How Much Will Feeding More and Wealthier People Encroach on Forests?

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IN RECENT DECADES some 50 countries have reported increases in the volume or area of their forests (UN ECE/FAO 2000). These increases, mainly in industrial countries, encourage the vision of a great restoration of nature in the form of a spreading forest canopy. The reforestation supports such a vision even while population continues to grow, albeit at a slowing rate, and the human condition improves. Geographers have dated the onset of reforestation in some areas as early as the nineteenth century and have called it the forest transition (Mather, Fairbairn, and Needle 1999).

The realization of the vision of course depends upon many factors, including how people prosper and eat, how farmers till, and how each change of cropland encroaches on forests. Here we examine population and economic growth, eating, and tilling to answer the question: How much will growing crops to feed more and wealthier people encroach on forests between now and 2050?

To many, the prospect is dire and the proscription of farming is clear. For example, Ayres (1999) wrote in a millennial issue of *Time* magazine, "Agriculture is the world's biggest cause of deforestation, and increasing demand for meat is the biggest force in the expansion of agriculture." A bird's-eye view of the landscape confirms that farming has historically transformed the most acreage, and so we shall concentrate on it, while recognizing that climate change, urban sprawl, and other forces can also change land use and land cover.

As for meat, although grazing to produce beef will affect forests, we shall concentrate on the more distinct impact of crops. Crops encompass corn to feed cows, pigs, and chickens as well as wheat, rice, and vegetables for people to eat directly. Poultry and swine depend almost entirely on feed. Cattle, too, have moved toward feedlots. In the United States, for example, the number of cattle not on feed shrank from about 120 million in 1975 to 90 million in 1997 (US Department of Agriculture 1989: 260, 266 and later years). In short, meat consumption requires more crops.

On the ground, of course, farming and forests interact in more ways than can be captured in a popular *Time* generalization. Angelsen and Kaimowitz (2000) summarized by Helmuth (1999) analyzed the manifold ways. For example, the magnet of rice-growing in irrigation projects in the Philippines drew people to lowlands and reduced pressure on forests. Laborious but profitable production of coca in plantations attracted farmers and reduced pressure on South American forests. Farmers in Honduras who lifted their maize yields by technology planted twice as many hectares of maize as those who did not, but the total land occupied by their cropping system shrank because they needed less fallow land. Labor-saving machinery and new crops expand cropland in some times and places. Unsurprisingly, farmers in Ecuador with chain saws cleared more forest than those without.

A generalization can explain these diverse outcomes. Labor-saving technology encourages cropland encroachment on forests when both the supply of labor and the demand for crops are elastic. Recurring farm surpluses, however, testify that low food prices often fail to increase demand. Already in the seventeenth century Gregory King recorded that the price inelasticity of farm crops could make a bumper crop worth less in total as well as per ton than a skimpy one (Samuelson and Nordhaus 1989). For the United States, classic studies show the farm price elasticities of demand vary from 0.2 for potatoes to 0.4–0.7 for beef, chicken, and apples; in the long run, elasticity at retail can rise to 0.7–1.0 for pork and beef (Tomek and Robinson 1972: 55–56). Richer eaters may purchase more steaks but about the same number of french fries. So, Angelsen and Kaimowitz concluded that the best technologies for conserving forests "greatly improve the yields of products that have inelastic demand."

Drawing on the resources of the UN's Food and Agriculture Organization (FAO) to anticipate world agriculture toward 2010, Alexandratos (1995) projected that those improved yields would temper farmers' need for more cropland. The FAO projection rests on detailed analysis of commodities, countries, and land availability; acknowledges prices but does not otherwise consider economies; estimates land balances and suitability; and uses knowledge and judgment of experts. It emphasizes developing countries. Past and projected production and cropland in the world and in developed and developing countries imply changes in yields. The summary in Table 1 shows the important result that an expected 2.2 percent annual rise in yields in the developing countries will hold their expansion of cropland to 0.4 percent per year. The conclusion: "Assuming some decline of agricultural land use in the developed countries (for which no land projections were made), it can be hypothesized that there will be only modest expansion of land in agricultural use for the world as a whole." Yields rising faster in

TABLE 1 Changes in total crop production, changes in cropland area, and changes attributable to changes in crop yields: 1970–90 and projected for 1990–2010

Changes in	1970–90 (actual) percent per year	1990–2010 (projected) percent per year
World		
Total crop production	2.3	1.8
Cropland	0.2	—
Crop yield	2.1	—
Developing world		
Total crop production	3.3	2.6
Cropland	0.4	0.4
Crop yield	2.9	2.2
Developed world		
Total crop production	1.4	0.7
Cropland	0.0	—
Crop yield	1.4	—

NOTE: Changes in cropland estimated by source were rounded to the nearest even one tenth of one percent, and changes in crop yield were calculated as the difference between changes in total production and changes in cropland.
SOURCE: Alexandratos (1995: 80, 166).

developing than developed countries show the poor closing the yield gap between themselves and the rich. Fifty years' expansion of the 1,510 million ha (million hectares) of 1997 cropland at, say, 0.2–0.3 percent per year equals 160–250 million ha of new cropland. The projected 250 million ha is four and a half times the land area of France.

Even the projected modest expansion of cropland in developing countries shown in Table 1 depends on a slowing of the rise in yields from the 2.9 percent per year to, say, 2.2 percent per year. Sustaining the recent rise of yields, of course, would spare cropland. Waggoner (1994) and Goklany (1999) calculated the rising yields and intensities of cultivation that will shrink or stabilize cropland during the next 50 years. Historical trends of yields do not preclude such future rises and their benefits. In an example from the United States, between 1967 and 1992 changing preference for meat and, especially, rising feed grain yields spared about 21 million hectares, an area equivalent to 24 Yellowstone parks (Waggoner, Ausubel, and Wernick 1996). Increased efficiency of use of nitrogen fertilizer relieves fears of environmental fallout from intensive strategies that spare land (Frink, Waggoner, and Ausubel 1999).

After this brief review of the popular image of farming's encroachment on forests, diverse effects of technology on encroachment, FAO's complex model that encompasses expert judgment, and demonstrations of how rising yields can contain cropland expansion, how shall we distinguish our analysis? Anticipating change through the next five decades, a time as long as the half-century since World War II, takes a robust method. We put our faith in extracting stable patterns from history. These patterns must be logical enough for us to reason about their changes but simple enough to grasp, and they must be so sturdy that they are not blown this way and that by prices, interest rates, preferences, and other fluctuations that set models adrift. We begin with a quantifiable model that identifies the large forces that historically expanded cropland; analyze the global historical experience and the experience of ten representative countries with the model; use the model to project global changes up to 2050; explore the implied cropland distribution for rich and poor countries; and conclude by relating cropland expansion to forest encroachment.

The cropland model

To decompose trends in land use into forces with trends stable and comprehensible enough to be projected logically for a half-century, we use a model of how growing population and wealth as well as changing diets and farming affect cropland area. Cropland can be calculated as the product of five forces in an identity, beginning with *Population* (P).

$$\text{Cropland} \equiv \text{P} \times \frac{\text{GWP}}{\text{P}} \times \frac{\text{Food}}{\text{GWP}} \times \frac{\text{Crop Production}}{\text{Food}} \times \frac{\text{Cropland}}{\text{Crop Production}}$$

where GWP means gross world product. *Income* per capita (represented by GWP/Population) multiplies population.[1] *Appetite*, the proportion of income devoted to food (represented by Food/GWP) adds its modification because the rich spend relatively less on food, and in spending on food they spend less on potatoes and buy more of their potatoes as chips.[2] The *nonfood* ratio, Crop Production/Food, recognizes that farmers use land to grow cotton, tobacco, coffee, and tea as well as food. Finally, because the land area to grow a ton of crop can vary, the *yield* ratio, Cropland/Crop Production, enters the identity. Note that correct dimensions require that yield in the identity be the reciprocal of the more common Crop Production/Cropland.

The first two forces are familiar. For population, we use simply total national numbers, from various UN reports. A model with more nuance might worry about age composition, since teenagers consume more calories than octogenarians. For aggregate income, we use various World Bank reports of GWP and gross domestic product, which have the advantage of relatively consistent measurement for most countries since about 1960. Of course, assets or wealth as well as income can influence food consumption.

The other three forces of the identity are less familiar and less directly measured. To measure production, all crops—from apples to wheat and zucchini—must be converted into a common currency to arrive at a single measure of production. Simply adding kilograms obviously will not do. A better common denominator could be calories, protein, or even vitamins. The FAO

(2000) weights commodities by the value or price people place on them. We adopt FAO's so-called Laspeyres indexes based on the sum of price-weighted production of crops after subtracting seed. Because the FAO presents the indexes on a calendar-year basis, the measure includes the effect of multiple crops per year. Because some crops are not food, we also use FAO's index of food production, which, unlike cereal production or calories alone, reflects the changing appetite and diet that Mitchell, Ingco, and Duncan (1997) documented for several crops and countries.

Our subject here, of course, is *changes* in cropland. For small changes, such as those that occur annually, the change in cropland can be calculated as the sum of the percentage changes of the five multiplying forces. Thus, the identity becomes in percent per year:

$$\begin{aligned}\Delta \text{ Cropland (ha)} \equiv\ & \Delta \text{ Population} + \Delta \text{ GWP/Population [\$/person]} + \\ & \Delta \text{ Food/GWP [index/\$]} + \\ & \Delta \text{ Crop Production/Food [index/index]} + \\ & \Delta \text{ Cropland/Crop Production [ha/index]}.\end{aligned}$$

That is to say:

$$\Delta \text{ Cropland} = \Delta \text{ Population} + \Delta \text{ Income} + \Delta \text{ Appetite} + \Delta \text{ Nonfood} + \Delta \text{ Yield}.$$

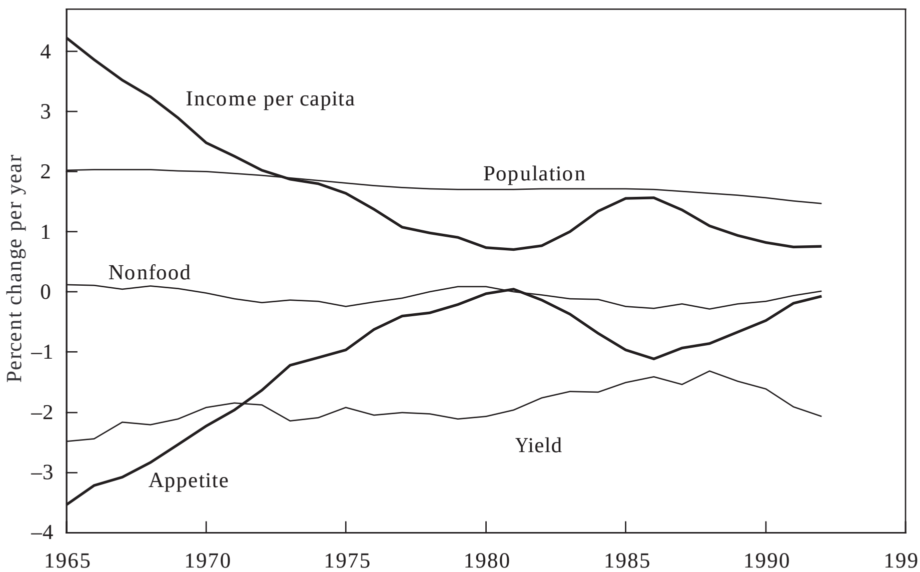
Recent global course of the component forces

Globally, the changes of two component forces, population and income, have been consistently positive since 1960 (see Figure 1). Although the growth in population and income both tended to slow, their effect on cropland changes remained nevertheless positive. The average annual 1.5 percent rise of population and 0.8 percent rise of income per capita during the final period, 1988–97, add to a 2.3 percent annual increase in GWP. The 2.3 percent in fact typifies growth rates sustained over many decades. Since 1860 world energy consumption, a good proxy for long-term growth of human economic activity, grew about 2 percent per year, as did US GDP per capita during the twentieth century. Booms and busts seem to average out and cause secular growth per year to range between 2 percent and 3 percent.

The appetite ratio Food/GWP reflects the fact that richer people spend a smaller portion of their income on food and derive less of their nutrition from staples. A relative change or elasticity of –0.7 related the appetite ratio to income.[3] The appetite ratio fell a rapid 3.5 percent per year when income rose 4.2 percent per year from 1961 to 1970; and when income later rose more slowly, the appetite ratio fell more slowly. Mirroring income in Figure 1, the course of the appetite ratio has remained negative.

In the identity the nonfood ratio, Crop Production/Food, modifies cropland use. The ratio generally declined because the production of nonfood crops rose less than general crop production. During the period 1971–95,

FIGURE 1 Five forces driving cropland change



NOTE: The plotted figures are ten-year moving averages of annual percentage changes calculated from the values centered on the year shown. Ten-year moving averages lessen the effect of short-term fluctuations, such as oil price shocks.
SOURCES: FAO (2000), World Bank (2000).

the FAO index of nonfood rose only an average of 1.3 percent per year, while the crop index rose by 2.0 percent. Although the nonfood crop of tea rose 2.9 percent per year, other major nonfood crops—coffee, tobacco, and cotton lint—rose only 0.7, 1.3, and 1.8 percent, respectively. When people, for example, smoke less or wear synthetic materials, the nonfood ratio declines a little in the identity and tempers the need for cropland.

The final force driving cropland use is yield represented by the ha per production index, the ratio Cropland/Crop Production. Although the ratio fell (that is, yield rose) slightly more slowly during the 1990s than the 1960s, it still fell 2.05 percent annually in 1988–97. Because Crop Production is an index, it indicates, as it should, improvements in value and multiple cropping as well as tons per ha per single crop. The moderating courses of the global forces of population and income sum with the tempering forces of appetite and yield to slow cropland expansion close to zero, and thus encourage the prospect of expanding forest land.

Recent courses in ten countries

To explore variation among countries we turn to ten exemplars that span climates and stages of development: Bangladesh, Brazil, China, Colombia, Congo (Democratic Republic), India, Indonesia, Mexico, Tanzania, and the United States. Along with Russia, these countries encompass about half of the global population and half of the global forest lands. (Because the Russian land-use record is not continuous, we omit its analysis.) Although most forest in the ten countries is tropical, as is most concern about deforestation, China and the United States, of course, contain much temperate forest land. In the ten exemplars the pressure to expand cropland into forests, measured by population per ha of cropland, ranges from 14 in Bangladesh to 1 in the United States.[4]

In the overview of the ten countries presented in Table 2, we simplify the courses of the forces as the annual average percentage change calculated from their levels in the years shown. Missing reports of GDP prevented our using a single period for all countries. The countries generally increased cropland use and lost forest land; India increased both. Population increases range from 3.3 percent per year in Congo DR to 1.0 percent in the United States. The rise of income per capita in China and its fall in the Congo DR represent the extremes. Falls and rises of the appetite ratio, Food/GDP, tempered the effect of rise and fall of income per capita. For example, in China the 4.1 percent annual fall of the appetite ratio held the impact of growing income to 4.0 percent per year in the rise of food per person. In Congo DR the 3.8 percent yearly rise of the appetite ratio held the decline in food per person to a more tolerable 0.8 percent per year fall. Faster increases of food

TABLE 2 Annual average changes (in percent) in forces determining cropland use and the estimated resultant average annual percentage and absolute change in cropland in ten countries

Country, years	Population (Pop)	Income (GDP/Pop)	Appetite (Food/GDP)	Nonfood (Agr/Food)	Yield (Land/Agr)	Cropland change	
						Percent	1000 ha
Bangladesh 1975–95	2.2	2.2	–2.7	–0.2	–2.1	–0.6	–46
Brazil 1971–95	2.0	2.5	–0.5	–1.1	–0.4	2.6	1,802
China 1978–95	1.3	8.1	–4.1	–1.5	–2.1	1.7	2,335
Colombia 1971–95	2.1	2.3	–1.4	–0.4	–3.0	–0.4	–24
Congo DR 1971–95	3.3	–4.5	3.8	–0.1	–2.1	0.3	26
India 1971–95	2.1	2.5	–1.6	–0.4	–2.5	0.1	227
Indonesia 1983–93	1.8	4.1	–1.5	–0.5	–2.3	1.5	454
Mexico 1980–95	2.0	–0.3	0.8	–0.7	–1.1	0.7	195
Tanzania 1987–95	3.2	–0.3	–2.0	–0.7	1.3	1.5	60
United States 1971–95	1.0	1.8	–1.2	–0.1	–1.7	–0.2	–441

NOTES: Missing reports of GDP prevented calculations for a uniform period. Negative yield ratios are actually rising crop per cropland. The final column of 1000 ha per year cropland expansion was calculated by multiplying the sums of the five forces (the penultimate column) by 1995 cropland areas. The reader can compare the annual cropland expansion that could cause forest loss shown in the final column to the 925,000 ha of the island of Cyprus or the similar-size Yellowstone National Park in the United States.
SOURCES: FAO (2000), World Bank (2000).

than general crop production lowered the nonfood ratio particularly rapidly in China and Brazil. Incorporating changes in the amount of food imported and exported affects the national courses little and, of course, sums to zero globally.[5] Although the land to produce crop, the yield ratio, rose in Tanzania, it fell faster than 2.0 percent per year in six countries.

The sum of the five forces shrank cropland in three countries (United States, Bangladesh, and Colombia) and expanded it in seven, from 0.1 percent annually in India to 2.6 percent in Brazil. The experience incorporated in the preceding figures and Table 2 provides a foundation for projections to 2050, our next task.

Prospective cropland use and the leverage of the forces affecting it

What is a feasible and attractive expectation for cropland use in 2050 and what leverage have the five forces driving cropland use in helping to realize such expectations? The opportunities, feasibility, and attraction for changing each of the five forces in the identity vary. The diversity of their rates of change in Table 2 gives clues to the available opportunities.

A Reference Scenario, Table 3, sets the stage for examining the consequences for cropland use and thus the leverage of plausible changes in the five forces. The UN 1998 medium fertility scenario to 2050 (UN 1998) implies an average annual population increase of 0.91 percent, which we adopt. The posited 1.80 percent per year increase for income per capita is faster than the global average of 1.21 percent achieved during 1971–95 and equal to the 1.80 percent achieved in the United States during the same period. Added to 0.91 percent for population growth, 1.80 percent growth in income per capita lifts GWP growth to 2.71 percent per year, a slightly slower rate than the global 2.90 and the US 2.73 during 1971–95. The 2.71 is considerably slower than in recent history in the developing countries of Bangladesh, Brazil, China, Colombia, and India but faster than in the Congo DR and Mexico. In 50 years a 1.80 percent annual rise increases per capita income about two and a half fold and, when amplified by population growth, increases GWP nearly fourfold.

TABLE 3 Reference Scenario of annual average changes (in percent) in five forces determining changes in cropland use to the year 2050 and the resulting annual cropland change and the cumulative shrinkage in cropland 1997–2050

					Cropland change	
Population (Pop)	**Income (GDP/Pop)**	**Appetite (Food/GDP)**	**Nonfood (Agr/Food)**	**Yield (Land/Agr)**	**Percent/ year**	**Million hectares 1997–2050**
0.91	1.80	–1.26	0	–1.70	–0.25	–187

The Reference Scenario specifies the appetite ratio as falling by 1.26 percent per year, which is –0.7 times the income ratio, 1.80. The –1.26 percent annual change in appetite combines with income change to lift the Food/Person ratio by 0.54 percent per year, close to the global 0.51 percent average yearly change during 1971–95. It would reverse the declines of Food/Person in Bangladesh and Congo and slow other countries to the rate of the United States during 1971–95.

Because the price-weighted production of nonfood represents only 5 percent of agricultural production, the Reference Scenario leaves the nonfood ratio unchanged.

In the Reference Scenario, the yield ratio falls 1.70 percent per year, a little more slowly than the corresponding global fall of 1.89 percent per year and near the American 1.66 percent during 1971–95. Globally, yields in specific crops during 1961–80 and 1980–97 improved by the following percentages per year: wheat, 2.8 and 1.5; maize, 2.5 and 1.5; rice, 2.0 and 1.9; and soybeans, 1.8 and 1.8.

In contrast to the cropland expansion projected in Table 1, the sum of the Reference forces of Table 3 yields a 0.25 percent annual shrinkage of cropland. By 2050 the Reference forces shrink global cropland by 187 million ha, which is about 12 percent of current global cropland and more than three times the land area of France.

What leverage do feasible changes of the five forces have to achieve even greater sparing of cropland? The UN's low fertility scenario corresponds to population growth of 0.55 percent per year, 0.36 percent less than the medium estimate of 0.91 percent. This slower rate would spare an added 230 million ha by 2050 for a total of 417 million ha.

How feasible are 0.36 percent per year changes in the other four forces? Experience shown in Table 2 is a reminder that income can grow more slowly than the 1.8 percent per year posited in our Reference Scenario. But given initial poverty, slower growth of income per capita is undesirable as well as inconsistent with moving other levers, such as slowing population growth and lifting yields. Besides, slowing the rise of income per capita from 1.80 to 1.44 percent per year has less leverage than slowing of population growth by an equal percentage because income affects appetite.[6]

The appetite ratio might fall if the present poor, as they become richer, choose not to imitate the expensive diet of the present rich, while the present rich adopt a simpler, lighter diet. Lowering the appetite ratio by 0.36 percent per year to 1.62 percent would make it similar to the ratio found in Tanzania, Indonesia, and India and lower than it is in China and Bangladesh (Table 2). Thus, leverage by this means is possible. Combined with the 1.80 percent per year rise of per capita income, appetite falling by 1.62 raises food per person by 0.18 percent per year, far faster than the 1971–95 rise of either calories or protein in the rich world but slower than the rapid increases in the poor world during the same period. Nevertheless, by 2050 the 0.18 percent annual increase would bring calories in the poor world to 90 percent of the 1995 level in the rich world and protein to 74 percent. The leverage of the acceleration to 1.62 percent per year is clear: It spares as much cropland as slowing population growth to 0.55 percent per year.

As we have noted, only a small share of agricultural production is not food. Although reasons for eliminating tobacco may be strong, no particular reasons exist for eliminating cotton, coffee, and tea. Globally, pulling the nonfood lever has little effect on cropland use, hence potentially on forest encroachment.

The fifth and final lever, yields and the yield ratio, could probably be pulled harder. Lowering the Reference Scenario level of –1.70 percent per year by 0.36 percent would still leave yield growth slower than attained by six of the ten countries shown in Table 2. Sustaining yield increases at 2.06 percent per year should be feasible. It shows its leverage by sparing as much cropland by 2050—an added 230 million ha—as slowing population growth to the level described in the UN's low-variant projection.

Pulling hard and smartly at various times and in various places over the next 50 years on the levers of population, appetite, and yield could enable humanity to move from the global Reference Scenario of sparing 187 million ha of cropland to sparing, say, 500 million ha, or nine times the land area of France.

Distributing the spared land

With the forests expanding in Europe and North America while shrinking in other continents, the assumption that the sparing of cropland and the consequent gain in forest land in the coming half-century will be wholly in the developed or rich world comes easily. How may the changes in cropland projected by the Reference Scenario be distributed between the poor and rich worlds that share the globe?

Our model's five parameters are robust enough to withstand the buffeting of human affairs averaged over a half-century and over the whole globe. Dividing it into two worlds, however, opens a Pandora's box of unknowable future variations. Nevertheless, some plausible values substituted in the Reference Scenario show us where the leverage lies and how much rates must be altered to reach desirable goals.

Let the globe be divided into a rich or developed world and a poor world corresponding to FAO's developing world with 78 percent of the current global population. Then, if we specify the rates of change in either the rich or poor world, the global rates in Table 3 determine the rates for the other.[7] In turn, from the rates in the rich and poor worlds within the global scenario we can calculate the outcomes in the year 2050. This calculation focuses on distribution. Instead of making the global outcome the sum of specified poor and rich worlds, it asks how a given global change of cropland will be distributed.

While the global Reference rates establish the change to be shared, Standard rates for the poor world must be specified before considering their alteration in the search for leverage. The UN medium-variant population projection for continents *except* Europe and Northern America, and thus our Standard, is 1.03 percent per year. A 2.0 percent per year rise in income per capita is a round number within the range of the 1971–95 changes in the countries in Table 2, and, combined with population growth, it means GDP grows at 3 percent per year, a good performance if maintained over 50 years. The Standard change in appetite can continue to be calculated as –0.7 times the change in income per capita or –1.40 percent per year. A 2.0 percent per year improvement of yield lies within the range of the improvement achieved by several countries in Table 2, and, as may be reasonably expected for countries far from a maximum yield, exceeds the global Reference rate of 1.70 percent.

These specifications and the consequent rates in the rich world do not project that the expected sparing of cropland would wholly occur in the rich world. Rather, they project that far more than half of the decrease in cropland use would take place in the poor world (Standard column in Table 4).

Altering the forces can dramatically shift the distribution of lands spared, as is evident in columns A through E of Table 4. Slowing the poor world's population growth to the global average of 0.91 percent per year gives the poor world all the spared cropland (col. A). On the other hand, either speeding up the rise of income per capita to 2.50 percent per year (col. B) or lowering appetite at –0.62 rather than –0.70 times the standard 2 percent rise of per capita income (col. C) divides the spared land equally between the poor and rich world. Change of yield, of course, would affect the distribution of spared land profoundly. Slowing its change in the poor world alone from 2.0 to 1.7 percent per year leaves little spared land in the poor world (col. D). Lifting yields to 2.1 percent per year in the poor world, on the other hand, would give all the spared

TABLE 4 Effect of modified rates of five factors in the poor world on the global distribution of the projected 187 million ha of spared cropland, 1997–2050

	Standard (No change)	Population (A)	Income (B)	Appetite (C)	Yield (D)	Yield (E)
Modified rates (percent per year)		0.91	2.50	–1.25	–1.70	–2.10
Spared cropland (million ha)						
Poor world	–152	–195	–94	–94	–31	–188
Rich world	–35	8	–93	–93	–156	1

NOTE: See discussion in text.

land to the poor world (col. E), a change in distribution nearly as great as slowing population growth from 1.03 to 0.91 percent per year.

Limiting the land sparing to the global values in the Reference Scenario of course creates a zero-sum game for any groupings of countries. In practice, were the poor world to achieve substantial land sparing, it would probably not come at the cost of the land of the rich, but would rather lift the global sparing above the Reference level.

The cropland encroachment factor

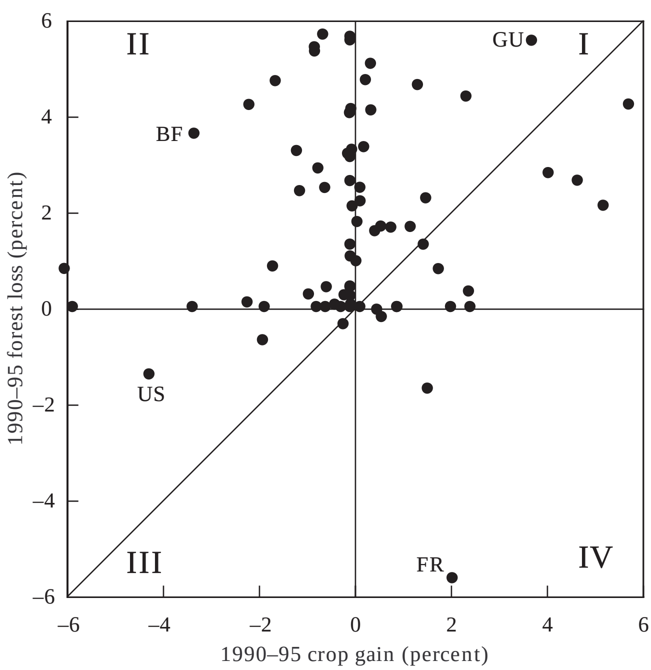
To answer the question how much feeding more and wealthier people will encroach on forests requires translating changes in cropland use to changes in forest area. Shrinkages in cropland use must be translated into forest expansion. Chain saws can make the encroachment swift, while the expansion requires time for trees to regrow.[8] Let loss of forest area equal a gain of cropland multiplied by an encroachment factor ε. In a world where land cover consists wholly of forest and cropland, one hectare of cropland gained would always be one hectare of forest lost and vice versa. This zero-sum game makes ε simply 1. On a chart of forest lost as a function of cropland gained, countries would fall on a line going through the origin with a slope of 1.

Cropland can, of course, come from uses other than forest. The FAO (2000) estimated that in 1994 forest encompassed 32 percent of global land, grassland 26 percent, and "other" land, including built-on areas, roads, and barren lands, 30 percent, while cropland occupied the remaining 12 percent. If new cropland were taken equally from the roughly equal other three uses, then ε would be 1/3. Some Brazilian small farmers cleared Amazonian forest, while other farmers have planted soybeans in Brazil's grassy cerrado. Although European settlers cleared eastern forests of North America for crops, later farmers planted wheat in the grassland of the Great Plains and fruits and vegetables in the California desert. Irrigation and soil management have reclaimed dry, infertile, or abandoned land classified as "other." The encroachment factor of 1/3 simply assumes crops expand equally into the other three types of land use. If, conversely, cropland shrinks, the same reasoning reckons ε will remain 1/3 as equal portions become forest, grassland, and other.

Using a similar basic logic, ε could well be higher, for example 2. Suppose clearing 2 ha of forest nets only 1 ha more cropland, because 1 ha of the cleared forest passes from crop to abandonment, development, or other use while none returns to forest or crops. Or, suppose the style of farming requires that one hectare sits fallow while one is cropped. Then, ε would be 2. Because the 56 million ha loss of global forests for all reasons during 1990–95 exceeded the 5 million ha gain of cropland by tenfold (FAO 1999), an ε of 2 for the cropland encroachment factor is not unreasonably large.

Historical experience can add to the common sense of ε being 1/3, 1, or 2. The FAO (1999) reported 1990–95 national changes of forest, and FAO (2000) reported national areas occupied by arable and permanent crops in the same pair of years for 135 countries with more than 50,000 ha of forest. In the 135 countries the changes in cropland and forest both relative to the 1990 forest area are uncorrelated, and the changes in the 75 countries with changes in the range of –6 to +6 percent of the 1990 forest area show why. In Figure 2 expanded cropland and lost forest are represented by points in quadrant I (in the upper right), and spared cropland and expanded forest in quadrant III (in the lower left). As noted above, in a world consisting of wholly forest land and cropland where ε equals 1, points representing national changes would lie on the diagonal line. They do not. The points not only lie off the diagonal line of ε equal to 1, some even lie outside quadrants I and III. In 15 countries the sum of forest land and cropland grew.[9]

FIGURE 2 Changes between 1990 and 1995 for 75 countries in cropland and forest land, both expressed as percent of forest land in 1990



NOTES: The relative changes in 60 other countries lay outside the range of –6 to +6 percent shown in the figure. Measured as a percent of its 1990 forest, Guinea (GU) in quadrant I gained 3.8 percent cropland and lost 5.6 percent forest; Burkina Faso (BF) in quadrant II lost 3.2 percent cropland and lost 3.7 percent forest; the US in quadrant III lost 4.2 percent cropland and gained 1.4 percent forest; and France (FR) in quadrant IV gained 2.1 percent cropland and gained 5.6 percent forest. If cropland gains equaled forest losses the points would fall on the diagonal line representing ε = 1.
SOURCES: 1990–95 national changes of forest land reported in FAO (1999) and national cropland reported in FAO (2000) as arable and permanent crops.

Despite the common perception that expansion of agriculture is the most important cause of deforestation, the lack of a simple encroachment factor relating deforestation to cropland expansion is not surprising. Designation of forest lands as parks, logging for timber, the building of roads and cities, and expansion of pastures shrink forests. Even the clearing of 2 ha for crops and abandonment of 1 ha with a net gain of 1 ha of cropland makes an ε different from 1.

The ten countries shown in Table 2, which span climates and stages of development, allow a closer look at the values of ε (see Table 5). In terms of Figure 2, five of the ten countries lie in quadrant I because they gained cropland and lost forest land. Losses of both cropland and forest land placed Bangladesh, Colombia, and Indonesia in quadrant II and made their ε negative. One country, the United States, lies in quadrant III because it lost cropland and gained forest land. India's gains of both cropland and forest placed it in quadrant IV and gave it a negative ε. The ε of the six countries in quadrants I and III was positive but ranged from 0.1 to 92.5.

To understand better why the familiar image of simple swapping between forest land and cropland is wrong, we examined land-use changes in the United States in detail. With its history as a forerunner in developmental trends over the past two centuries, it is always worth carefully observing the example of the United States. Comparing the combined loss of forest, wilderness, and rural parks in 11 US regions during 1987–92 to gains of cropland in use,[10] we found regions in all quadrants with ε ranging from –8 to +20. In some US regions, used cropland expanded into unused cropland rather than into forest. In some regions the land-use class designated as forests shrank because it was reclassified as wilderness or rural parks.

TABLE 5 Gain of cropland and loss of forest in ten countries and the encroachment factor ε indicating loss of forest land per gain of cropland

	Crop gain 1000 ha	Forest loss 1000 ha	ε
Bangladesh	–1,289	44	0.0
Brazil	8,900	12,772	1.4
China	3,303	433	0.1
Colombia	–570	1,311	–2.3
Congo DR	40	3,701	92.5
India	362	–36	–0.1
Indonesia	1,793	5,422	–3.0
Mexico	1,400	2,540	1.8
Tanzania	110	1,613	14.7
United States	–8,776	–2,943	0.3

SOURCE: See Figure 2.

Yet, the transitions among seven land-use classes observed for the decade 1980–90 in the tropics (FAO 1997) show forest land losing an average of 0.6 percent per year and cleared land gaining an almost equal amount.[11] The equal loss and gain indicate an ε near 1. The class designated as cleared, however, encompasses cattle ranching, water reservoirs, and other uses as well as cropland. So we cannot claim these transitions prove an ε of 1.

In a real world of many uses and swaps, what value of ε will convert projections of changed cropland to forest encroachment? Let us ignore the case of quadrant II, which suggests that losing cropland would also cause a loss of forest, and the case of quadrant IV, which suggests that gaining cropland would cause a gain of forest. In these cases, the linkage is surely not causal between cropland and forest land. For the other cases common sense argues for encroachment factors of 1/3, 1, and 2, a range of values observed in the United States, Brazil, and Mexico, among other countries. So, after projecting cropland change to 2050, cropland expansion may be translated into forest encroachment by an ε in the range of 1/3 to 2. And, cropland shrinkage may be translated into forest expansion by an ε of 1/3, as the example of the United States indicates.

Conclusion

We began with a conjecture affirming the possibility of a great restoration of forests, even while population continues to grow and the human condition improves. Clouding the optimistic picture was the worry that the need to grow crops to feed more and wealthier people would require expansion of cropland that would encroach on forest.

An identity shows cropland expansion driven by five forces from population and income per capita to appetite and crop yields. This identity connecting cropland expansion to driving forces is iron. Anyone forecasting expansion of cropland must be able to state in terms of this identity the assumptions driving the expansion. For example, what plausible changes in the driving forces would cause the expansion of cropland as shown in the projections presented in Table 1? Or, what plausible forces in combination with what values of the encroachment factor would cause crops to continue to encroach on the forest at the rate of 0.6 percent per year as extrapolation of the recent tropical transition probabilities might suggest?

In our view, feasible, indeed likely values of the five forces for the next 50 years suggest that cropland will shrink globally by about 200 million ha, or more than three times the land area of France. Pulling hard and smartly on the levers revealed by the identity could more than double the area spared. Applying to our Reference Scenario an encroachment factor of 1/3, similar to the US experience of the past half-century, this shortage of cropland would return about 70 million ha to forest land globally. Although this is only 2 percent of the present world forest area, it is five times the size of France's forest land and equal to the forest land of Peru or of India. It may signal the beginning of a secular transition portending restoration.

The recent encroachment factors much above 2 in such countries as Tanzania and Congo DR suggest that factors besides farming will strongly influence changes in forest land. New forces such as increasing atmospheric carbon dioxide concentrations and climate change will also affect the forests of 2050, either shrinking them or expanding them into grass and other lands. Although the global shrinkage of cropland cannot by itself prevent deforestation everywhere, plausible values of the five forces in the poor and rich world show that the poor as well as rich worlds can spare cropland. In any case, tracking the forces in the identity and the encroachment factor can pinpoint leverage to help realize a great restoration of forests or at least lessen their degradation.

We do not rashly believe that the future we have outlined here will come true by itself. The gains in yields during the past 50 years, for example, were won by investment, experiment, and exertion combined with the belief that science can improve the human condition. With continuation of similar efforts, farmers and all those who work with them need not passively let croplands encroach on forests. They can, instead, become the best friends of the forest.

Notes

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1 Although GWP and the sum of national incomes differ, the two are sufficiently close in absolute terms and especially in their percentage annual changes for us to designate GDP or GWP divided by population simply as per capita income.

2 These changes in preference are sometimes referred to as Engel's and Bennett's laws (Mitchell, Ingco, and Duncan 1997: 73–74).

3 Income lifts food consumption per person with elasticity less than 1. Income, however, lowers food per GDP with elasticity equal to the food-per-person elasticity minus 1. The slope of the regression of logarithms of the global appetite ratio on logarithms of the income ratio during 1961–97 was –0.7. The –0.7 means 10 percent higher income increases Food/Person by 3 percent. In three of the countries in Table 2 (Bangladesh, Mexico, and Tanzania) the slopes for the available years were insignificant. In the other seven countries the slopes were significant and ranged from –0.2 in Brazil to –0.8 in Congo DR. The elasticities of appetite vs. income ranged from –0.6 for animal protein to –0.9 for calories, indicating caloric consumption per person scarcely changed with rising income (the 1994 calorie and protein supply reported in 63 countries by the FAO (2000) related to their GDP reported by the U.S. Census Bureau (1996)).

4 From Bangladesh to Russia the number of people per ha of cropland are: Bangladesh, 14.3; China, 9.1; Colombia, 7.8; Tanzania, 7.4; Indonesia, 6.4; Congo DR, 5.6; India, 5.4; Mexico, 3.3; Brazil, 2.6; United States, 1.4; Russia, 1.1.

5 Changing trade or stocks can make the change of a national appetite ratio of food production per GDP different from the change in food use per GDP. Because the FAO does not

report a food use index number, we could not incorporate an FAO ratio of production/use in the identity with the other ratios calculated from FAO indexes. Nevertheless, we estimated the effect of changing production/use. Laspeyres indexes of production and use were calculated for seven commodity groups and for 1989–91 US prices. The seven commodities provided two-thirds of humanity's calories and protein. In three countries (China, Tanzania, and India) the change in production/use was less than 1 percent of that in the appetite ratio. On the other hand, in three countries the change of production/use was substantial. In Mexico production rising faster than consumption, as for vegetables and milk, raised the production/use ratio, while in Brazil a slower rise in production than consumption, as for milk and cereal, lowered the production/use ratio. In Indonesia, production rising faster than consumption, as for starchy roots and milk, raised the production/use ratio. In none of the ten countries did changing production/use alter the direction of the change in the appetite ratio shown in Table 2. So while the appetite ratios of Table 2 are food production rather than use per GDP, they may be taken as clues to changing use per GDP.

6 The constituent percentages in the Reference Scenario add to the annual percentage change of cropland, a 0.25 percent shrinkage. Because the constituent rates simply add up, one expects at first glance that the consequence will simply depend upon the size of each parameter; i.e., 10 percent of 0.91 for population should have less impact than 10 percent of the 1.80 percent per year for income or 1.70 percent per year for the land ratio. The elasticity connecting appetite to income, however, modifies this simple outcome. So, subtracting 10 percent of most constituents, e.g., 0.1 ∗ 0.91 for population, changes the –0.25 percent per year of land by the same, e.g., –0.25 – 0.1 ∗ 0.91 = –0.34 percent per year. Slowing the growth of income by 0.1 ∗ 1.80, however, only slows the figure of –0.25 to –0.30. That is –0.25 – 0.1 ∗ (1 – 0.7) ∗ 1.8 = –0.30 where the –0.7 is the elasticity connecting appetite to income.

7 Let the globe be divided into two worlds where p_1 and q_1 are the states of two basic parameters such as GDP in the poor and rich worlds at time 1. Let p and q grow at relative rates r and s to states p_2 and q_2 after n years. Let the global sum $(p + q)$ increase at the rate R. Then

$$s = \frac{1}{n}\ln\left\{\frac{(p_1 + q_1)\exp(nR) - p_1\exp(nr)}{q_1}\right\}.$$

8 The expansion of forest over five New England states after 1850 gives clues to the speed of expansion. Despite growing population and industrialization, as farming receded the forest land that had shrunk to half of its original size regrew in a century to cover three-quarters of the land area of these states (Foster 1995).

9 Parenthetically and briefly, we remark how weak a foundation supports reports of forest change. We expect that the foundation of data is weak not because of lack of effort, but because definition of a forest will always be arbitrary. Examples abound. Annex 2 of FAO (1997) defines forest as land in developed nations with more than about 20 percent tree cover but in developing nations as an ecosystem with a minimum of 10 percent cover of trees or bamboos. FAO (1999) reported 210 million ha of forest in the United States, but the US Department of Agriculture (1989) estimated 296. Table 3 of FAO (1999) estimates the global forest covered 3,511 million ha in 1990 whereas the long-running FAO categorization of all land into five classes estimated 4,318 million ha were forests and woodland. In 1994 FAO simply abandoned its five classes and now reports only arable and permanent crops with a residuum of other. Kauppi, Liski, and Myneni (2000) discuss the problem of indefinite estimates elsewhere. Progress will likely depend on defining forests in quantities of such aspirations as cubic meters of wood, tons of carbon, or populations of desired flowers and creatures. In the meantime, we like Mather, Fairbairn, and Needle (1999: 67) "have attempted to steer a delicate course between a strategy of despair, which regards the reconstruction of forest trends as completely impossible, and an uncritical acceptance of data at face value."

10 Land-use areas and definitions from «http://usda.mannlib.cornell.edu/data-sets/land/89003/». The areas generally conform to those reported in annual *Agricultural Statistics*, e.g., US Department of Agriculture (1989). USDA analysts compiled the 1945–92 series by

reconciling past reports. We analyzed the more recent period of change, 1987–92.

11 FAO (1997) included about two-thirds of the global tropics within the assessment of land-use changes classified into seven classes, 1980–90. Categorizing land entirely into seven classes created a zero-sum game among the seven. The "closed" and "open" forest plus "long fallow" were simplified into forest. The "other land cover" or cleared class included permanent agriculture, cattle ranching, water reservoirs, etc. The forest class comprised 56 percent and the cleared class 28 percent of the 3,068 million ha encompassed by the seven classes in 1980. The changes among the class areas form a transition matrix for the tropical zone. Assumptions that the two-thirds of the tropics covered by the assessment are representative, that the future use of land depends only on present use, and that the changes during 1980–90 are stationary transition probabilities allow projection to 2050. Through the seven decades forest shrinks an average of 0.56 percent per year; and cleared land, which includes other uses besides cropland, expands by 0.67 percent per year.

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