Peak Farmland and the Prospect for Land Sparing

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Expecting that more and richer people will demand more from the land, cultivating wider fields, logging more forests, and pressing Nature, comes naturally. The past half-century of disciplined and dematerializing demand and more intense and efficient land use encourage a rational hope that humanity's pressure will not overwhelm Nature. Beginning with the examples of crops in the large and fast-developing countries of India and China as well as the United States, we examine the recent half-century. We also look back over the past 150 years when regions like Europe and the United States became the maiden beneficiaries of chemical, biological, and mechanical innovations in agriculture from the Industrial Revolution. Organizing our analysis with the *ImPACT identity*, we examine the elements contributing to the use of land for crop production, including population, affluence, diet, and the performance of agricultural producers.

India and China

In 1960 the population of India was about 450 million. In 1961, Indian affluence, as measured by GDP, equaled about 65 billion recent US dollars (World Bank 2012). The average Indian consumed 2,030 food calories (kilocalories) per day, a level that approaches minimum calorie thresholds for hunger.[1] Indian farmers tilled 161 million hectares (MHa) of land to grow crops, while the country imported a net 4 million to 10 million tons[2] a year of cereal grains, over 6 percent of its demand on average during the decade of the 1960s (Food and Agriculture Organization [FAO] 2012). In the United States in 1960, youngsters were admonished to finish their peas and be grateful that theirs was not the lot of the hungry children in India.

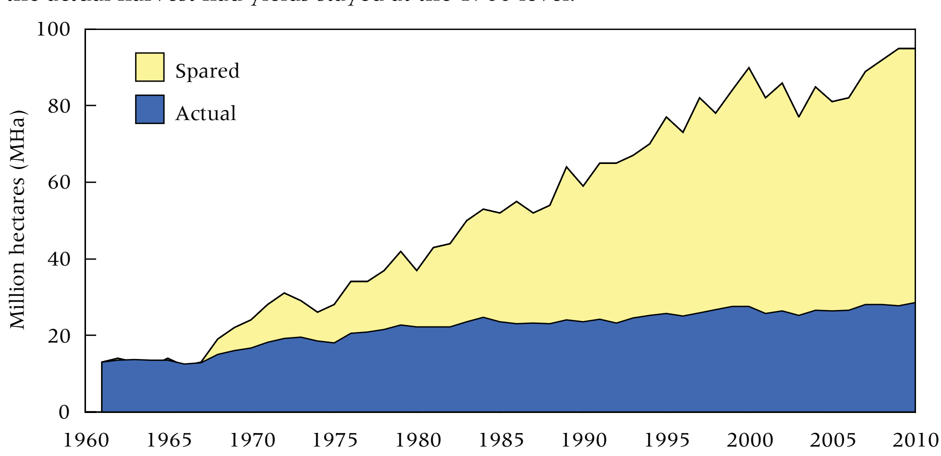
The years between 1960 and 2010 saw more babies, more affluence, and better nutrition. India's population rose over two and a half times, while national income rose 15 times. By 2010, the average Indian ate a sixth more calories than in 1960. While a majority of Indians still lived in the countryside, many moved to the cities, where they depended less on forest resources (Chandramouli 2011; Ministry of Environment and Forests, Government of India 2009). The 15 MHa added to Indian forests from the 1960s to 2000 exceeds the size of the state of Iowa in the US. The reversal of deforestation hints at an associated peak in farmed land.

India, which had net imports of wheat throughout the 1960s, had net exports in four years between 1970 and 1989 and 11 years between 1990 and 2009 (FAO 2012). Because of agricultural technologies introduced in the 1960s and 1970s and persistent efforts to raise yields since, cropland occupied only 5 percent more land, 170 MHa, in 2009 (FAO 2012).

As depicted in Figure 1, the actual land harvested for wheat in India rises as a plateau against a Himalayan-like background, the amount of land that would have been harvested absent the productivity gains since 1960. The 65 MHa of land spared is an area the size of France or more than four Iowas. After the Green Revolution received its name during the 1960s, the land sparing continued into the twenty-first century. Unlike some other revolutions of that era, this one has proven enduring and provides the continuing benefit of reducing cropland expansion to feed ever more mouths.

FIGURE 1 Actual and potential land used for wheat production, India 1961–2010

Upper segment shows the hectares farmers would have tilled to produce the actual harvest had yields stayed at the 1960 level.



SOURCE: FAO (2012).

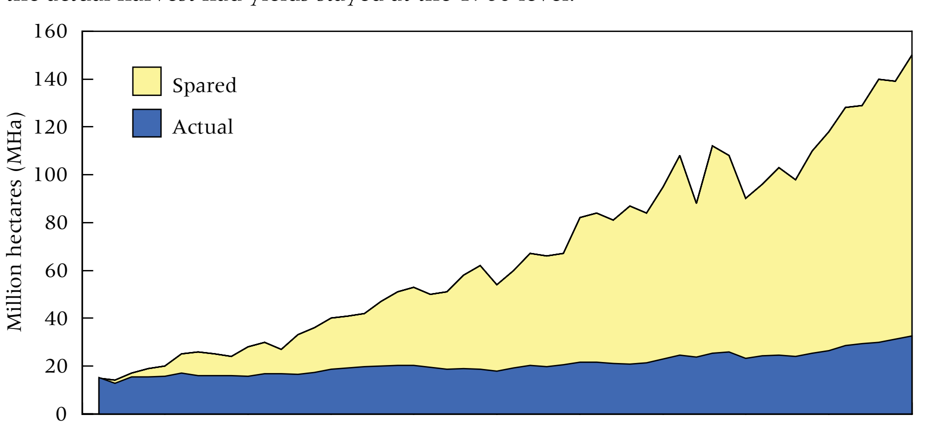
A comparison of FAO reports of meat consumption with GDP per capita shows that Indians, like Pakistanis and Japanese, eat little meat considering their level of affluence (FAO 2012). Do the many vegetarians in India enable the nation to cover fewer hectares with crops, notably, crops for feed? The sparing of land from maize (corn) production in China, where two-thirds of the maize is fed to animals, tests the necessity of vegetarianism for land sparing. As in India, China's population and income grew, and many moved to the cities since 1961. During the last half-century, China's population doubled, while GDP multiplied over 45 times (World Bank 2012). As they multiplied and prospered, the average Chinese consumed twice as many calories, including calories from 8 times more eggs and 14 times more milk and meat. Although rising meat consumption in China did contrast with that in India, the multiplication of meat consumption was far slower than the multiplication of affluence: 45 times more affluence gave rise to only 14 times more meat consumption.

While the area of harvested Chinese corn doubled during the half-century, each harvested hectare became more than four and a half times more productive (Figure 2). The 120 MHa of land spared is the equivalent of 2 Frances or 8 Iowas. While disciplined consumers and effective farmers restrained the expansion of cropland area, the extent of Chinese forests reportedly expanded 30 percent from 1990 to 2010 (FAO 2010a, 2010b).

Despite more and wealthier mouths to feed, Indian and Chinese farmers fed their populations while restraining the expansion of cultivated area.

FIGURE 2 Actual and potential land harvested for maize production, China 1961–2010

Upper segment shows the hectares farmers would have tilled to produce the actual harvest had yields stayed at the 1960 level.



SOURCE: FAO (2012).

Rising incomes brought better nutrition, but average human food consumption grew much more slowly than rising incomes and began to plateau. Even the appetite for meat in China grew more slowly than affluence. In both countries, agricultural techniques improved the yields for all crops using new high-yielding seed varieties, new crop rotation schedules, synthetic fertilizers, irrigation, weather forecasts, and better management. As these nations became more technologically competent, better information allowed for more precise agriculture and greater resource efficiency.

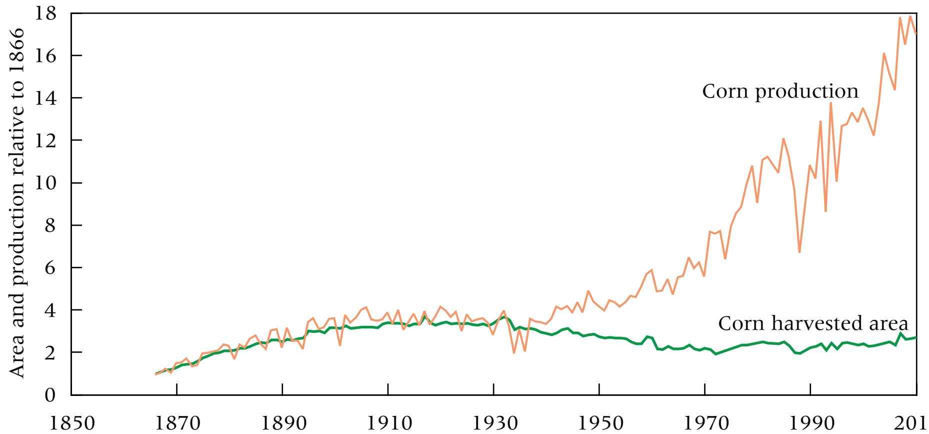
A look at development of cropland from 1700 to very late in the twentieth century shows that traditionally fertile areas of India and China saw their established cropland areas undergo early intensification (Ramankutty and Foley 1999). Cropland expanded little outward from areas of agricultural development. Unlike southern and eastern Asia, most of North America supported a sparse human population before 1700, and arable land was plentiful to acquire, respectful or not of prior claims. North (and South) American farmers initially favored technologies such as horses and later tractors to extend their reach, producing larger crops from larger areas with little lifting of yields. Greater productivity on North American farms would have to wait.

United States

The United States provides a longer, century-and-half trajectory with reliable data. During the longer span, expanding settlement and transportation corridors along with soil exhaustion and new crops affected the course of agricultural production. Increasing the immediate meaning of the example, the United States and other wealthy countries produce much of the world's food supply today. For example, in 2007, Canada, the European Union, and the United States accounted for about half of global maize and a third of global wheat production (FAO 2012).

Between the 1860s and 2010, the population of the United States grew nine times. Income, as measured by GDP, grew 130 times. Corn production in the United States rose 17-fold from 1866 to 2010 (US Bureau of the Census 1975 and 2012). Yet, more land was planted with corn in 1925 than in 2010 (Figure 3). Note the arc in the corn harvested area separating from the corn production ascent around 1940. For several decades before the 1970s, the area of land used for corn cultivation in the United States declined absolutely, despite growing production. The rise over the last several decades in the extent of the US corn harvest accompanied rising demand for biofuels made from corn. The percentage of US corn used for ethanol grew from about 2 percent of total usage in 1990 to 20 percent by 2006/07 (Trostle 2008) and nearly 40 percent in 2011(Agricultural Marketing Resource Center 2012).[3] Globally in 2006/07 12 MHa of corn was harvested for ethanol, which approaches the land area of Iowa or one-quarter that of France.

FIGURE 3 Area of corn harvested and corn production, United States 1866–2010 (indexes, 1866 = 1)



SOURCE: US Bureau of the Census (1975, 2012).

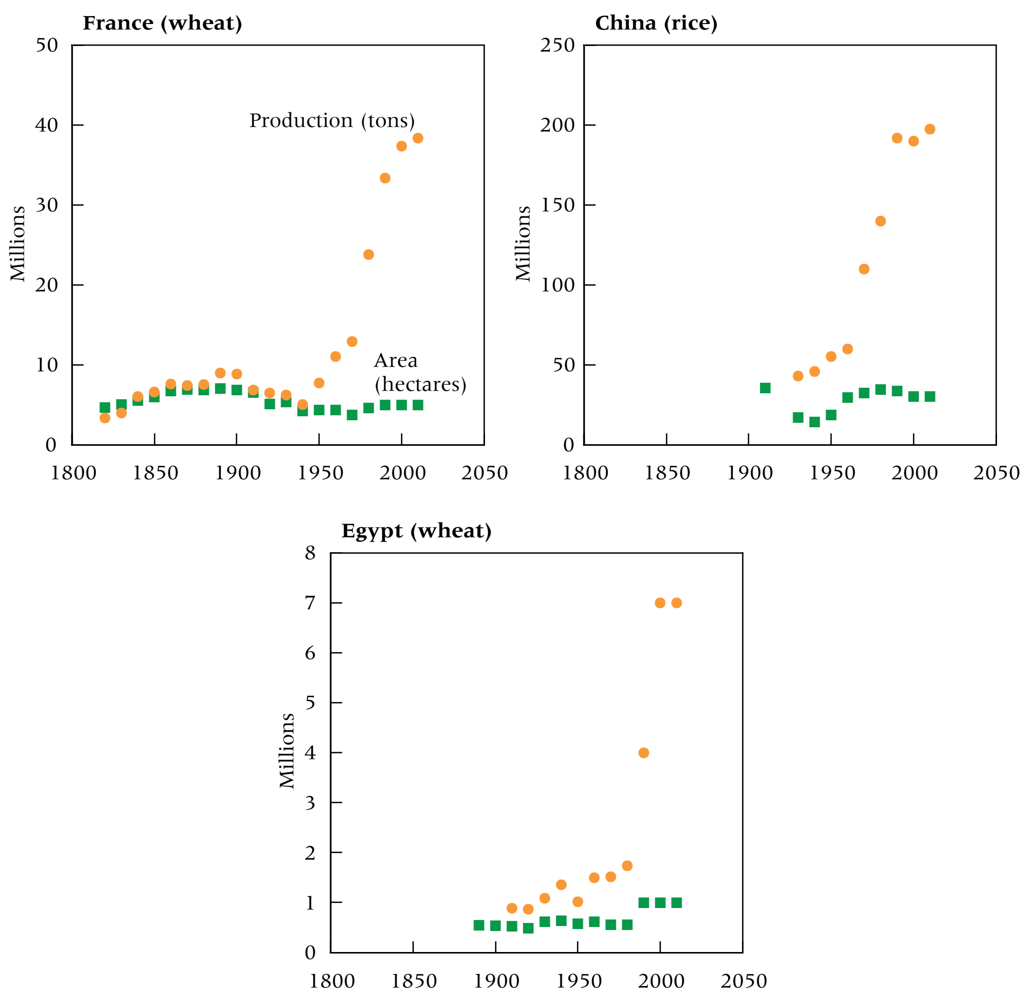
From about 1850 until 1910, expanding numbers of farmers, helped by energetic loggers filling demand for wood as fuel and railroad ties, cleared US forests at an unprecedented rate. Later in the twentieth century, the extent of US forests stabilized while the volume of timber standing in US forests increased appreciably from 1952 to 2007 (Smith et al. 2009).

Over the course of three centuries after European settlement, agriculture in the United States spread rapidly in extent to feed expanding populations, domestically and globally. Subsequently, as farmers learned, agricultural activity shifted to the more productive geographic regions, yields increased, and the expansion of cropland slowed and reversed. Production and cropland area also went separate ways in France, China, and Egypt in the twentieth century—in France nearly simultaneously with the separation in the United States, and, in China and Egypt, within a few decades (Figure 4).

The ImPACT identity

Are the trajectories of the countries examined so far typical? Can we generalize that stabilizing, and perhaps falling, cropland area accompanies rising population and affluence for all regions? To broaden the analysis beyond three disparate countries, we examined world data and reports produced by the World Bank and FAO, generally for the years from 1961 to 2010.[4] We summarize performances with the parameters of an identity that separates factors levered by parents, workers, consumers, and farmers (Waggoner and Ausubel 2002). The identity we use equates the amount of cropland used

FIGURE 4 Area harvested and production for wheat in France 1820–2010, rice in China 1920–2010, and wheat in Egypt 1890–2010



SOURCES: Mitchell (1992, 1993, 1995); FAO (2012).

with the product of population, affluence, food calories consumed per GDP, crop production per calorie, and land required per unit of production. These factors can be expressed as follows:

$$Im = \text{Impact} = P \cdot A \cdot C_1 \cdot C_2 \cdot T$$

where:

Im = Cropland (in hectares) taken as the amount of arable land and permanent crops[5] (representing land currently used for crop cultivation, not land that is potentially cultivable), as defined and reported by the FAO.

P = Population (persons)

A = Affluence (in GDP per capita)

C_1 = Consumption 1 (in kcal/GDP), where kcal refers to the annual national or global food supply in kilocalories from both vegetal and animal sources. C_1 tracks the dietary response to affluence in calories, an indicator of both hunger and excess.

C_2 = Consumption 2 (in Crop Production Index [PIN]/kcal) using the FAO Crop Production Index, which measures the relative level of aggregate volume of agricultural crop production indexed to a base year. C_2 tracks the ratio of crop production for food, feed, fuel, fiber, and tobacco to the supply of food calories. It monitors farmers' planting choices relative to caloric supply.

T = Technology (in hectares/Crop PIN) tracks how much land farmers use relative to total crop value.

Our identity in this case states that

$$Im\ [\text{hectares}] = P\ [\text{persons}] \cdot A\ [\text{GDP per capita}] \cdot C_1\ [\text{kcal/GDP}] \cdot C_2\ [\text{PIN/kcal}] \cdot T\ [\text{hectares/PIN}]$$

Changes in these factors encompass food demand and production. Straightforward mathematical considerations[6] allow for estimating the annual changes in this product by adding together the logarithmic changes, and hence approximate percentage changes, of the factors. Representing the annual changes by lowercase letters, one can write

$$im = p + a + c_1 + c_2 + t$$

We recognize the importance, especially over the long term, of the interactions of the variables. For example, one needs prosperity A for technical change T; with little research and development or capital, yield and T will suffer. Exporting grain or growing crops not eaten will lower C_1 and raise C_2. While the *PACT* variables are not independent of one another, analytically we can use them to attribute their leverage or contributions to a particular impact, such as land used for crops. The dimensions of the percentages in change per unit of time are commensurable and can be compared, equated, added, or subtracted.[7]

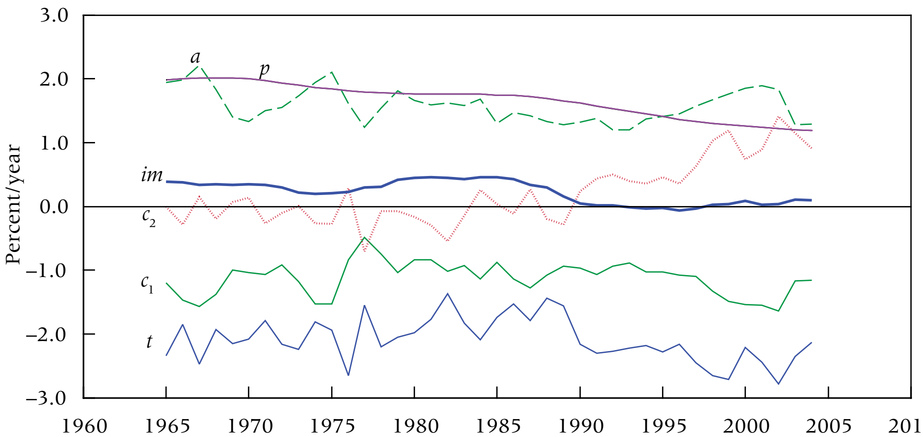
Global patterns

The values of the annual changes for the world during the period from 1961 to 2010 of the five ImPACT factors reveal diverse, durable patterns and explain collective impact. Figure 5 displays the patterns created by parents, workers, consumers, and farmers with ten-year moving averages.

Around 1970, the annual increase of global population began to slow. Population continued to grow after that time, but more slowly as seen in the

FIGURE 5 Annual change of ImPACT factors in global cropland shown by ten-year moving averages 1961–2010

The thick "impact" (*im*) line sums the other five. Population (*p*) and affluence (*a*) raise impact, while technology (*t*) lowers it, and forms of consumer behavior (*c*) may lower or raise it. When the value of the impact line falls below zero, cropland is released for other uses.



SOURCES: FAO (2012); World Bank (2012).

positive, but falling, *p* in Figure 5. Averaged over the surrounding decade, annual population growth dropped from about 2 percent centered on 1970 to about 1.3 percent centered on 2004. Although parents have chosen slower growth, farmers will need to accommodate annual population growth near 0.7 percent for the next half-century according to standard UN forecasts.

The factor *a*, affluence, fluctuated but always grew 1–2 percent per year during the half-century alongside a steady decline in population growth. The economic downturn beginning in 2008 disrupted the general rise of affluence, but that rise persisted.

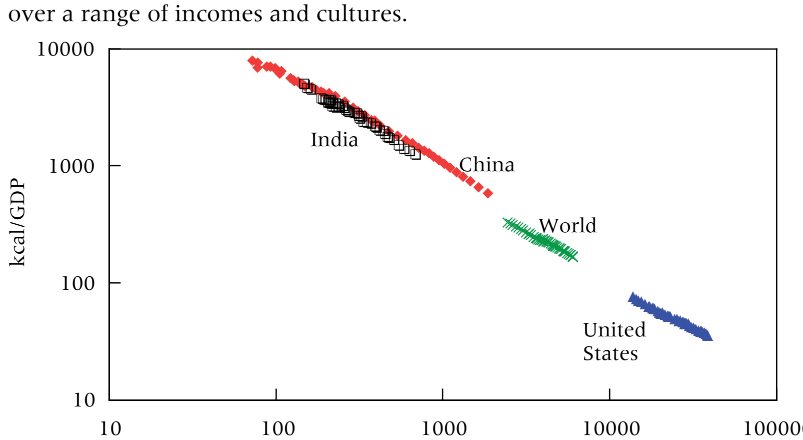
The change in available food calories per GDP, c_1, fell about 1 percent a year on average during the period. In other words, consumers did not increase caloric consumption in step with increases in GDP. Industrial ecologists call declining c_1 "dematerialization." Economists use the ratio of dematerialization to changing affluence, c_1/a, plus 1, to generate what they call "income elasticity." In this case, the global elasticities were 0.25 from 1961 to 2010 and only 0.12 from 1995 to 2010, both low values characteristic of staples.

A comparison of the composite world of Figure 5 with three large countries argues for the general validity of the fact that the poor will use more new income for food calories, while the wealthy will spend it elsewhere. Manifesting Engel's Law, in country after country after calories exceed minimum levels, caloric intake rises, slows, and may eventually level off as affluence grows. The range charted in Figure 6 from China in 1961 to the United States in 2007 covers a rise in GDP per capita of 498-fold and a drop in kcal/GDP of 187-fold, which together correspond to a global income elasticity of 0.16.[8]

Of course, in the long run, excursions or pauses may occur. Amid the general rise of affluence, an example of declining affluence raising income elasticity for food comes from Romania, a formerly Communist economy on the European margins of the former Soviet Union. During the decade 1989 to 1999, when affluence fell as much as 24 percent in Romania, the number of food calories per person fell no more than 3 percent, and C_1, the food calories per GDP, actually rose 33 percent. The similar, though not as stark, experiences of Hungary, Poland, and Bulgaria demonstrate that the dematerialization of calories reverses when affluence declines. Returning prosperity restores the downward trend of dematerialization.

Producing a grain such as maize to feed animals represents an alternative to growing a crop such as wheat that directly adds calories to the human food supply. Growing grain for feed increases the ratio C_2 of crop production per calorie in the food supply because the feed consumed exceeds the amount of animal product. Meat for many is a luxury rather than a staple, and affluence increases meat consumption more than it increases calorie consumption. As the Chinese grew more affluent after about 1970, their meat consumption grew rapidly with little dematerialization. By the 1990s, however, the FAO reported Chinese meat consumption rising less than half as fast as affluence and dematerializing 6 percent per year from 1995 to 2007. As Indian consumers grew more affluent, they behaved differently. They scarcely increased their meat consumption during the half-century to 2010, causing rapid dematerialization and even exhibiting income elasticities below zero. Globally, average

FIGURE 6 Dematerialization of food, 1961–2007
The plot of kcal/GDP as a function of GDP per capita for China, India, the United States, and the world shows globally consistent behavior over a range of incomes and cultures.



SOURCES: FAO (2012); World Bank (2012).

meat consumption per capita dematerialized little from 1980 to 1995, but then as in China, it rose only half as fast as affluence from 1995 to 2007.

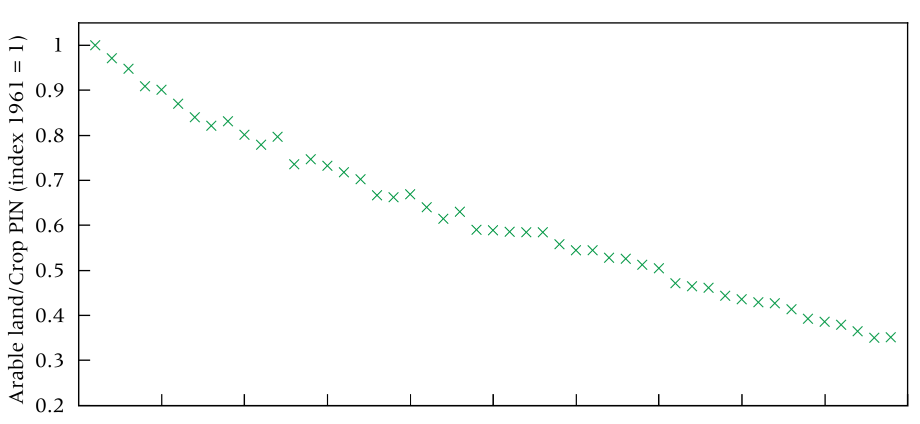
The change in crop production per calorie in the food supply c_2 has risen recently. Starting around 1990, farmers began raising crop production more rapidly than the calories of the food supply rose, lifting the factor c_2, indicating the diversion of production into higher-value, lower-calorie food crops, feed crops, and especially fuel crops, a phenomenon also noted elsewhere (Jensen and Miller 2011).

From cornfields in Iowa to sugar cane plantations in Brazil and monoculture palm forests in Indonesia, farmers around the world have dedicated cropland to "energy" crops, particularly in the last decade. Encouraged by expensive oil and by government policies, global fuel crops expanded from 4 to 25 MHa in a recent dozen years, as we detail below. Looking ahead, however, environmental and economic objections seem set to discourage expansion of energy crops (Michel 2012; National Research Council 2011).

Finally, over the last half-century, farmers around the globe have consistently squeezed more crop from the same area, annually lowering the hectares of cropland per unit of production, t, by around 2 percent. A combination of agricultural technologies raised yields, keeping downward pressure on the extent of cropland, sparing land for Nature.

Countering the global rise of population and affluence by parents and workers, consumers and farmers restrained the expansion of arable land by changing tastes and lifting yields. The noticeable shrinkage in the extent of cropland as a function of the Crop Production Index since 1990 (Figure 7) provides encouragement that farmers will continue sparing land.

FIGURE 7 Arable land/Crop PIN, *T*, for the world, 1961–2009
To produce an equivalent aggregate of crop production (PIN) in 2009 required only about 35 percent of the land needed in 1961.



SOURCE: FAO (2012).

While the ratio of arable land per unit of crop production shows improved efficiency of land use, the number of hectares of cropland has scarcely changed since 1990. Absent the 3.4 percent of arable land devoted to energy crops (Trostle 2008), absolute declines would have begun during the last decade.

Looking back and looking forward

If humanity has not already passed its peak use of farmland, are we near? Table 1 presents annual changes of ImPACT factors corresponding to past data and future projections. A comparison of the first two rows in the table shows notable differences between the full half-century and the most recent 15 years. Population growth slowed consistently during the recent period. Always with fluctuations, affluence continued to grow, but more slowly in the recent period. The ratio of food supply to income, and the ratio of arable land to crop production both continued to fall at slightly steeper rates. Unexpectedly, the ratio of crop production to food supply sped up. The net result of all the changes was a sixfold reduction in the growth rate for land used for crop production, which slowed from 0.24 percent per year in 1961–2010 to 0.04 percent per year in 1995–2010. For the coming half-century, 2010 to 2060, and following the organizing principle of the ImPACT identity, we examine changes that can be rationally projected.

Population, changing gradually and steadily, is the most foreseeable of the factors affecting cropland. The *2010 Revision* of the UN's *World Population*

TABLE 1 Actual and projected changes of global ImPACT factors, percent per year

	ImPACT factor					
	Population (*P*)	Affluence: GDP per capita (*A*)	Food supply/ GDP (C_1)	Crop PIN/ Food supply (C_2)	Arable land/ Crop PIN (*T*)	Arable land (*Im*)
Data for 1961–2010	1.68	1.67	–1.20	0.24	–2.15	0.24
Data for 1995–2010	1.24	1.53	–1.35	1.04	–2.42	0.04
2001 projection for 1997–2050[a]	+0.91	+1.80	–1.26	0.0	–1.70	–0.25
2012 projections (and alternatives) for 2010–2060[b]	+0.9 (+0.7)	+1.8 (+1.5)	–1.6 (–1.4)	+0.4 (0.0)	–1.7 (–2.1)	–0.2

NOTES: Rows 1 and 2 show actual average annual changes during the half-century from 1961 to 2010 and during its concluding 15 years from 1995 to 2010. Row 3 shows projections for the half-century from 1997 to 2050 made by two of the authors writing in *Population and Development Review* (Waggoner and Ausubel 2001). Finally, after a decade of experience since 2001, Row 4 shows our updated projection for 2010–2060, with alternative projections in parentheses.

[a]In the 2001 projection (Waggoner and Ausubel 2001) C_1 and C_2 differ slightly from those used here. In that publication, C_1 denotes Food PIN/GDP, not Food supply/GDP used here; and C_2 denotes Crop PIN/Food PIN, not the Crop PIN/Food supply used here.

[b]See text for bases of alternative projections.

Prospects (United Nations Department of Economic and Social Affairs 2012) projects a slowing from the 1995–2010 rate of 1.2 percent per year to a 0.7 percent annual increase during the next 40 years, so our projection of 0.9 percent for the next half-century seems conservative. The UN projection of 0.7 percent for the next 40 years provides a realistic alternative.

Affluence, fluctuating from booms to busts, challenges projection from anything but a long view. From 1961 to 2010 and from 1995 to 2010, affluence rose a bit more than 1.5 percent a year on average. The general upward trend evident in Figure 5 for the past half-century suggests that projecting 1.8 percent in the future seems reasonable and provides a margin of safety for the impact of additional wealth in demanding land for crops. The factual 1.5 percent during the 1995–2010 boom and recession provides a realistic alternative.

Together, population and affluence present a challenge to the environment. Our projections of 0.9 percent and 1.8 percent combine annually to increase this challenge by the GDP growth rate of 2.7 percent. The forces for restraining and possibly reducing land use must be the remaining factors, C_1, C_2, and T, driven by the restraint of consumers and the effort of farmers.

From 1961 to 2007, per capita food supply rose 27 percent, with meat slightly increasing its share of the whole (Table 2). Changes in the factor C_1 measure how many more calories people eat as their income rises. Globally from 1961 to 2010 while affluence rose 1.67 percent annually on average, the number of kilocalories per capita rose at an annual rate of only 0.5 percent (Figure 5). Because the average global citizen today is richer, we expect that demand for new calories will fall even more with new income, resulting in an elasticity of 0.1, just below the 0.12 of 1995–2010. An income elasticity of 0.1 combined with affluence rising at 1.8 percent per year corresponds to a c_1 of –1.6 percent. The alternative of affluence rising only 1.5 percent per year and income elasticity of 0.1 corresponds to a c_1 of –1.4 percent.

Changes in the factor C_2, crop production per kilocalorie of food supply, measure how much more farmers produce relative to the food supply. Simply looking at the ratio of food calories produced to those available for consumption from cereal and oilseed crops shows the large difference between what

TABLE 2 Global food supply in kilocalories per person per day and distribution by major category, 1961 and 2007

		Percent distribution			
Year	Total (kcal)	Total	Cereals	Animal products	Other vegetal
1961	2,201	100	49	15	36
2007	2,798	100	46	17	37

SOURCE: FAO (2012).

farmers produce and what consumers eat. In 2007, the FAO reported that farmers produced 2.35 billion tons of cereals and 0.79 billion tons of oilseeds. At 4,000 kcal per kg, this translates to the production of 12.57 million billion food calories or nearly 5,000 kcal/person/day for 7 billion people from cereals and oilseeds alone. Because the FAO reported 2,798 kcal/person/day in the world food supply in 2007, we estimate that only half the calories in these crops—and less than half of all calories from crops—entered the food supply. The trend in C_2 reflects the changes in the fraction reaching the food supply. Table 1 shows that for the period 1961–2010 C_2 rose modestly, and for the period 1995–2010 it rose sharply.

Knowing the causes for the last 15 years of rising C_2 would improve rational projection of its future course. Globally, trade cancels out as countries exporting nutrition are balanced by those importing it. An alternative cause, production of more nonfood crops like cotton, hemp, or tobacco, is an unlikely cause of rising crop production per kilocalorie of food supply because FAO's Nonfood PIN rose more slowly than its Crop PIN, both between 1961 and 2010 and between 1995 and 2010. The FAO's Livestock PIN also rose more slowly than its Crop PIN, leaving increased animal production as an unlikely source for the rapid rise.

Trying to identify the cause for the sharp rise in C_2, we arrive at alternative uses for crops, exemplified historically by George Washington Carver's discovery of 202 products in the peanut (Merritt 1929) and chemurgy, the industrial use of crops. The new products offered new markets to absorb the bounty produced by farmers. More recently, expensive petroleum, the desire for energy independence, and climate fears combined with carbon accounting have encouraged biofuel mandates and support policies. These policies encourage production with the consequential use of cropland, some formerly used to grow other crops (Wallander, Claassen, and Nickerson 2011). Starting from a baseline of less than 4 MHa in 1995, by 2007 according to the USDA and FAO, nearly 25 MHa worldwide were devoted to crops used for fuels (Trostle 2008).[9] This number exceeds the additions to arable land globally from 1995 to 2010, suggesting that much of the addition to cropland over this period was used to grow fuels.

In Figure 5 we saw that until about 1990, c_2 oscillated around zero, more often than not in negative territory. The entry of biofuels as major crops in the mid-1990s helps explain the fourfold increase in c_2 from 0.24 percent in the 1961–2010 period to 1.04 in the last 15 years of that period. Cheaper oil, penetration of natural gas into the market for mobility either directly or through electricity, and removal of subsidies and environmental considerations could discourage biofuels, thus sparing land for Nature, and realize the low or zero growth of c_2 predicted in the final row of Table 1. As the shortcomings of biofuels become evident to governments and champions of the environment alike, we conservatively project c_2 as slowing to 0.4 percent annually, slightly less than half the 1995–2010 level. This value would allow the growth in nonfood crop production to still exceed growth in the food supply by more than 20 percent. A biofuels bust would lead to a negative value. Alternatively, the ratio of crop production to food supply could very well resume its oscillation around zero, absent new nonfood markets for crops profitable at a global scale. The steady ratio of crop production to diet and its oscillation near zero before 1990, seen in Figure 5, support an alternate c_2 projection of 0.0 percent.

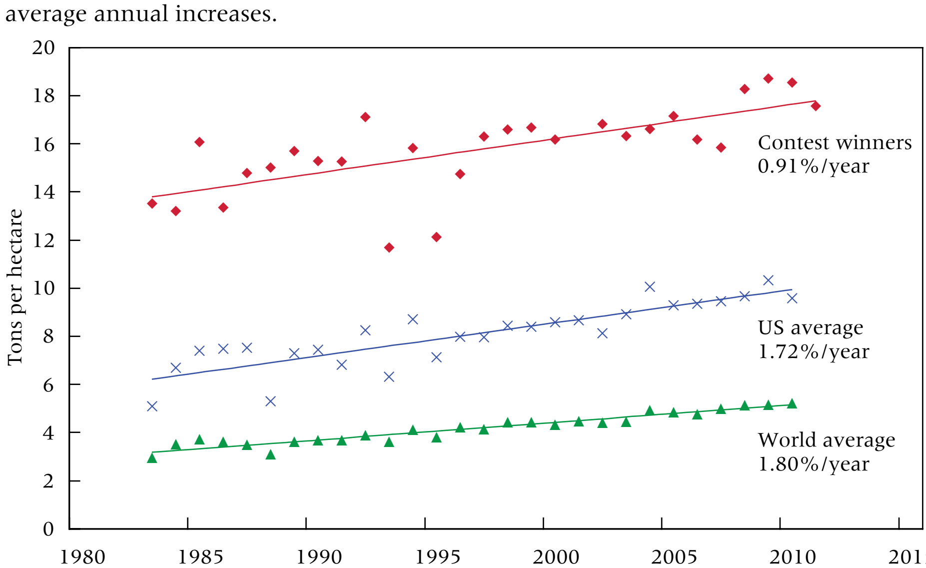
Although the global average of the caloric supply—which FAO uses to indicate hunger—has risen more than a quarter and stands well above the requirement of around 2,000 kcal/person/day, the FAO still finds several African countries undernourished. In six representative African countries,[10] each having a food supply of less than 2,000 kcal/person/day in the early 1990s, five increased calories per person and five increased crop production faster than population since Sen reported their low intakes in 1992 (Sen 1994). Despite improvements, however, the FAO reports showed that poor nutrition remained a problem in these countries, where neither increasing affluence nor crop production raised the number of kilocalories per person per day to a level of 2,100. Large differences in rates of population increase and in levels of nutrition lurk within global averages and projections (Alexandratos and Bruinsma 2012). Because demographers now expect that population growth rates in Africa will be responsible for much of the future increase in global population, the extent that such African countries as Nigeria, Congo, and Ethiopia raise yields, extend their fields, import food, and export citizens warrants attention by those concerned about land use. The forces behind the distribution of the food supply lie outside the forces we encompass. Although we cannot say whether distribution will be more equal in the future, our global projections of factors a plus c_1 raise average supply to about 3,100 kcal/person/day after 50 years, considerably above the requirement of about 2,000.

Factor T, the cropland per unit of crop production or PIN, measures farmers' intensity versus sprawl, and it is the inverse of tons per hectare, or yield. In the United States, farmers merely maintained corn yields from 1.53 tons/ha in 1866 to a similar value of 1.47 tons/ha on average in the 1930s. Then they lifted the yields over seven decades (Figure 3) to 10.07 tons/ha in the bumper year of 2004. Accordingly, their intensification lowered the hectares per ton, factor T, from 0.65 in 1866 and 0.68 in the 1930s to 0.10 in 2004 (US Bureau of the Census 1975 and 2012). The past half-century of t charted in Figure 5 shows the continuation of intensification (i.e., land sparing), globally and for all crops. The joint Organisation for Economic Co-operation and Development (OECD)/ FAO outlook for 2011–2020 anticipates agricultural production growing 1.7 percent annually, slower than the 2.6 percent in the previous decade (OECD/FAO 2011).

Although farmers persistently exceed predictions, just as their 1995–2010 performance exceeded our own expectations of 1.7 percent in 2001, we shall adopt the 1.7 percent as a standard, below the actual rise in world average corn yields of 1.8 percent per year achieved between 1983 and 2011 (Figure 8). Annual improvement of 1.7 percent sustained to 2060 would multiply world production per area by 2.3 times. For corn, the average global yield in 2060 would resemble the average US yield in 2010 (Figure 8). Farmers maintaining their 1961–2010 rate argues for the alternate projected rate of –2.1 percent per year.

Looking ahead, one must ask whether a biological limit on photosynthesis will soon constrain the rise in yields and accordingly slow the decline of *T* and farmers sparing land. The curves of production in Figure 4 suggest saturation or S-curves. However, these show production, not yield, and probably express lack of profitable markets or other incentives to produce bigger crops. Surpluses have long vexed farmers. (They may largely explain the diffusion of the hamburger since the 1950s, as farmers sought markets for their corn.) A clue about biological limits lies in the rise of winning Iowa yields in the National Corn Growers Association contest, which continue to rise and maintain their margin far above both the US and world average yields of this important crop (Figure 8).[11] For, say, the next half-century, this clue suggests

FIGURE 8 Corn yields, 1983–2011
The highest maize yields in Iowa entered in the National Corn Growers Association contest compared with US and world averages. The percentages show average annual increases.



SOURCES: Rachel Jungermann, manager, National Corn Yield Contest, Chesterfield, MO, personal communication 2012; FAO (2012).

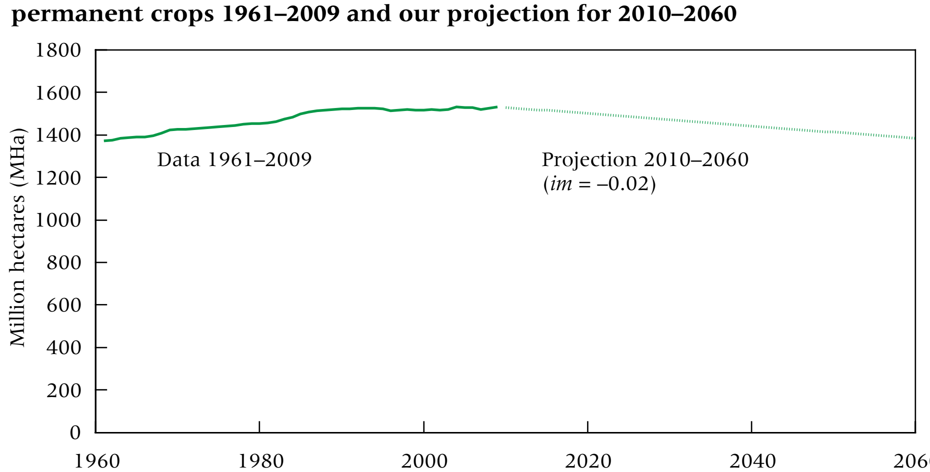
no approaching biological limit and supports our projection of improvements of *T* shown in row 4 of Table 1.

The changes of all global ImPACT factors shown in row 4 of Table 1 project a trajectory in global cropland change over the next 50 years. Figure 9 shows the combined consequence of the predicted values for each of the ImPACT factors on the extent of global arable and permanent crops. Of course, wild cards may confound projections, but we contend that our assumptions are conservative, transparent, and based on historical trajectories. After detailed regional analysis, Alexandratos and Bruinsma (2012) sound the theme of inevitably slower growth of demand for food production similar to our theme of peak farmland. According to our projection, by 2060 some 146 MHa could be restored to Nature, an area equal to one and a half times the size of Egypt, two and a half times France, or ten times Iowa.

The alternate values in the last row of Table 1, one by one, raise the predicted 146 MHa restoration of cropland. Slowing population growth to 0.7 percent instead of the 0.9 percent or more rapid dematerialization from –1.4 percent to –1.6 percent would each spare an additional 132 MHa. Uninterrupted yield growth, –2.1 percent instead of –1.7 percent, or the almost complete demise of nonfood agricultural production, could spare an additional 252 MHa.

Slower population growth, restraint in taste perhaps reflecting concern about obesity and the increasing popularity of a vegetarian diet, abandonment of biofuels, and continued improvement of technology sum to reversal in demand for land. Sustained for 50 years, such a performance would take humanity from its current peak use of farmland into an era of land sparing.

FIGURE 9 Peaking farmland: Extent of global arable land and permanent crops 1961–2009 and our projection for 2010–2060



SOURCE: For 1961–2009: FAO (2012).

Global arable land and permanent crops spanned 1,371 MHa in 1961 and 1,533 MHa in 2009, and we project a return to 1,385 MHa in 2060.

Undoubtedly, the use of irrigation and fertilizer has fueled the growth in yields. Their use has grown more efficient over the last half-century and especially over the last 20 years. The magnitude of irrigation can be measured as the area equipped for irrigation in millions of hectares, or as the volume of water consumed in cubic kilometers. Globally, irrigated area expanded at 1.4 percent per year from 1900 to 1950, accelerated to 2.1 percent per year from 1950 to 1995, and then slowed to 0.5 percent per year from 1995 to 2003 (Freydank and Siebert 2008). In 2010, the total area actually irrigated was 253 MHa globally, and total consumption of irrigation water was 1,277 km^3/yr (Siebert et al. 2010). Historical data for irrigation water use are difficult to find, but according to the FAO the annual rate of growth for all water withdrawals was about 1.4 percent (FAO 2012; United Nations Environment Program 2002). In the United States, the withdrawal of irrigation water peaked in 1980, and has since declined relative to crop production by an average of 2.0 percent per year (Kenny et al. 2009). Water-conserving practices and shifting irrigation to more humid and cooler areas achieved this improvement, which may foreshadow global adaptation to a stable irrigated area while still allowing the continued decline of cropland per crop value, *T*.

Nitrogen fertilizer, like water, raises yields and shrinks the area of land needed to produce a particular quantity of crop. After World War II, economical synthetic nitrogen became available for farming, and its increasing consumption outraced crop production in the 1960s by as much as 10 percent, but the increase slowed by the 1980s to an annual rate between 0.5 percent and 2.5 percent. Global data show that fertilizer consumption per unit of crop production rose only 0.72 percent annually from 1970 to 2009 (International Fertilizer Association 2012; FAO 2012). Because nitrogen comprises 16 percent of protein, neither humans and other animals nor plants grow and survive unless roots extract it from the soil, a process that soon exhausts soil stocks. The 50 g per day of protein that each person requires equals 3 kg per year of nitrogen. Room for greater precision and less waste in nitrogen application can be deduced from the fact that, globally, the average fertilizer application per capita of 14.6 kg per year still far exceeds the human requirement for nitrogen in protein.

Conclusions

Our analysis encompasses the leverage on cropland exerted by parents, workers, consumers, and farmers. Since 1960, their combined behaviors have spared areas of land that are immense when compared with what continuation of birth rates, appetites, yields, and other factors might have led us to expect. India and China alone have spared an area more than three times the size of France or a dozen times Iowa. Absent the slowing population growth, evolving tastes, and improving agricultural practices, unimaginable destruction of Nature would have occurred.

The past 50 years have already witnessed important peaks for environment and resources. The rate of increase of world population peaked around 1970 and has slowed considerably since then. Peaks of forest destruction also have passed with a transition from less to more forests in many countries and regions. By the 1980s wooded areas in all major temperate and boreal forests were expanding. After 1990, growing stock expanded in many forested countries (Kauppi et al. 2006), and during 1990–2010 the density of forests grew in all world regions, albeit unevenly (Rautiainen et al. 2011). Like farms and their crops, the productivity of forests providing wood products has risen. Meanwhile consumption has fallen as e-readers replace paper and as demand for other wood products, such as railroad ties and telephone poles, has declined. As we hinted above, peaks of farmers' use of nitrogen and water may also have passed.

The peak of cropland anticipated in Figure 9 does not derive from depletion of the resource. The envisioned cropland peak rises in part from another peak, that in the rate of population growth. Whether affluence will peak depends on the continuing competition between seemingly boundless desire for more and acceptance of the essential and possible.

In any case, the calories in the food supply per GDP, the use of affluence for nutrition, begins the inventory of tools to counter the environmental challenge of population and affluence. And unlike humanity's striving for affluence, its striving for food has limits that help meet the challenge. The survival level near 2,000 kcal/person/day sets a lower limit. The upper limit at, say, 4,000 set by obesity is the one that moderates the ratio of food to GDP. While the dematerialization common to staples such as food and calories helps counter the challenge of population and affluence, the limit of obesity adds another effect. Producing grain to feed animals represents an alternative to crops that directly adds calories to the food supply and so increases the ratio of crop production per calorie in the food supply. Fortunately for the sparing of cropland, meat consumption is rising only half as fast as affluence.

We were surprised by the recently rising ratio of crop production to calories in the food supply. The growth of biofuels illustrates the wild cards that can disrupt projections. If government policy or opportunity encourages farmers to grow alternative crops that do not reach the food supply, less cropland will be spared than anticipated by thinking only food comes from cropland. Cotton and flax illustrate that alternative crops are not new. In the past, proponents have encouraged alternative crops to relieve farm surpluses and depressed prices.

This broad sweep should not obscure the crucial, final role of yields and the shrinking of hectares per unit of crop production. The new varieties of the Green Revolution in the 1960s, bred to exploit better fertilization, water supply, and crop protection, accelerated the shrinking of cropland. Precise interventions in DNA, fertilizer, irrigation, pest control, and weather forecasts offer improving tools to help continue lifting yields.

Again, however, wild cards remain part of the game, both for and against land sparing. As discussed, the wild card of biofuels confounded expectations for the past 15 years. Most wild cards probably will continue to come from consumers. Will people choose to eat much more meat? If so, will it be beef, which requires more land than poultry and fish, which require less? Will people become vegetarian or even vegan? But if they become vegan, will they also choose clothing made from linen, hemp, and cotton, which require hectares? Will the average human continue to grow taller and thus require more calories? Will norms of beauty accept obesity and thus high average calories per capita? Will a global population with a median age of 40 eat less than one with a median age of 28? Will radical innovations in food production move humanity closer to landless agriculture (Ausubel 2010)? Will hunger or international investment encourage cropland expansion in Africa and South America? (Cropland may, of course, shrink in some countries while expanding in others as the global sum declines.) And will time moderate the disparities cloaked within global averages, in particular disparities of hunger and excess among regions and individuals?

Allowing for wild cards, we believe that projecting conservative values for population, affluence, consumers, and technology shows humanity peaking in the use of farmland. Over the next 50 years, the prospect is that humanity is likely to release at least 146 MHa, one and a half times the size of Egypt, two and a half times that of France, or ten Iowas, and possibly multiples of this amount.

Notwithstanding the biofuels case, the trends of the past 15 years largely resemble those for the past 50 and 150. We see no evidence of exhaustion of the factors that allow the peaking of cropland and the subsequent restoration of Nature.

Our analysis of cropland, concentrating on sparing land for Nature, overlooks everything about farmers except their efficient choice of crops and yield. Wilderness wanderers enjoying Nature at a relic cellar hole, perhaps with a lilac or rusting tool nearby, are witnessing farmers' hopes dashed by surplus crops.

Another 50 years from now, the Green Revolution may be recalled not only for the global diffusion of high-yield cultivation practices for many crops, but as the herald of peak farmland and the restoration of vast acreages of Nature. Almost 20 years ago we made a wild surmise about land sparing (Waggoner 1994). Now we are confident that we stand on the peak of cropland use, gazing at a wide expanse of land that will be spared for Nature.

Notes

1 The FAO measures chronic hunger by calories: "The average minimum energy requirement per person is about 1800 kcal per day. The exact requirement is determined by a person's age, body size, activity level and physiological conditions such as illness, infection, pregnancy and lactation." «http://www.fao.org/hunger/en/».

2 Throughout this essay, "tons" refers to metric tons.

3 When corn is processed into ethanol, a considerable fraction remains as dry distillers grains and solubles (DDGS), a medium protein feed ingredient. Correcting the 40 percent of the corn production used for ethanol production for this feed ingredient lowers the percentage to about 31 percent of corn production in 2011, raises the corn fed to animals to about 48 percent, and moderates an alarm that ethanol production was equaling the corn fed to animals. See the Agricultural Marketing Resource Center Ethanol Usage Projections & Corn Balance Sheet at «http://www.extension.iastate.edu/agdm/crops/outlook/cornbalancesheet.pdf».

4 To reach 2010, it was necessary to estimate cropland area for 2010 as equal to 2009 and kilocalories per person per day for 2008–2010 as the average of 2002–2007.

5 For the rest of this essay, the terms "cropland" and "arable land" refer to the FAO category of "Arable land and Permanent crops."

6 To estimate annual changes denoted by lowercase letters, we use the convention $x = \ln(X_f/X_i)/(f - i)$ where X_f and X_i denote the value of X for final and initial years of the period being analyzed and $(f - i)$ is the number of years in the interval. This operation is justified for small changes (i.e., $x << X$) such that higher orders can be neglected. In our case, we get the equation $im = p + a + c_1 + c_2 + t$.

7 Parents', consumers', and producers' leverage of impact by *p, a, c,* and *t* is identical to changing impact. Nevertheless, we might have chosen other dimensions than GDP, calories, and crop production. For example, we might have chosen a dimension of median family income rather than GDP for *A*, food expenditures rather than calories for C_1, and tons of a crop rather than the crop production index for C_2. Replacing GDP with a slower rising median income would slow *a*. That choice, combined with replacement of calories and its upper limitation with almost unlimited expenditure on food, would speed the rise of C_1 and lift income elasticity. Then combining that choice of faster rising food expenditures with replacement of the crop production index with a slowly rising production of a single sort of crop would lessen producers' C_2. While alternative dimensions might shift the blame and credit among parents, consumers, and producers, the consequent impact of changing hectares would remain the same. We chose GDP because it encompasses all economic activity, is generally used to measure national economies, and is almost universally used in industrial ecology. We chose calories because, as FAO has decided, they measure hunger and excess. And we chose the crop production index because it encompasses all crops and reflects farmers' combined ability to lift yields and respond to demand.

8 If the dimension of GDP is removed from the vertical axis of Figure 6 and it becomes instead kcal/person, the correlation is less and the slope becomes income elasticity *b* rather than changing intensity of use C_1. The new coordinates and alternate estimation still support the conclusion that the elasticities are low and similar among the three countries and the world. For 1961 to 2007, the elasticities thus estimated are: China 0.2, India 0.1, US 0.3, and world 0.3. For the three countries and world combined, *b* is 0.1.

9 Trostle (2008) reported area harvested for "energy" crops other than palm fruit, and UN data reported area of date palm fruit harvested «http://data.un.org/Data.aspx?q=palm+fruit&d=FAO&f=itemCode%3a254». Accessed 3/15/12.

10 Angola, Central African Republic, Chad, Ethiopia, Mozambique, and Zambia.

11 The Contest Winners in Figure 8 are the highest yields for all classes, irrigated or non-irrigated, in the National Corn Yield Contest, except the remarkable yields of 20 to 25 tons/ha grown by Francis Childs during 1997–2005.

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