Supporting Information

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SI Materials and Methods

Data on Political, Economic, Agricultural, and Climatic Variables. We compiled annual national data (Table S1) for 1961–2007 on population from Food and Agriculture Organization's PopSTAT database (Food and Agriculture Organization of the United Nations, Rome, 2009; http://faostat.fao.org) (Fig. S2) and gross domestic product (GDP; expressed in real 1990 international dollars) from the Total Economy Database (Groningen Growth and Development Centre, New York, 2008; www.conference-board.org/data/economydatabase/) on the production, area harvested, imports, exports, and stores of up to 275 nutritious crops (Table S2) and N fertilizer use from the FAOSTAT database (Food and Agriculture Organization of the United Nations, Rome, 2009; http://faostat.fao.org). Annual N fertilizer use intensity was calculated as the annual N use of a nation divided by the total area harvested for all crops. Using commodity- and nation-specific conversion factors from FAOSTAT, we calculated total annual caloric and protein production for each crop, summing across all crops to find national calorie and protein production totals and yields for all nutritious crops combined.

We obtained global 5-min latitude/longitude raster data on the within-nation geographic distribution of croplands as well as climate, soil, and elevation variables from the SAGE 1992 Croplands Dataset (Center for Sustainability and the Global Environment, University of Wisconsin–Madison, 1998; www.sage.wisc.edu/mapsdatamodels.html). The national average values of precipitation, elevation, potential evapotranspiration (PET), soil organic carbon, and soil pH weighted across areas cropped in each nation in 1992 were calculated using Esri ArcGIS 9.3.

Analyzed Nations, Economic Aggregates, and Global Estimates. We analyzed crop demand (utilization) and yield patterns and trends using data from the 100 more populous nations, representing 91% of total 2006 global population, for which sufficient annual data on nutritious crop production and other variables were available for 1961–2007. Some nations, however, had been formed during this period when a former nation split into two nations. Their data reported after the split had to be combined to make them comparable with the earlier data. This combination reduced the number of distinct entities, which for brevity, we call nations in the text, to 95. A few large nations, including the former USSR and its derivatives, could not be included in our trend analyses because of years of missing data associated with dissolution of state or periods of civil unrest or war. Each nation was assigned to one of seven economic groups ranging from highest (Group A) to lowest (Group G) national average 2000–2007 per capita real (inflation-adjusted) GDP (Table S1).

For specific analyses, some otherwise included nations were excluded from regressions. Malaysia (Group B) was excluded from caloric analyses, but not protein analyses, because of poor data on exports and food vs. biodiesel use of palm nut oil, an energy dense commodity. Data from Ireland (Group A), The Netherlands (Group A), and New Zealand (Group B) were excluded when performing regressions against N use, because these nations have applied large proportions of their N fertilizer to pasture rather than nutritious crops, with annual data on amounts so applied being unavailable.

The global estimates of the environmental affects of future crop demand that we present in this paper are scaled to encompass the populations of all nations, including the remaining small nations and the few larger nations not included in trend analyses for lack of data. For all these nations, we obtained populations, GDPs, and cropland areas, assigning each nation the mean per capita crop demands and yields of the economic group to which it belonged (according to its per capita GDP).

Crop Demand. We use the term crop demand interchangeably with FAOSTAT's annual domestic supply, both being defined as annual production + imports − exports + decrease in stocks. Because of low use of crops for biofuels before 2007 (1), we did not exclude such use from demand. For 1961–2003, per capita nutritious crop demand of each economic group was dependent on per capita inflation-adjusted GDP. Two fits were obtained for each of the two nutritional units (tonnes protein and calories), with per capita GDP square root transformed to capture the nonlinear response observed. One was a universal fit, where data from all nations were fit simultaneously to the square root of per capita GDP (Fig. 1 *A* and *B*). The other was a specific fit, where data from each economic group were fit separately to the square root of per capita GDP by adding an interaction between economic group and the square root of per capita GDP to the statistical model. Square root was chosen over logarithmic transformation because of its superior fit based on R^2 and Akaike Information Criterion (AIC) values.

We then used the four resulting fitted formulas to estimate 2050 per capita nutritious crop demand for each of the economic groups based on their predicted 2050 per capita GDP (see below). Group per capita 2050 demand is reported as the average of the two forecasts for each nutritional unit (Table S3). Global crop demand in 2050 was calculated by multiplying each group's 2050 per capita demand by the total population (included + non-included nations) forecasted for 2050 by the United Nations (UN) Population Division's median variant projection (UN Department of Economic and Social Affairs, New York, 2011; http://esa.un.org/unpd/wpp/unpp/panel_population.htm) (Fig. S2) and then summing demand across all seven economic groups (Table S3).

Projections of per Capita GDP. Trajectories of the rate of change of per capita GDP are a Kuznets (2) function of per capita GDP (2–4). This empirical functional relationship is used to forecast per capita GDP (4), especially when information on future values of other terms in the Solow (5) income model are unavailable. To project the per capita GDP that each economic group might achieve by 2050, we statistically fit by least squares the dependence of the observed annual rate of change of per capita GDP for each economic group on its per capita GDP, obtaining the Kuznets (2) curve of Fig. S1. Then, using the method of Seldon and Song (4), we numerically solved the resultant ordinary differential equation to forecast per capita GDP to 2050 for each economic group. We did not make any forecasts for individual nations because these forecasts are not needed for our projections and might be more idiosyncratic than projections for groups of many nations. The model solutions (Fig. S1) gave results similar to other estimates of 2050 per capita GDP (6, 7).

Yield Regressions. We used past yield relationships and trends to estimate the yields that might be achievable by 2050. All analyses used 5-y mean data on a nation by nation basis (for example, the mean for 1965 is the average for 1963–1967). In particular, we used four regressions paired in two. One pair, the time series regressions, used nine points in time comprised of 1965, 1970, 1975, . . . , and 2005 averages and included year as one of its variables (Table S4). The other pair, the 2005 regressions, only used average 2005 (average for 2003–2007) data (Table S5).

Within each of these pairs, a four-variable regression determined the dependence of yield on economic group, the 1.333 root of national N use intensity per hectare (that is, $N^{0.75}$), precipitation, and year (if a time series regression). The other kind of regression, a seven-variable regression, determined the dependence of yield on those variables plus soil pH, elevation, and potential evapotranspiration. Only $N^{0.75}$ was used in all regressions, because the relationship between yield and N use intensity for the 95 analyzed nations was increasing but nonlinear and $N^{0.75}$ provided a better fit based on R^2 and AIC than N (linear), log[N], $N^{0.5}$ (square root), or $N^{0.667}$ (the 1.5 root of N use intensity) for all regressions.

For the two time series regressions, each of the variables in both the four-variable regression and the seven-variable regression was significant at $P < 0.01$, and the overall regressions were significant at $P < 0.0001$. For the two 2005 regressions, all variables were significant at $P < 0.01$ in the four-variable regression and remained so in the seven-variable regression, but in the seven-variable regression, none of the three added variables was significant ($P > 0.05$ for each).

Four 2050 Yield Curves and Land-Cleared Curves in Fig. 3. Each of the two 2005 regression fits provides estimates on which the current technology yield curve in Fig. 3*A* is based. In particular, each 2005 regression was used to calculate the caloric yield of each nation (adjusted for all other regression variables) for each of six different N use intensities (60, 80, 100, 120, 140, and 160 kg ha^{-1} N fertilizer). We then calculated the yield for each economic group at each N use intensity by weighting national yields by areas harvested in each nation. Global yields for each N use intensity were similarly calculated as area-weighted means of yields of all seven economic groups; 6 of the 12 2050 global yield points to which the current technology yield curve in Fig. 3*A* is fit come from one of the 2005 regression variations (one point per N use intensity), and the other 6 come from the other variations. All 12 points are shown in Fig. 3*A*. The forecasts based on the seven-variable regression and those forecasts based on the four-variable regression are indistinguishable. Although none of the three added variables in the seven-variable regression was significant, those six points predicted by this regression are shown precisely to illustrate how insensitive these forecasts were to inclusion of added soil and climate variables. The 2050 total global N use values associated with these 12 global yields were calculated from 2050 economic group yields and projected 2050 economic group caloric demands as follows (Eq. **S1**):

$$\text{2050 Area Harvested} = (\text{2050 Projected Demand})/(\text{2050 Yield}) \quad \textbf{[S1]}$$

and (Eq. **S2**)

$$\text{2050 N Use} = (\text{2050 N Use Intensity}) \times (\text{2050 Area Harvested}). \quad \textbf{[S2]}$$

Global N use is the sum of the 2050 N use across all seven economic groups.

The 2005 regressions were also used to estimate the 2050 yields of the technological transfer curve. The calculations were identical to those calculations just described except that, in using the regressions to project 2050 values, all nations were assigned to be members of economic Group A. The yields so calculated thus represent the yields that could be achieved if each nation by 2050 was able to achieve a yield comparable with the yields of Group A nations in 2005 but adjusted for its own climate and/or soil and elevation.

The two time series regressions were similarly used to obtain the technology improvement curve by using the observed time dependence of yield on year in the multiple regressions to estimate the yields of all nations in 2050 under the assumption that yields would continue to increase along the fitted trend line until 2050. As before, yields of each nation were adjusted for its own climate and/or soil and elevation. Group yields and then global yields were then calculated as above.

The technology improvement and transfer curve was also similarly obtained from the two time series regressions under the assumption that all nations would achieve by 2050 the yields that the temporal trends projected for Group A nations in 2050. As before, yields of each nation were adjusted for their own climate and/or soil and elevation. Group yields and then global yields were then calculated as above.

The four curves of cropland cleared in Fig. 3*B* were calculated from the group yields calculated above and the groups' 2050 projected caloric demands. Each group's cropland cleared for a given model at a given N use intensity was calculated using the following equation (Eq. **S3**):

$$\text{2050 Cropland Required} = (\text{2050 Area Harvested}) \times (\text{2005 Cropland})/(\text{2005 Area Harvested}) \quad \textbf{[S3]}$$

and (Eq. **S4**)

$$\text{Cropland Cleared} = (\text{2050 Cropland Required}) - (\text{2005 Actual Cropland}). \quad \textbf{[S4]}$$

Global cropland cleared is the sum of cropland cleared across all seven economic groups.

The greenhouse gas (GHG) emission curves in Fig. 3*C* were calculated, as described below, using forecasts of global cropland cleared and associated global N use values. GHG emissions were calculated as the sum of GHG emissions from land conversions to cropland and from N fertilizer manufacture and application in accordance with Intergovernmental Panel on Climate Change (IPCC) Tier 1 methodology (8).

Calculation and Projections of GHG Emissions from Land Use Conversion. IPCC Tier 1 methodology (8) was used to quantify the following three pathways of global GHG emissions after land conversion to cropland.

i) Immediate C release from biomass in year of clearing ($c_1 = 84$ tC ha^{-1}) (Table S6).
ii) Annual soil C loss ($c_{20} = 1.195$ tC ha^{-1}) (Table S7) during the first 20 y after clearing.
iii) Annual N_2O release from soil N mineralization ($n_{20} = 0.102$ tC eq ha^{-1}) associated with the annual soil C loss during the first 20 y after clearing [using a 100-y global warming potential (GWP) of 298 for N_2O] (8).

Annual land clearing rates were calculated on a group by group basis, assuming a constant clearing rate between 2006 (mean = 2005–2007) and 2050.

Total annual GHG release from land conversion to cropland was calculated using the equation (cropland cleared past year) (c_1) + (cropland cleared past 20 y) ($c_{20} + n_{20}$).

For annual soil C loss during the first 20 y after clearing, we made the conservative assumption that all cleared croplands were on mineral as opposed to organic soils. For each of the five biomes, the appropriate average IPCC default organic soil C stocks (IPCC table 2.3) (8) together with the appropriate average IPCC relative stock change factors for cropland use (Table S7) (IPCC table 5.5) (8) were used to calculate annual soil C loss for 20 y after clearing with the following formula (IPCC equation 2.25) (8) (Eq. **S5**):

annual soil C loss

$$C_{20} = \frac{(\text{soil org.C stock})(1 - \text{stock change factor over 20 y})}{20\text{ y}}. \quad \textbf{[S5]}$$

The average value for all biomes was weighted, as c_1 above, by the relative proportion of anticipated land use change, yielding the value of $c_{20} = 1.195$ tC ha^{-1}.

The annual N_2O release from soil N mineralization during the first 20 y after clearing ($n_{20} = 0.102$ tC ha^{-1}) was calculated from c_{20} using IPCC equation 11.8 (8), assuming the IPCC default C: N ratio of 15:1 and default N_2O emission factor of 0.01 t(N_2O-N) t(N)$^{-1}$ and converting to tC equivalents using a GWP of 298 (IPCC equations 11.1 and 11.8) (8) (Eq. **S6**):

$$n_{20} = c_{20}\left(\frac{\text{tC}}{\text{ha}}\right) \times \left(\frac{1\text{t N}}{15\text{t C}}\right) \times \left(\frac{0.01\text{t N}_2\text{O} - \text{N}}{\text{t N}}\right) \times \left(\frac{44\text{t N}_2\text{O}}{28\text{t N}_2\text{O} - \text{N}}\right) \times \left(\frac{298\text{t CO}_2}{\text{t N}_2\text{O}}\right) \times \left(\frac{12\text{t CO}_2 - \text{C}}{44\text{t CO}_2}\right) = 0.102\left(\frac{\text{tC}}{\text{ha}}\right). \quad \textbf{[S6]}$$

Estimation of GHG Emissions from N Fertilizer Manufacture and Application. The following three pathways of global GHG emissions from N fertilizer manufacture and application were estimated using IPCC Tier 1 methodology (8):

i) CO_2 emissions from ammonia production (IPCC table 3.1) (8): good practice default value of 3.273 (tCO_2) (t NH_3)$^{-1}$ = 1.08 (tC equiv.) (tNH_3-N)$^{-1}$.

ii) Direct N_2O emissions from N addition to managed soils: default value (IPCC table 11.1) (8) of 0.01 (tN_2O-N emission) (tN input)$^{-1}$ = 1.28 (tC equiv.) (tN input)$^{-1}$.

iii) Indirect N_2O emissions from N volatilization (IPCC equation 11.9) (8): 0.001 (tN_2O-N emission) (tN input)$^{-1}$ = 0.13 (tC equiv.) (tN input)$^{-1}$.

The sum of GHG emissions from these three pathways equals 2.49 (tC equiv.) (tN fertilizer)$^{-1}$. Multiplying this factor by annual global N fertilizer consumption yields annual global GHG emission values from N fertilizer manufacture and application. We acknowledge the uncertainties with ii and iii above (9). In our analyses, increased N use in underyielding nations gives a net GHG benefit compared with the same crop production on newly cleared land, even if N_2O emissions were up to about four times the values used by the IPCC.

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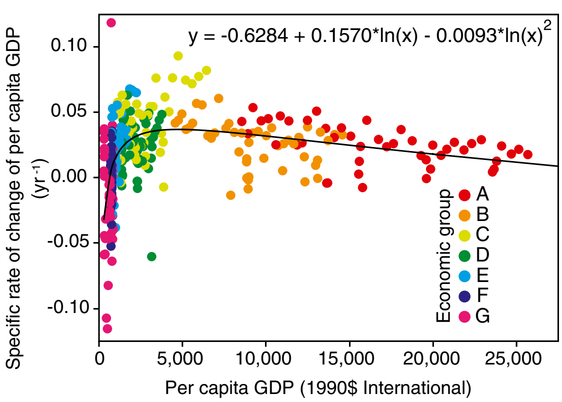

Fig. S1. Fits of the annual specific rates of change of per capita gross domestic product (GDP) against per capita real GDP from 1961 to 2006 for economic Groups A–G give a Kuznets (1) curve. Note the long-term decline in growth rates as economies become wealthier. In the fitted equation shown, y is $dG/dt \times 1/G$, where G is the per capita GDP, and x is per capita GDP or G. The differential equation is $dG/dt = G(-0.6284 + 0.157 \times \ln[G] - 0.0093 \times \ln[G^2])$. Using the work by Seldon and Song (2), we solved this differential equation to forecast 2050 values of per capita GDP for each economic group based on 2005 initial conditions. Our numerical solutions used the NDSolve[ ] function of Mathematica.

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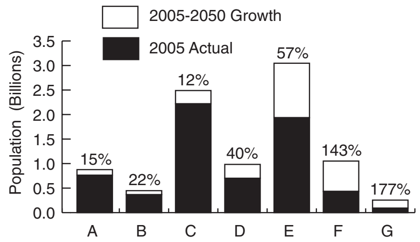

Fig. S2. Population in 2005 (black bars) and projected increase to 2050 (white bars; percent increase above) for economic Groups A–G (all nations) from the UN Population Divisions 2009 Medium Variant forecasts (UN Department of Economic and Social Affairs, New York, 2011; http://esa.un.org/unpd/wpp/unpp/panel_population.htm).

Table S1. Analyzed nations in the seven economic groups (A–G)

Economic group	100 analyzed nations used as basis for projections	Analyzed percent of world population 2006 (2050)
A	Australia, Austria, Canada, Denmark, Finland, France, Germany, Ireland, Japan, The Netherlands, Norway, Sweden, Switzerland, United Kingdom, and United States	11.4 (9.4)
B	Argentina, Chile, Greece, Israel, Italy, Malaysia, Mauritius, New Zealand, Portugal, Saudi Arabia, South Korea, Spain, Trinidad and Tobago, Uruguay, and Venezuela	4.9 (4.3)
C	Botswana, Brazil, China, Colombia, Costa Rica, Ecuador, Guatemala, Iran, Jordan, Mexico, South Africa, Syria, Thailand, Tunisia, and Turkey	30.2 (24.9)
D	Algeria, Bolivia, Cuba, Dominican Republic, Egypt, El Salvador, Indonesia, Jamaica, Lebanon, Morocco, Paraguay, Peru, Philippines, Sri Lanka, and Swaziland	8.3 (8.6)
E	Bangladesh and Pakistan, Benin, Cameroon, Cote d'Ivoire, Ghana, Honduras, India, Libya, Mozambique, Myanmar (Burma), Nicaragua, Nigeria, North Korea, Senegal, and Vietnam	28.7 (31.8)
F	Burkina Faso, Eritrea and Ethiopia, Gambia, Guinea, Haiti, Kenya, Madagascar, Malawi, Zambia and Zimbabwe, Mali, Nepal, Rwanda and Burundi, Sudan, Tanzania, Togo, and Uganda	5.9 (9.7)
G	Central African Republic, Chad, Democratic Republic of the Congo (former Zaire), Niger, and Sierra Leone	1.4 (2.8)
A–G	Total of all Groups A–G	90.8 (91.5)

Nations were assigned to economic Groups A–G based on their ranking by per capita GDP (average for 2000–2007); Group A had the highest and Group G had the lowest per capita GDP. Of the 100 current nations listed, eight nations have had their data reported by the FAO in composite with another of those eight nations in the past, resulting in the 95 distinct nation/composite data units we used in our analyses. The average population of these 95 nation/composites was 67 million in 2006. The 128 other nations had a much smaller average population of 4.9 million, and data sets that generally had too many missing points to be usable.

Table S2. Crop categories that encompass the 275 nutritious crops included in our analyses and the percent that each crop contributed to total 2005 kcal production within the 100 analyzed nations

Crops (in aggregate)	%	Crops (in aggregate)	%	Crops (in aggregate)	%
Maize (3)	23.56	Watermelons	0.11	Pistachios	0.02
Rice from paddies	17.20	Pigeon peas	0.11	Hazelnuts	0.02
Wheat (3)	15.98	Other pulses (6)	0.10	Papayas	0.02
Soybeans	7.43	Cabbages (4)	0.10	Other citrus fruits (4)	0.01
Oil palm fruit	5.09	Taro	0.09	Okra (2)	0.01
Sugar cane	3.78	Other fresh fruit (15)	0.09	Vetches	0.01
Barley	3.23	Other roots/tubers (10)	0.09	Kapok seed	0.01
Rapeseed	2.23	Dates	0.08	Fonio (2)	0.01
Cassava (4)	2.05	Green chillies and peppers (3)	0.07	Apricots	0.01
Sorghum (3)	1.99	Eggplants	0.07	Canary seed	0.01
Cottonseed	1.60	Dry chillies/peppers (3)	0.07	Strawberries	0.009
Potatoes	1.51	Tangerines (2)	0.07	Asparagus	0.008
Groundnuts	1.38	Pears	0.07	Cashew apple	0.008
Sweet potatoes	1.23	Other tropical fruit (15)	0.06	Green onions (3)	0.008
Sugar beet	1.20	Peaches and nectarines (3)	0.06	Other nuts (6)	0.007
Millet (7)	1.01	Carrots and turnips (2)	0.06	Grapefruit (3)	0.007
Coconuts	0.68	Cashew nuts	0.06	Cherries (3)	0.006
Beans (8)	0.58	Pineapples	0.05	Figs	0.006
Oats	0.56	Lupins	0.04	Kiwi fruit	0.005
Other fresh vegetables (21)	0.55	Other melons	0.04	String beans	0.004
Yams	0.48	Almonds (2)	0.04	Mushrooms (3)	0.004
Sunflower seed	0.44	Green maize	0.04	Yautia	0.004
Bananas	0.41	Karite nuts	0.04	Chestnuts	0.003
Grapes	0.36	Cucumbers	0.04	Artichokes	0.003
Dry peas (2)	0.30	Squash and gourds (3)	0.04	Bambara beans	0.003
Chick peas	0.29	Buckwheat	0.03	Hempseed	0.003
Plantains	0.29	Plums and sloes (2)	0.03	Other legumes	0.002
Apples (2)	0.22	Mixed grain	0.03	Other berries (5)	0.002
Tomatoes	0.21	Green peas	0.03	Quinoa	0.002
Onions	0.21	Cauliflowers and broccoli (2)	0.03	Cranberries	0.002
Sesame seed	0.18	Lettuce and chicory (4)	0.03	Poppy seed	0.002
Triticale	0.18	Persimmons	0.03	Sour cherries	0.001
Oranges	0.17	Green beans	0.02	Carobs	0.001
Rye	0.16	Melon seed	0.02	Blueberries	0.001
Cow peas (2)	0.15	Walnuts	0.02	Quinces	0.001
Broad beans (3)	0.15	Avocados	0.02	Other stone fruit	0.001
Linseed	0.13	Spinach	0.02	Raspberries	0.001
Other cereals (4)	0.13	Lemons and limes (3)	0.02	Currants (2)	0.000
Lentils (2)	0.13	Other oilseeds (12)	0.02	Gooseberries	0.000
Mangoes and guavas (3)	0.12	Safflower seed	0.02	Brazil nuts	0.000
Olives	0.12	Other sugar crops (3)	0.02		

(Number) of distinct crops included in a category if the number is more than one.

Table S3. Caloric and protein demand for 2005 and projections for 2050 for the group of 100 analyzed nations and extrapolations to all global nations

	Per capita demand for analyzed nations*			Total demand for analyzed nations†			Total global demand (all nations)†		
	2005	2050	Change (%)	2005	2050	Change (%)	2005	2050	Change (%)
Calories									
Universal fit	1.74	2.45	41	10,200	20,400	99	11,300	22,400	98
Specific fit	1.74	2.50	44	10,200	20,800	103	11,400	22,900	102
Mean	1.74	2.48	42	10,200	20,600	101	11,300	22,700	100
Protein									
Universal fit	0.054	0.086	58	323	722	123	355	790	122
Specific fit	0.054	0.077	41	323	645	100	355	706	98
Mean	0.054	0.082	50	323	683	112	355	748	110

The universal fit is a regression, using one data point per nation, of demand against the square root of per capita GDP. In contrast, the specific fit also groups nations by economic group and separately determines the dependence of demand on the square root of per capita GDP by adding an interaction term between economic group and the square root of per capita GDP to the statistical model. The mean is the average of the universal and specific fits. The mean total global demands for calories and protein are the estimates of 2050 demand for the 275 nutritious crops that we use in our 2050 projections.

*Units of measure are million kilocalories per year for calories and tonnes protein per year for protein.

†Units of measure are trillion kilocalories per year for calories and million tonnes protein per year for protein.

Table S4. Fit statistics for the two 1965–2005 regressions of yield against N intensity, precipitation, year, and economic group (four-variable analysis) or against these variables plus potential evapotranspiration, elevation, and soil pH (seven-variable analysis)

	1965–2005 Four-variable analysis		1965–2005 Seven-variable analysis	
Parameters	Fit	Estimate (10^6 kcal/ha)	Fit	Estimate (10^6 kcal/ha)
Overall	$F_{9,778} = 338$ $P < 0.0001$ $R^2 = 0.796$		$F_{12,755} = 259$ $P < 0.0001$ $R^2 = 0.804$	
Intercept	$F_{1,778} = 77.4$ $P < 0.0001$	−103.3	$F_{1,755} = 76.7$ $P < 0.0001$	−103.6
N intensity ($N^{0.75}$)	$F_{1,778} = 547$ $P < 0.0001$	25.7	$F_{1,755} = 552$ $P < 0.0001$	26.6
Precipitation	$F_{1,778} = 213$ $P < 0.0001$	0.68	$F_{1,755} = 55.4$ $P < 0.0001$	0.49
Year	$F_{1,778} = 81.7$ $P < 0.0001$	0.05	$F_{1,755} = 84.8$ $P < 0.0001$	0.05
Economic group	$F_{6,778} = 39.6$ $P < 0.0001$	Group A: 3.52 Group B: 0.16 Group C: −0.44 Group D: −0.12 Group E: −1.05 Group F: −0.98	$F_{6,755} = 30.9$ $P < 0.0001$	Group A: 3.72 Group B: 0.26 Group C: −0.27 Group D: −0.05 Group E: −1.05 Group F: −1.23
PET			$F_{1,755} = 4.99$ $P = 0.0258$	0.01
Elevation			$F_{1,755} = 7.58$ $P = 0.0060$	0.001
Soil pH			$F_{1,755} = 10.1$ $P = 0.0015$	−0.50

Table S5. Fit statistics for the two 2005 regressions of yield against N intensity, precipitation, year, and economic group (four-variable analysis) or against these variables plus potential evapotranspiration, elevation, and soil pH (seven-variable analysis)

	2005 Four-variable analysis		2005 Seven-variable analysis	
Parameters	Fit	Estimate (10^6 kcal/ha)	Fit	Estimate (10^6 kcal/ha)
Overall	$F_{8,71} = 30.3$ $P < 0.0001$ $R^2 = 0.773$		$F_{11,66} = 22.2$ $P < 0.0001$ $R^2 = 0.787$	
Intercept	$F_{1,71} = 15.0$ $P < 0.0001$	3.06	$F_{1,66} = 1.85$ $P = 0.1787$	6.76
N intensity ($N^{0.75}$)	$F_{1,71} = 48.5$ $P < 0.0001$	30.1	$F_{1,66} = 47.2$ $P < 0.0001$	30.7
Precipitation	$F_{1,71} = 26.6$ $P < 0.0001$	1.03	$F_{1,66} = 8.70$ $P = 0.0044$	0.87
Economic group	$F_{6,71} = 4.14$ $P = 0.0013$	Group A: 4.32 Group B: −0.24 Group C: 0.19 Group D: −0.12 Group E: −1.21 Group F: −1.47	$F_{6,66} = 2.49$ $P = 0.0314$	Group A: 4.47 Group B: 0.39 Group C: 0.33 Group D: 0.14 Group E: −1.37 Group F: −1.93
PET			$F_{1,66} = 0.237$ $P = 0.6283$	0.01
Elevation			$F_{1,66} = 1.11$ $P = 0.2952$	0.001
Soil pH			$F_{1,66} = 0.563$ $P = 0.4557$	−0.73

Table S6. Calculations of carbon emissions per hectare from land cleared for crops in the first year after clearing based on IPCC Tier 1 methods (1)

Biome	Cropland use increase weight*	Biomass estimation	Above-ground biomass (tC ha^{-1})	Ratio of total to above-ground biomass (IPCC table 4.4)	Live biomass loss, year 1 (tC ha^{-1})	Dead organic matter (IPCC table 2.2)	Dead organic matter loss, year 1 (tC ha^{-1})	Live + dead biomass loss, year 1 (tC ha^{-1})
Grassland	2	Mean of four temperate categories in IPCC table 6.4; CF = 0.47 (above- + below-ground biomass)	4.66	N/A	4.66	N/A	0.00	4.66
Savanna	3	Subtropical steppe in IPCC table 4.12	35.00	1.32	46.20	Mean of subtropical value	3.45	49.65
Tropical forests	4	Mean of three tropical forest categories in IPCC table 4.12; CF = 0.5	101.67	1.33	135.22	Mean tropical value	3.65	138.87
Mediterranean	1	Mean subtropical dry forest and subtropical steppe in IPCC table 4.12; CF = 0.5	50.00	1.37	68.50	Mean subtropical value	3.45	71.95
Southern temperate forest	1	Temperate oceanic forest in IPCC table 4.12, (see also IPCC figure 4.1); CF = 0.5	90.00	1.30	117.36	Mean warm temperate (dry and moist) value	20.88	138.24
Weighted average								84.0

*4, most use; 1, least use.

1. IPCC (2006) *IPCC Guidelines for National Greenhouse Gas Inventories*, eds Eggleston S et al. (IGES, Hayama, Japan).

Table S7. Carbon emissions per hectare from land cleared for crops for the 2nd to 20th y after clearing based on IPCC Tier 1 methodology and land use changes (1)

Biome	Cropland use increase weight*	Soil climate region (IPCC table 2.3)	Initial soil organic C stocks (tC ha^{-1})	Stock change factor climate region (IPCC table 5.5)	Soil organic C stock change factor, croplands (over 20 y)	Annual soil C loss from cropland years 1–20 (tC ha^{-1})
Grassland	2	Mean four temperate categories	65.09	Mean temperate/ boreal; dry, moist	0.745	0.830
Savanna	3	Mean tropical dry and tropical moist	54.70	Mean tropical	0.530	1.285
Tropical forests	4	Mean three tropical categories (excluding tropical montane)	62.20	Mean tropical	0.530	1.462
Mediterranean	1	Mean of warm temperate dry, moist and tropical dry, moist	56.95	Mean tropical, temperate/boral; dry, moist	0.638	1.032
Southern temperate forests	1	Mean two warm temperate categories	59.20	Mean temperate/ boreal; dry, moist	0.745	0.755
Weighted average						1.195

*4, most use; 1, least use.

1. IPCC (2006) IPCC Guidelines for National Greenhouse Gas Inventories, eds Eggleston S, et al. (IGES, Hayama, Japan).