Global food demand and the sustainable intensification of agriculture

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Global food demand is increasing rapidly, as are the environmental impacts of agricultural expansion. Here, we project global demand for crop production in 2050 and evaluate the environmental impacts of alternative ways that this demand might be met. We find that per capita demand for crops, when measured as caloric or protein content of all crops combined, has been a similarly increasing function of per capita real income since 1960. This relationship forecasts a 100–110% increase in global crop demand from 2005 to 2050. Quantitative assessments show that the environmental impacts of meeting this demand depend on how global agriculture expands. If current trends of greater agricultural intensification in richer nations and greater land clearing (extensification) in poorer nations were to continue, ~1 billion ha of land would be cleared globally by 2050, with CO_2-C equivalent greenhouse gas emissions reaching ~3 Gt y^{-1} and N use ~250 Mt y^{-1} by then. In contrast, if 2050 crop demand was met by moderate intensification focused on existing croplands of underyielding nations, adaptation and transfer of high-yielding technologies to these croplands, and global technological improvements, our analyses forecast land clearing of only ~0.2 billion ha, greenhouse gas emissions of ~1 Gt y^{-1}, and global N use of ~225 Mt y^{-1}. Efficient management practices could substantially lower nitrogen use. Attainment of high yields on existing croplands of underyielding nations is of great importance if global crop demand is to be met with minimal environmental impacts.

food security | land-use change | biodiversity | climate change | soil fertility

Global demand for agricultural crops is increasing, and may continue to do so for decades, propelled by a 2.3 billion person increase in global population and greater per capita incomes anticipated through midcentury (1). Both land clearing and more intensive use of existing croplands could contribute to the increased crop production needed to meet such demand, but the environmental impacts and tradeoffs of these alternative paths of agricultural expansion are unclear (1, 2). Agriculture already has major global environmental impacts: land clearing and habitat fragmentation threaten biodiversity (3), about one-quarter of global greenhouse gas (GHG) emissions result from land clearing, crop production, and fertilization (4), and fertilizer can harm marine, freshwater, and terrestrial ecosystems (5). Understanding the future environmental impacts of global crop production and how to achieve greater yields with lower impacts requires quantitative assessments of future crop demand and how different production practices affect yields and environmental variables.

Here, we forecast 2050 global crop demand and then quantitatively evaluate the global impacts on land clearing, nitrogen fertilizer use, and GHG release of alternative approaches by which this global crop demand might be achieved. To do these analyses, we compiled annual agricultural and population data for 1961–2007 obtained from the FAOSTAT database (Food and Agriculture Organization of the United Nations; http://faostat.fao.org/) and other sources (*SI Materials and Methods*) for each of 100 large nations that comprised 91% of the 2006 global population (Table S1). We then calculated net national demand for crop calories and crop protein for each nation for each year based on national annual yields, production, imports, and exports of 275 major crops (those crops used as human foods or livestock and fish feeds) (Table S2). The resultant per capita demand for calories or protein from all food or feed crops combined (*SI Materials and Methods*) encompasses annual human crop consumption, crop use for livestock and fish production, and all losses (waste and spoilage during food and crop production, storage, transport, and manufacturing). To determine long-term global trends and better control for economic differences among nations, nations were aggregated into seven economic groups ranging from highest (Group A) to lowest (Group G) national average per capita real (inflation-adjusted) gross domestic product (GDP) (Table S1).

Results and Discussion

Global Crop Demand. Analyses reveal a simple and temporally consistent global relationship between per capita GDP and per capita demand for crop calories or protein. Across all years, per capita crop use was similarly dependent on per capita GDP both within and among the seven economic groups (Fig. 1). The magnitude of this dependence is surprisingly large. In 2000, for example, per capita use of calories and protein by the richest nations (Group A) were 256% and 430% greater, respectively, than use by the poorest nations (Groups F and G). These large differences in crop demand partially result from greater dietary meat consumption at higher income (6, 7) and the low efficiency with which some types of livestock convert crop calories and protein into edible foods (8).

We suggest that the observed relationships between per capita crop use and per capita real GDP (Fig. 1) provide a means of forecasting future crop demand. Specifically, using the fitted curves in Fig. 1, we forecasted per capita crop caloric and protein demand for 2050 for each economic group by its estimated 2050 per capita GDP (Fig. 2 *B* and *C*) (Table S3). The GDP estimate (*SI Materials and Methods* and Fig. S1) assumes that per capita real GDP would grow at ~2.5% per year globally, with rates for developing nations being greater than developed nations (Fig. 2*A*). Using United Nations (UN) projections of 2050 population (9) (Fig. S2), we next calculated the total 2050 demand for crop calories or crop protein for each economic group and then summed these values to estimate 2050 global crop demand (*SI Materials and Methods*).

These analyses forecast that global demand for crop calories would increase by 100% ± 11% and global demand for crop protein would increase by 110% ± 7% (mean ± SE) from 2005 to 2050 (Table S3). This projected doubling is lower than the 176%

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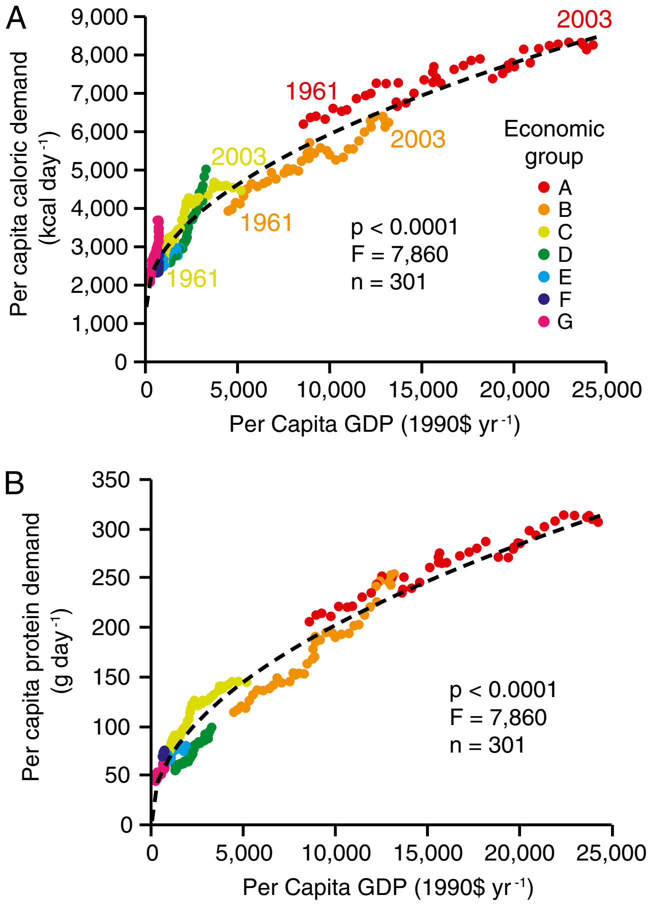

Fig. 1. Annual dependence of per capita demand for (*A*) crop calories and (*B*) protein on per capita real GDP for each of economic Groups A–G (*SI Materials and Methods*). Each color of points shows the trajectory for a particular economic group (one point per year for each group). Curves are fitted to the square root of per capita GDP.

(caloric) and 238% (protein) increases in global crop use that would occur if per capita demands of all nations in 2050 reached the 2005 levels of Group A nations.

Any projection of future global crop production entails many elements of uncertainty and of necessity emphasizes some potentially causative factors over others. Our forecast of a 100–110% increase in global crop production by 2050 is larger than the 70% increase that has been projected for this same period (10). Although our projection methods and the methods of the earlier study differ in many ways, the different forecasts may occur because of our use of quantitative global trends in per capita crop demand that emphasize income-dependent dietary choices (Fig. 1) vs. their use of expert opinion of national and regional demand trends (10).

Quantification of Yield, Input, and Climate Relationships. The environmental impacts of doubling global crop production will depend on how increased production is achieved (11, 12). Production could be increased by agricultural extensification (that is, clearing additional land for crop production) or intensification (that is, achieving higher yields through increased inputs, improved agronomic practices, improved crop varieties, and other innovations). Here, we quantify the global impacts on land clearing, GHG emissions, and nitrogen fertilization of alternative pathways of agricultural development that meet the 2050 global crop production that we forecast. In particular, we evaluate the combinations of current or improved agricultural technologies, enhancements to soil fertility, and land clearing that could meet our projected 2050 global caloric demand and what their environmental impacts would be. For brevity, results for protein are not presented here but are similar. Because of data availability, we use past N fertilization rates as quantitative measures of soil fertility enhancement, but we emphasize that soil fertility can also be enhanced by legumes, cover crops, and other means and that yields could increase with less N fertilizer than in the past if N use efficiency increases (1, 2, 13).

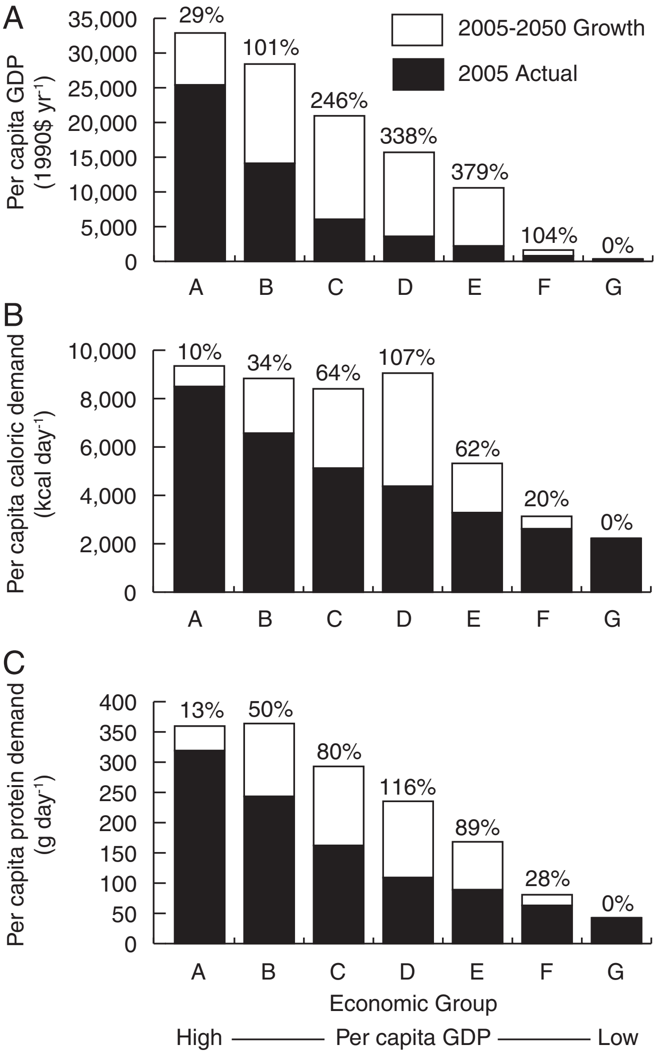

Fig. 2. (*A*) Per capita GDP, (*B*) per capita demand for crop calories, and (*C*) per capita demand for crop protein in 2005 (black) and mean projected 2050 increases (white; percent increases above bars).

We used multiple regressions to quantify how nation to nation and year to year differences in caloric yields have been related to N fertilization intensity (N ha^{-1}) and other variables that are thought to impact yields (*SI Materials and Methods*). We found that caloric yields were simultaneously related to N fertilization intensity, precipitation, potential evapotranspiration, soil pH, elevation, time (year), and economic group (Table S4). A simpler regression that included just N fertilization intensity, precipitation, economic group, and time gave similar results (Table S4). Two otherwise similar regressions used just 2005 data (Table S5).

These four regressions show that ~80% of national-level variation in caloric yields was statistically explained by a few underlying variables. We use these fitted relationships to quantify scenarios, exploring the potential effects of changes in these variables on caloric yields and the environment. We do so with the caveat that the fitted relationships need not be indicative of causation, while noting that fits are consistent with other analyses of controls of yields (12, 14, 15).

After controlling for N fertilization intensity, climate, soil, and elevation in these regressions, we will, for brevity, refer to the residual yield differences ascribed to economic groups as mainly reflecting technological and infrastructure disparities among the economic groups, and we will refer to the residual yield differences that are ascribed to time (year) as mainly reflecting technological improvements from 1965 to 2005.

Alternative Pathways of Agricultural Expansion. These regressions can estimate the dependence of global yields on N use (soil fertility enhancement) if future technological advances were to continue along observed temporal trends to 2050 (technology improvement), if underyielding nations were to overcome technological disparities by adapting and then adopting the high-yielding technologies of Group A nations (technology transfer), or if both technology improvement and technology transfer were to occur. In particular, we used our regression results to quantify curves defining the dependence of global caloric yields on global N use for four cases that all meet our projected 2050 crop caloric demand forecast (Fig. 3*A* and *SI Materials and Methods*). For all cases, we assumed that the currently large disparities among nations in agricultural intensities (measured here as N ha^{-1}) were eliminated by 2050. We call this equalization of N use strategic N utilization, because it provides a larger increase in global crop production per unit of N than would occur from greater N use in nations already applying N at high rates.

The current technology curve in Fig. 3 retains each economic group's N-dependent yield at its 2005 relationship and thus assumes no technological improvements or transfer from 2005 to 2050. This curve provides a potential lower bound for 2050 yields. It is defined by six data points calculated from each of the two regressions that used just 2005 data (Table S5). These two regressions, which differ in the number of variables included, give results so similar to each other as to be almost indistinguishable in Fig. 3 *A*–*C*.

A potential upper bound is provided by the technology improvement and transfer curve for which complete technology transfer is assumed to allow all nations to achieve (by 2050) the technological improvements and soil- and climate-adjusted yields projected for Group A nations by 2050. The two regressions on which it is based also gave highly similar predictions (Fig. 3 *A*–*C* and Table S4).

Two intermediate curves, each defined by two regressions, provide benchmarks within the region defined by the upper and lower bounds. The technology improvement curve assumes that yields continue to increase until 2050 along the 1965–2005 time trajectory (Table S4) but that all nations otherwise retain the technology of their economic group. The technology transfer curve has each nation, based on its climate and soils, achieve (in 2050) the climate- and soil-adjusted N-dependent yield of Group A nations in 2005 (Table S5). All four curves in Fig. 3 explore what might occur should lower-yielding nations achieve, by 2050, significant soil fertility enhancements (here quantified by increased N use but potentially achievable by other means).

Any point in the shaded region of Fig. 3*A* represents different combinations of technology improvement and technology transfer that, for the given global N use or its equivalent soil fertility enhancement, would meet global caloric demand in 2050. The increased global yields that could result from various degrees of technology improvement, technology transfer, or N use would meet 2050 crop demand with less cropland clearing (1, 2) (Fig. 3*B*). For instance, if global N use were held at 200 Mt, achieving the technology transfer and improvement benchmark by 2050 would decrease land clearing by ∼1.2 billion ha compared with current yields (Fig. 3*B*).

Land clearing, soil cultivation, and N fertilizer manufacturing and use all emit GHG. We quantified global emissions from these sources for each curve using Intergovernmental Panel on Climate Change (IPCC) Tier 1 methods (16, 17) (*SI Materials and Methods* and Tables S6 and S7). Although estimates of N_2O emissions that result from N fertilizer are variable (18), such variability is small compared with the other sources of emissions that we quantified. Our analyses found that, when increased global N is focused on croplands of underyielding nations, projected global 2050 net GHG emissions are reduced, as shown by the negative slopes for each of the four curves of Fig. 3*C*. Reduced GHG emissions occurred because increased N use decreased land clearing. The resultant reduction in GHG emissions from lower land clearing was approximately three times the emissions increase from the N fertilizer.

Environmental Impacts of Meeting Increased Crop Demand. These relationships among global N use, yield, land clearing, and GHG emissions allow exploration of the environmental impacts of different pathways of global agricultural development. Four hypothetical pathways that start on the current technology curve at the 2005 global average N use intensity of 94 kg ha^{-1} (Fig. 3 *D*–*F*) illustrate that our forecast of 2050 global crop demand may be met in ways that have markedly different environmental impacts. First, consider a pathway that mimics past trends (black arrows), with poorer, lower-yielding nations increasing crop production mainly through land clearing and richer, higher-yielding nations doing so mainly by yield increases from intensification and yield improvement. The environmental impacts of this past trend trajectory would, as illustrated, increase global land clearing to a total of ∼1 billion ha by 2050, global agricultural GHG emissions to ∼3 Gt y^{-1} of CO_2-carbon equivalents, and global N use to ∼250 Mt y^{-1}. These increases would have major environmental impacts through resultant species extinctions, loss of ecosystem services, elevated atmospheric GHG levels, and water pollution (3–5, 19).

Greater global investments in technology improvement and technology adaptation and transfer could markedly reduce these impacts, as illustrated by the other three trajectories, all of which attain the technology improvement and technology adaptation and transfer frontier by 2050. For instance, the N-minimizing trajectory shown (brown arrows) (Fig. 3 *D*–*F*) could retain global N use at its current 100 Mt y^{-1}, have land clearing of ∼0.5 billion ha, and have GHG emissions of 1.6 Gt y^{-1}. Alternatively, a current N-intensity trajectory (yellow arrows), with global N intensity staying at 94 kg ha^{-1} until 2050, would move global values to N use of ∼125 Mt, land clearing of ∼0.4 billion ha, and GHG emissions of ∼1.4 Gt y^{-1} in 2050.

A land sparing trajectory (white arrows) would minimize both land clearing and GHG emissions. It could meet our 2050 projected global crop demand while clearing only ∼0.2 billion ha land globally and producing global GHG emissions of just ∼1 Gt y^{-1}. Global N use would be ∼225 Mt y^{-1}. This analysis suggests that a land sparing trajectory of agricultural development might be the best option for minimizing biodiversity loss and GHG emissions, but it comes with the environmental cost associated with greater global N use.

However, a variety of practices can greatly decrease this environmental cost by increasing the efficiency of agricultural nitrogen utilization (1, 11–13, 20, 21). For instance, recent field trials of an integrated soil–crop management system in China achieved a 90% increase in maize yields with no increase in N use (13). Because N inputs in excess of plant uptake increase nitrate loading into surface and ground waters and contribute to marine anoxic zones (20, 22), greater development and adoption of agronomic practices that increase nutrient efficiency (23, 24) could further decrease environmental impacts of increased yields (25–27).

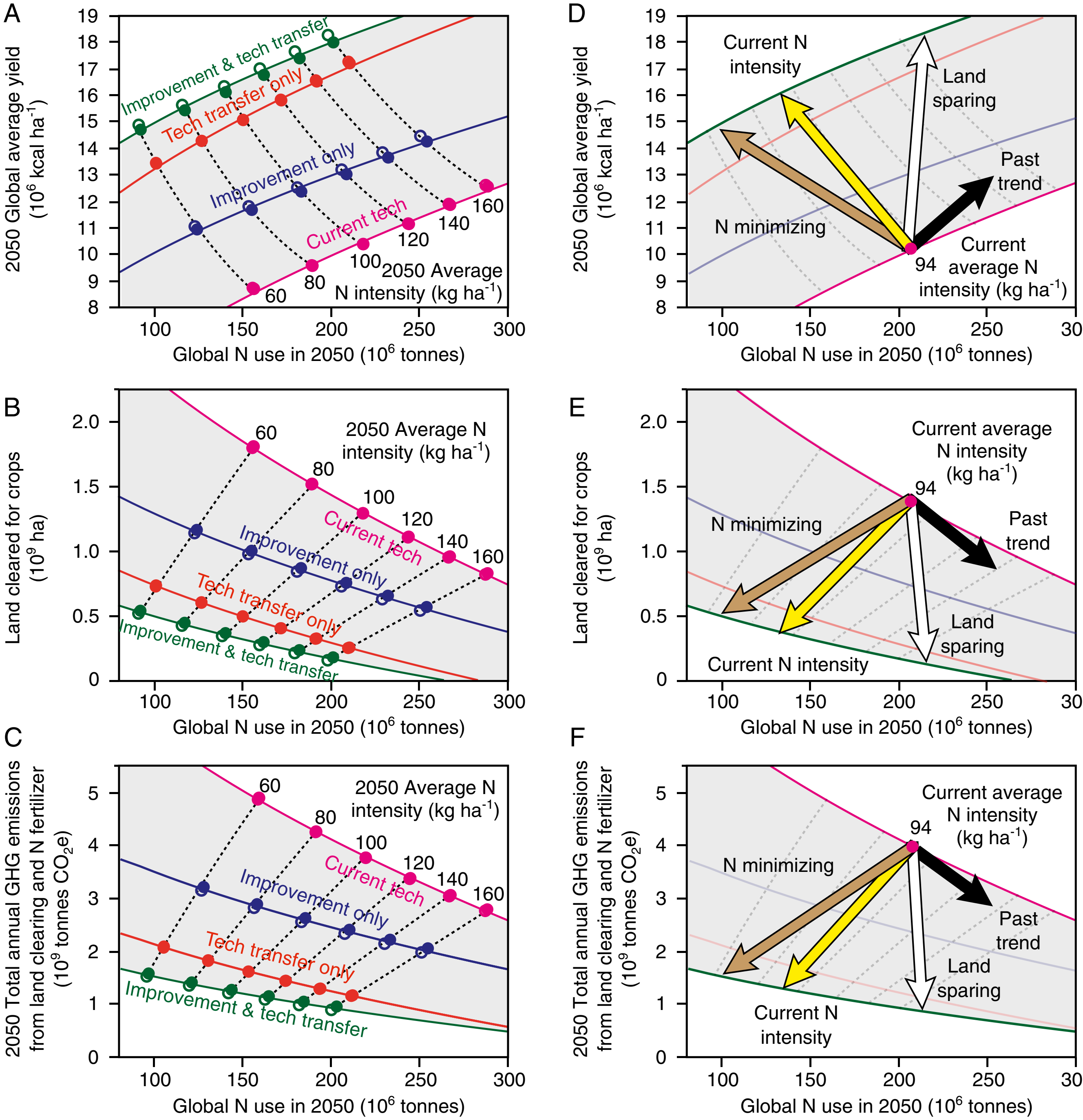

Fig. 3. Projections of 2050 values for (*A*) global yields, (*B*) global land clearing, and (*C*) global agricultural GHG emissions and (*D*–*F*) the yields and environmental impacts of four alternative hypothetical trajectories along which agriculture might develop by 2050. Tonnes CO$_2$e in (*C*) and (*F*) represents the equivalent tonnes of C that would have been emitted had all GHG emissions in our analyses been in the form of CO$_2$. All abscissas are global annual N use in 2050 calculated as the sum across all economic groups of N use intensity (N ha^{-1}) times total cropland area (ha) needed to meet projected 2050 caloric demand. To derive the curves shown, current N use intensities of lower-yielding nations were strategically increased to equal global mean intensity, which was set at 60, 80, 100, 120, 140, or 160 kg ha^{-1} to calculate the 12 points shown for each curve (*SI Materials and Methods*). The four curves shown in each graph (magenta, current technology; blue, improvement only; orange, technology adaptation and transfer only; green, improvement and technology transfer) are regression-based estimates of yields (*A* and *D*) and associated land clearing (*B* and *E*) needed to meet 2050 global caloric demand and resultant GHG emissions (*C* and *F*). Land clearing = (cropland needed to meet 2050 crop demand) − (2005 cropland).

Conclusions

Trajectories of global agricultural development that are directed to greater achievement of the technology improvement and technology transfer frontier would meet 2050 crop demand with much lower environmental impacts than trajectories that were continuations of past trends (19). This difference occurs because strategic intensification that elevates yields of existing croplands of underyielding nations can meet the majority of 2050 global crop demand, and in so doing can greatly reduce land clearing and GHG emissions.

Current yield differences among nations are large. In 2005, for example, caloric yields for Group A nations were 308% greater than for Groups F and G, 138% greater than for Group E, and 37% greater than for Groups B, C, and D. Our analyses, which incorporate the effects of climate and soils on yields, suggest that agricultural intensification through technology adaptation and transfer and enhancement of soil fertility in poorer nations would greatly reduce these yield gaps (14), provide a more equitable global food supply, and greatly decrease the GHG emissions and species extinctions that otherwise would have resulted from land clearing (4). Our analyses explore the implications of the 100% increase from 2005 to 2050 in global crop production that we forecast. If global crop demand were lower (10), less land clearing and/or N use would be needed, and environmental impacts would be smaller.

Our evaluations of the environmental benefits of alternative pathways of global agricultural development are not meant to imply that they might be similarly attainable or feasible. Global yields will likely be impacted by climate change (15). Yield increases in richer nations may be more difficult than in the past if some major crops are approaching yield ceilings (21, 28). Yield increases in poorer nations will require significant investments in innovative adaptation of technologies to new soil types, climates, and pests (29, 30) as well as new infrastructure (2). However, yields have been increased in some nations in which they were long stagnant, such as Malawi and Zimbabwe (31, 32). In Zimbabwe, for instance, field trials on >1,200 farms showed that technology transfer (farmer education) and intensification (N fertilizer use at ~13% of use by Group A nations) increased maize yields 40%, giving market value returns ~400% greater than the cost of fertilization (32).

Global food demand is growing rapidly, much of the world's current cropland has yields well below their potential, and the current global trajectory of agricultural expansion has serious long-term implications for the environment. The environmental impacts of escalating crop demand will depend on the trajectory along which global agriculture develops. The preservation of global biodiversity and the minimization of the GHG impacts of agriculture may well hinge on this trajectory. A trajectory that adapts and transfers technologies to underyielding nations, enhances their soil fertility, employs more efficient nutrient use worldwide, and minimizes land clearing provides a promising path to more environmentally sustainable agricultural intensification and more equitable global food supplies.

Materials and Methods

Detailed descriptions of our data sources and analyses can be found in the *SI Materials and Methods*. These include data on political, economic, agricultural, and climatic variables; analyzed nations, economic aggregates, and global estimates; crop demand; projections of per capita GDP; yield regressions; four 2050 yield curves and land cleared curves in (Fig. 3); calculation and projections of GHG emissions from land use conversion; and estimation of GHG emissions from N fertilizer manufacture and application.

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