

The net benefits of many transgenics, even to producers, are by no means clear and their widespread use poses a range of threats to food security.

- adverse effects on non-target organisms,
- insect pests are developing resistance to crops with *Bt* toxin (as they do to synthetic biocides).

In short, the net benefits of many transgenics, even to producers, are by no means clear and their widespread use poses a range of threats to food security (quite apart from any possible risk associated with consuming genetically engineered food). It is telling, in this light, that the transgenic revolution is being developed and promoted by the same corporate interests that brought us the first wave of agrochemically based agriculture. Altieri (2004) argues: “As long as transgenic crops follow closely the pesticide paradigm, such biotechnological products will do nothing but reinforce the pesticide treadmill in agroecosystems, thus legitimizing the concerns that many scientists have expressed regarding the possible environmental risks of genetically engineered organisms.”

In summary, at this stage it seems that (Wolfenbarger and Phifer, 2000):

neither the risks nor the benefits of [GM organisms] are certain or universal. Both may vary spatially and temporally on a case-by-case basis... At the same time there is increasing evidence of significant unanticipated negative consequences to the unchecked spread of transgenics. Our capacity to predict ecological impacts of [GM organisms] is imprecise and [available data] have limitations.

WHY DO WE STAY THIS ERRATIC COURSE?

Wall Street science will find only what satisfies Wall Street. The fact that it is championed as sound science makes it no more sound or truthful than a cult leader on an ego trip (Salatin, 2004).

More than a decade ago, a World Resources Institute study compared conventional and organic farming practices in Pennsylvania and Nebraska. In Pennsylvania, conservation cultivation of corn and corn-soybean production eliminated chemical fertilizer and pesticides, cut costs by 25%, reduced erosion by 50% and actually increased yields over conventional norms after 5 years. Researchers estimated that these practices would reduce off-farm damages by \$75 per hectare of farmland, and avoid 30-year income losses (present value \$306 per hectare) by preventing a 17% loss in soil fertility. All things considered, the resource-conserving practices outperformed conventional approaches in economic value per hectare

by a two-to-one margin. In flat-land Nebraska, where the costs of erosion are lower, low-input cultivation was slightly less financially competitive than the prevailing high-input corn-bean rotation but was found to be environmentally superior overall (Faeth *et al.*, 1991, cited in WRI, 1992).

This is only one of many studies suggesting that more-sustainable agricultural practices work and can be learned by farmers in developed as well as less-developed countries. Indeed, enough evidence is available to suggest that low-input ecologically based agro-technologies could contribute to food security at many levels.

Just how productive and sustainable agroecological systems are is to some degree still an empirical question. Certainly, as critics of alternative production systems like to point out, there may be lower yields of particular crops than in high-input conventional systems. Yet, as Altieri *et al.* (2004) argued:

All too often it is precisely the emphasis on yield—a measure of the performance of a single crop—that blinds analysts to broader measures of sustainability and to the greater per-unit-area productivity obtained in complex, integrated agroecological systems that feature many crop varieties together with animals and trees. There are also cases where even yields of single crops are higher in agroecological systems that have undergone the full conversion process.

Altieri *et al.* (2004) recognized that some of this apparent advantage may be due to the well known inverse relationship between farm size and production—smaller farms make far more productive use of the land resources than do large farms. Yet, in some situations:

even medium- and large-scale producers are increasingly making use of the agroecological approach, recognizing the advantages of these principles and techniques over conventional approaches.

If agroecology and other approaches to sustainable agriculture show such promise, why is it that mainstream agro-biotechnology remains steadfastly focused on chemically based agriculture and genetic engineering? Part of the answer emerges from the fundamental “value program” that underpins techno-industrial society. John McMurtry (2004) built the case that:

the deep causal structure at work in the cumulative environmental catastrophe of our era is the deciding values of the global market economy itself.

The dominant value-system of our contemporary growth-oriented globalizing world is a social construct that philosopher McMurtry (1998) refers to as “the money sequence of value”: “The name of the game of the money sequence of value is to maximize money or money-equivalent holdings as a good in itself...” Money is invested in processes or commodities that lead to more money outputs

for investors in a kind of self-perpetuating economic perpetual motion machine. Since its proponents purport to believe that this system has the potential to enhance human well-being better than any other, it follows that any other value or position that opposes it must be overridden. Dominance of the money sequence of value is thus ruinous to the alternative life sequence of value” (investment in things that sustain life leads to more opportunities for life). The money sequence of value (McMurtry, 1998):

now expropriates and attacks the civil commons at its edges, trunk and roots, ‘privatizing,’ ‘axing,’ and ‘developing’ so that its life-spaces and functions are stripped across society with no sense of loss.

It follows that in this value framework, the decisions of the marketplace are supreme.

McMurtry’s framing of the global market paradigm provides a perfect context for Jack Manno’s explanation of why certain goods become “privileged” in modern societies. Manno (2000) asked:

Why, when it is clearly rational...to do so, can’t we put at least as much attention and resources toward conserving energy and materials as we do toward mining and harvesting more and more?...Why not do as much research into organic agriculture as the fertilizer and pesticide [and TC] industries do on their R&D? Why do we not spend as much on disease prevention as we do on pharmaceuticals and high-tech treatments?

The choices seem self-evident, yet it is just as obvious that modern society is not about to pour anything like the equivalent resources into alternative energy systems, sustainable agriculture, public health, etc., as it does into the prevailing ecologically destructive alternatives.

If anything, the opposite is true: ecologically destructive ways of living are continually spreading into societies and cultures that once managed to live more frugally and in balance with nature. Why? (Manno, 2000).

Manno answered his own question by arguing that in market societies goods with certain qualities tend to be favoured over all others (Table 2). Driven by the money sequence of values, markets automatically work to address every human need and desire with those goods that can most easily be produced for market and sold. Other goods and services—even those that might give more satisfaction and cause less damage—tend to wither and fade away. For example, “soil additives, chemical fertilizers, and insecticides (and we might add GM seeds) are all products patented, packaged, distributed and sold. The farmer who knows and protects the soil from erosion and overuse has as her most important product her knowledge and skill, which cannot easily be packaged and sold” (Manno, 2000). Thus the hard-edged products of commerce dominate agriculture today while the softer intimate knowledge of the land fades from cultural memory.

**TABLE 2. SELECTED CHARACTERISTICS OF PRIVILEGED COMMODITIES
CONTRASTED WITH THOSE OF NON-PRIVILEGED COMMODITIES
(AFTER MANNO, 2000).**

Attributes of goods and services with low commodity potential	Attributes of goods and services with high commodity potential
Openly accessible—widely available; difficult to establish property rights; hard to price and market.	Appropriable—excludable; enclosable; assignable; easy to establish property rights; easily priced and marketed.
Rooted in local ecosystems and communities.	Mobile and transferable; easy to package and transport.
Particular, customized, decentralized and diverse; unique to each culture and environment.	Universal, standardized, centralized and uniform; adaptable to multiple contexts.
Systems-oriented—development occurs in context of wider system; goal is overall optimization; products develop to serve the system.	Product-oriented—development focuses on maximizing output; goal is profit maximization; system is transformed to serve the product.
Dispersed energy—energy is used and dissipated at the site of the activity or at point of exchange or consumption.	Embodied energy—production is energy intensive; packaging, promotion and transportation add to energy ‘content’ of the product.
Low capital intensity.	High capital intensity.
Design follows and mimics natural flows and cycles.	Design resists or alters natural flows and cycles.
Variable—unpredictable, unreliable, discontinuous.	More stable—predictable, reliable, continuous.
Contributes little to GDP—non-market goods don’t show up in national statistics.	Contributes to GDP—GDP is essentially a measure of marketed goods and the scale of commoditization.

Various material inputs to “traditional” production agriculture—fertilizer, pesticides, irrigation equipment, mechanized tools and equipment—all possess the properties of highly commoditizable goods and services, the kinds so privileged by techno-industrial society and its money sequence of value. Genetically modified seeds and genetic material generally share these qualities, particularly since the courts have supported the rights of firms to patent and licence the use of “their” inventions for profit.

Manno (2000) calls this subtly unconscious process “commoditization”:

At its core, commoditization is the continuous pressure to transform as much of the necessities and pleasures of life as possible into commercial commodities.

Given the nature of the market economic process, it is to be expected that many of the qualities that characterize privileged commodities are precisely the qualities that concentrate energy and materials and do the greatest ecological and social damage.

Even a cursory look at Table 2 confirms that the various material inputs to “traditional” production agriculture—fertilizer, pesticides, irrigation equipment, mechanized tools and equipment—all possess the properties of highly commoditizable goods and services, the kinds so privileged by techno-industrial society and its money sequence of value. Genetically modified seeds and genetic material generally share these qualities, particularly since the courts have supported the rights of firms to patent and licence the use of “their” inventions for profit. Little wonder that the transgenic revolution in agriculture is being brought to us by “the same corporate interests that brought us the first wave of agrochemically-based agriculture” (Altieri, 2004). As Salatin suggested, what passes for “sound science” in the marketplace is that science that adds the most to the short-term corporate bottom line. Contemporary sound science in agriculture may well be “killing” us (Salatin, 2004).

EPILOGUE

According to popular and even much “scientific” belief, the good Reverend Malthus’s dismal theorem has long been put to rest. However, the foregoing analysis suggests that, despite advances in technology, humanity may yet be confronted

The aggregate human ecological footprint of consumption and waste dissipation made possible by abundant energy supplies is 20% greater than the biocapacity of the planet.

with a global food/population crisis in coming decades. The industrial revolution and industrial agriculture greatly increased global food production and staved off starvation for billions in the twentieth century, but hundreds of millions more have yet to join the table, and the human family is expected to grow by an additional 2 to 3 billion in the first half of this century. Meanwhile, increased intensity of crop production has accelerated the degradation of arable soils, irreversibly dissipating thousands of years' accumulations of vital nutrients and organic matter. While irrigation, mechanization and chemical inputs have temporarily made up for productivity losses, these technologies are dependent on fossil fuels that are, in turn, rapidly being consumed.

The second law of thermodynamics cannot be overturned. The much-exalted seemingly vibrant far-from-equilibrium state of the modern human enterprise, and the very existence of today's 6.3 billion people, is possible only because of the prior accumulation of large stocks of natural capital (resource stocks). In particular, since 1850, the plot of human population growth is virtually identical with the plot of fossil energy usage. Unfortunately, the most critical of our natural capital stocks—soils and oil—are rapidly being irreversibly depleted and the dissipated by-products (e.g., carbon dioxide) now threaten to double the damage through climate change. Meanwhile, the aggregate human ecological footprint of consumption and waste dissipation made possible by abundant energy supplies is 20% greater than the biocapacity of the planet (WWF, 2002).

The introduction of transgenic crops is arguably just one more step down the slippery slope toward entropic disorder and systemic chaos.

This situation is not sustainable. To the truly rational mind—not the merely self-interested utility-maximizing economic mind—it would seem to call for a radical change in humanity's relationship to the ecosphere. Ecosystems are self-producing and self-perpetuating, and in the right physical environments they accumulate species, biomass and life-giving nutrients while forever recycling the chemical basis for life. By contrast, industrial agroecosystems are self-consuming quasi-parasitic systems that shed biodiversity, dissipate energy and nutrients and convert natural cycles into terminal throughput. Attempting to maximize pro-

duction of a single variable—the food crop—using an external energy subsidy destroys the structure and functional integrity of the whole. The introduction of transgenic crops is arguably just one more step down the slippery slope toward entropic disorder and systemic chaos.

In these circumstances, we need instead “an agriculture that more nearly mimics the structure and functions of natural ecosystems” (Jackson, 2004). Indeed, we need to extend the concept of biomimicry to the whole-systems level. Species in ecosystems co-evolve in mutual dependence and support. Ecosystems are autopoietic: the relationships among the interacting components—living organisms—are essential for the continued production and functioning of the components themselves (Maturana and Varela, 1987). We humans must learn to be a constructive participant in, rather than a combatant against, the ecosystems that sustain us. Adopting this goal would actually move us toward a much more intensely knowledge-based system of agriculture. Ecologically sustainable agriculture requires a vastly more sophisticated understanding of complex systems theory and ecosystems behavior than does the corporate, high-input, “brute force” production agriculture ravaging the planet today. Ecosystems science should become the agricultural biotechnology of the twenty-first century. Without an evolutionary ecologically based agriculture, our arable lands and soils, our rural families and communities, will continue to languish in a state of siege.

Ecologically necessary and economically feasible, sustainable agriculture based on an agroecological model is also socially desirable for rural areas. The realistic pricing of resources, attention to the ecology of land, and eco-technology implies a return to smaller farms and more labor- and information-intensive practices. The countryside might, therefore, regain population as human labor and ingenuity once more become an important (renewable) factor in primary food production. In this way, sustainable agriculture would help restore an historical cultural landscape through salvation of the family farm and revitalization of dependent communities. Meanwhile, urban society would reap special dividends with the restoration of ecological diversity and beauty to the rural landscape, and through reduced pollution of air, water, and soil and other off-farm impacts. We might even enjoy more-wholesome, safer food.

If Homo sapiens does not learn to live within the means of nature, we will wind up permanently dissipating our habitat.

The motive for the needed revolution is simple and strong. If *Homo sapiens* does not learn to live within the means of nature, we will wind up permanently dissipating our habitat. Resources degraded, the human enterprise would necessarily plunge toward a new (and dismal) closer-to-equilibrium state. Food production could fall below pre-industrial levels and the human population to fewer than 2 billion.

REFERENCES

- Altieri MA (2000) Executive Summary, International Workshop on the Ecological Impacts of Transgenic Crops. March 2–4, 2000. <http://www.biotech-info.net/summary1.pdf>.
- Altieri MA *et al.* (2004) The Potential of Agroecology to Combat Hunger in the Developing World. *Agroecology in Action*. Berkeley: University of California. http://www.agroeco.org/doc/the_potential_of_agroecology.html.
- Altieri MA (2004) The Ecological Impacts of Transgenic Crops on Agroecosystem Health. *Agroecology in Action*. Berkeley: University of California. http://www.agroeco.org/doc/the_ecological_impacts.html.
- Benbrook, M (2001a) Troubled Times Amid Commercial Success for Roundup Ready Soybeans. *AgBioTech Infonet Technical Paper #4*. Sandpoint Idaho: Northwest Science and Environmental Policy Center.
- Benbrook M (2001b) Do GM crops mean less pesticide use? *Pesticide Outlook* (Royal Society of Chemistry) October 2001.
- Brower M Leon W (1999) *The Consumer's Guide to Effective Environmental Choices*, New York: Three Rivers Press.
- Brown LR (2004) World Food Security Deteriorating: Food Crunch in 2005 Now Likely. Washington, DC: Earth Policy Institute. <http://www.earth-policy.org/Updates/Update40.htm>.
- Canadian Agricultural Energy End-Use Data Analysis Center (CAEEDAC) (1998) *Energy Consumption in the Canadian Agricultural and Food Sector* (Report Presented to Agriculture and Agri-Food Canada). Saskatoon: Canadian Agricultural Energy End-Use Data Analysis Center, University of Saskatoon.
- Campbell CC (1999) The Imminent Peak of World Oil Production. <http://www.hubbertpeak.com/campbell/commons.htm>.
- Cassman KG (1999) ecological intensification of cereal production systems: yield potential, soil quality, and precision agriculture. *Proceedings of the National Academy of Sciences* 96 5952–5959
- Conforti P Giampietro M (1997) Fossil Energy Use in Agriculture: An International Comparison. *Agriculture, Ecosystems and Environment* 65 231–243.
- Duncan RC (1993) The Life-expectancy of Industrial Civilization: The Decline to General Equilibrium. *Population and Environment* 14 325–357.
- Duncan RC Youngquist W (1999) Encircling the peak of world oil production. *Natural Resources Research* 8 219–232.
- Ervin D *et al.* (2000) *Transgenic Crops: An Environmental Assessment*. Morrilton: Wallace Centre for Agriculture and Environmental Policy at Winrock International.
- Faeth P *et al.* (1991) *Paying the Bill: US Agricultural Policy and the Transition to Sustainable Agriculture*, Washington: World Resources Institute.
- Food and Agriculture Organization (FAO) (2000) *Land Resource Potential and Constraints at Regional and Country Levels*. Rome: Land and Water Development Division, Food and Agriculture Organization of the United Nations.

- Gregory PJ *et al.* (2002) Environmental consequences of Alternative Practices for Intensifying Crop Production. *Agriculture, Ecosystems and Environment* 88 279–290.
- Hall C *et al.* (2003) Hydrocarbons and the evolution of human culture. *Nature* 426 318–322.
- Jackson W (2004) Agriculture: The primary environmental challenge of the 21st Century. In: *The Human Ecological Footprint* (Chesworth W *et al.* Eds.). Guelph: Faculty of Environmental Sciences, 85–99.
- Kay J Regier H (2000) Uncertainty, complexity, and ecological integrity. In: *Implementing Ecological Integrity: Restoring Regional and Global Environment and Human Health*. NATO Science Series IV: Earth and Environmental Sciences, Vol. 1 (Crabbé P *et al.* Eds.). Dordrecht: Kluwer Academic Publishers, 121–156.
- Laherrere J (2003) Forecast of oil and gas supply to 2050. Paper presented to Petrotech 2003, New Delhi. <http://www.hubbartpeak.com/laherrere/Petrotech090103.pdf>.
- Longwell HJ (2002) The future of the oil and gas industry: Past approaches, new challenges. *World Energy* 5 102–105.
- Malthus TR (1798) *An Essay on the Principle of Population: A View of its Past and Present Effects on Human Happiness; with an Inquiry into Our Prospects Respecting the Future Removal or Mitigation of the Evils which It Occasions* (Sixth Edition, 1826). London: John Murray.
- Manning R (2004) The oil we eat: following the food chain back to Iraq. *Harper's Magazine* 2 37–45.
- Manno J (2000) *Privileged Goods*. Boca Raton: Lewis Books.
- Maturana H Varela F (1987) *The Tree of Knowledge*. Boston: Shambala.
- Matson PA *et al.* (1997) Agricultural intensification and ecosystem properties. *Science* 277 504–509.
- McMurtry J (1998) *Unequal Freedoms: The Global Market as an Ethical System*. Toronto: Garamond Press.
- McMurtry J (2004) The life code versus the money code of value: Understanding the planetary ecological crisis. In: *The Human Ecological Footprint* (Chesworth W *et al.* Eds.). Guelph: Faculty of Environmental Sciences, 115–134.
- Pimentel D Pimentel M (1999) Population growth, environmental resources and global food. *Journal of Sustainable Forestry* 9 35–44.
- Prigogine I (1997) *The End of Certainty: Time, Chaos and the New Laws of Nature*. New York: The Free Press.
- Rees WE (1992) Ecological footprints and appropriated carrying capacity: What urban economics leaves out. *Environment and Urbanization* 4 121–130.
- Rees WE (1996) Revisiting carrying capacity: Area-based indicators of sustainability. *Population and Environment* 17 195–215.
- Rees WE (1999) Consuming the earth: The biophysics of sustainability. *Ecological Economics* 29 23–27.

- Rees WE (2001) Ecological footprint, concept of. In: Encyclopedia of Biodiversity Vol. 2 (Levin S Ed-in-Chief). San Diego: Academic Press 229–244.
- Rees WE (2003) Economic development and environmental protection: an ecological economics perspective. *Environmental Monitoring and Assessment* 86 29–45
- Rissler J Mellon M (1996) *The Ecological Risks of Engineered Crops*. Cambridge: MIT Press.
- Salatin J (2004) Sound science is killing us. *Acres* 34.
http://www.acresusa.com/toolbox/reprints/April04_Salatin.pdf.
- Schneider ED and Kay JJ (1994) Complexity and thermodynamics: toward a new ecology. *Futures* 26 626–647.
- Schneider ED Kay JJ (1995) Order from disorder: the thermodynamics of complexity in biology. In: *What is Life: The Next Fifty Years. Reflections on the Future of Biology* (Murphy MP O'Neill LAJ Eds.). Cambridge: Cambridge University Press.
- Schrödinger E (1945) *What is Life: The Physical Aspect of the Living Cell*. Cambridge: Cambridge University Press.
- Sustainable Development Information Service (SDIS) (2004) *Disappearing Land: Soil Degradation*. Sustainable Development Information Service, Global Trends. Washington: World Resources Institute. <http://www.wri.org/wri/trends/soilloss.html>.
- Wackernagel M Rees WE (1996) *Our Ecological Footprint: Reducing Human Impact on the Earth*. Gabriola Island, BC: New Society Publishers
- Wolfenbarger LL Phifer PR (2000) The ecological risks and benefits of genetically engineered plants. *Science* 290 12 2088–2093.
- World Resources Institute (WRI) (1992) *World Resources 1992–93*. Oxford and New York: Oxford University Press.
- World Wide Fund (WWF) (2002) *Living Planet Report 2002*. Gland, Switzerland: World Wide Fund For Nature International.



WILLIAM REES has taught at the University of British Columbia since 1969 and is currently professor in the School of Community and Regional Planning. His teaching and research emphasize the public policy and planning implications of global environmental trends and the necessary ecological conditions for sustainable socioeconomic development.

Much of Dr. Rees's work is in the realm of ecological economics and human ecology. He is best known in this field for his invention of "ecological footprint analysis," a quantitative tool that estimates humanity's ecological impact on the ecosphere in terms of appropriated ecosystem (land and water) area. This research reveals the fundamental incompatibility between continued material economic growth and ecological security, and has helped to reopen debate on human-carrying capacity as a consideration in sustainable development.

Rees is currently a co-investigator in the Global Integrity Project, oriented toward determining the necessary ecological conditions for biodiversity preservation. He has been lectured on his work across Canada and the United States, as well as in Australia, Austria, China, Finland, Germany, Great Britain, Japan, Mexico, the Netherlands, Norway, Indonesia, Italy, Korea, the former Soviet Union, Spain, Sri Lanka, and Sweden.

In 1996, he was awarded a UBC Killam Research Prize in acknowledgement of his research achievements.