doi:10.1038/nature10452

Supplementary Materials – Figures

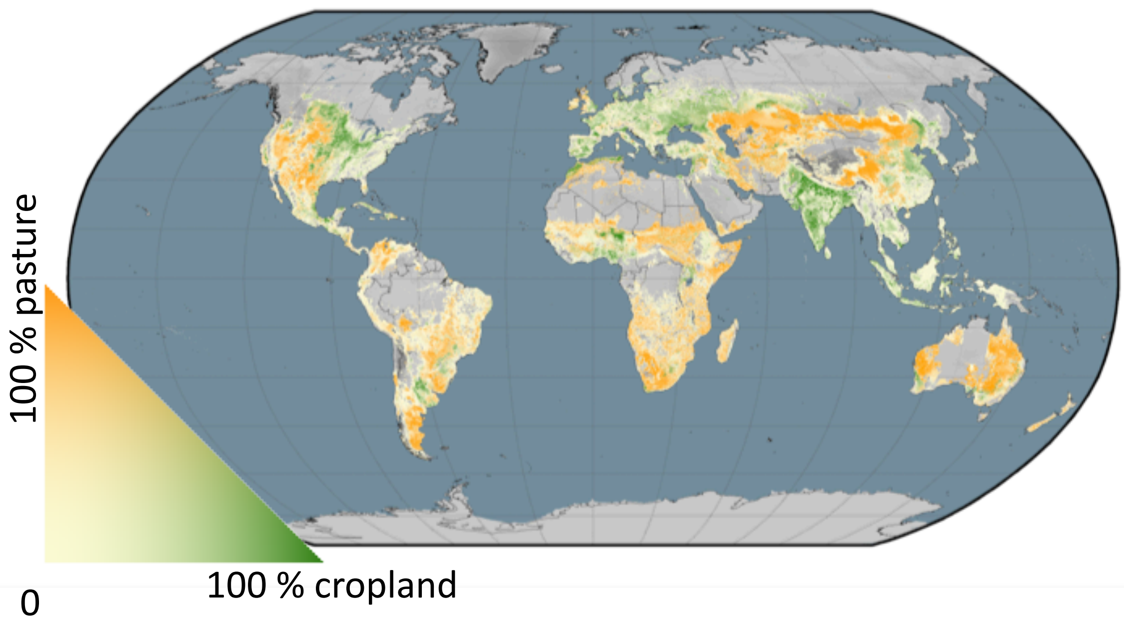

Figure S1. Extent of Global Agricultural Lands. This map illustrates the global extent of croplands (green) and pastures (brown), as estimated from satellite- and census-based data by Ramankutty *et al.*[1]. According to U.N. FAO statistics, croplands currently extend over 1.53 billion hectares (~12% of the Earth's land surface, not counting Greenland and Antarctica), while pastures cover another 3.38 billion hectares (~26% of global land). Altogether, agriculture occupies ~38% of the Earth's terrestrial surface, emerging as the largest use, by far, of land on the planet[1,2].

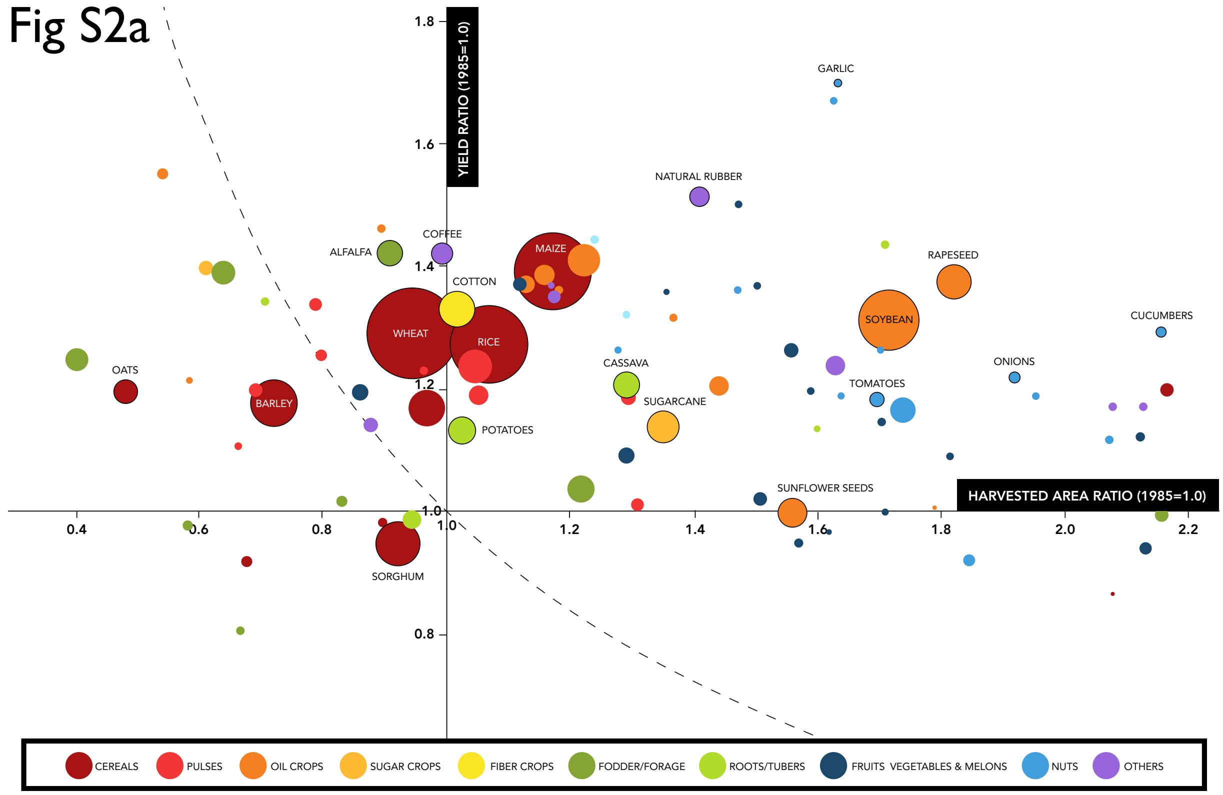

Figure S2. Trends in Global Crop Production, 1985–2005. In Figure S2a, we illustrate recent changes in yield and harvested area for 174 crops. The vertical axis shows changes in yield, expressed as a ratio of yields reported in 2005 and 1985. The horizontal axis reports relative changes in harvested area between 1985 and 2005. The size of the circle is based on each crop's harvested area in 2005, while the color corresponds to major crop groupings. We see that crops show changes in total production through changing harvested area (moving left or right), changing average yields per hectare (moving up or down), or both. The dotted curve divides the figure into two regions: Crops above the curve experienced increases in total production from 1985 to 2005 while production of crops below the curve declined.

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Fig S2b

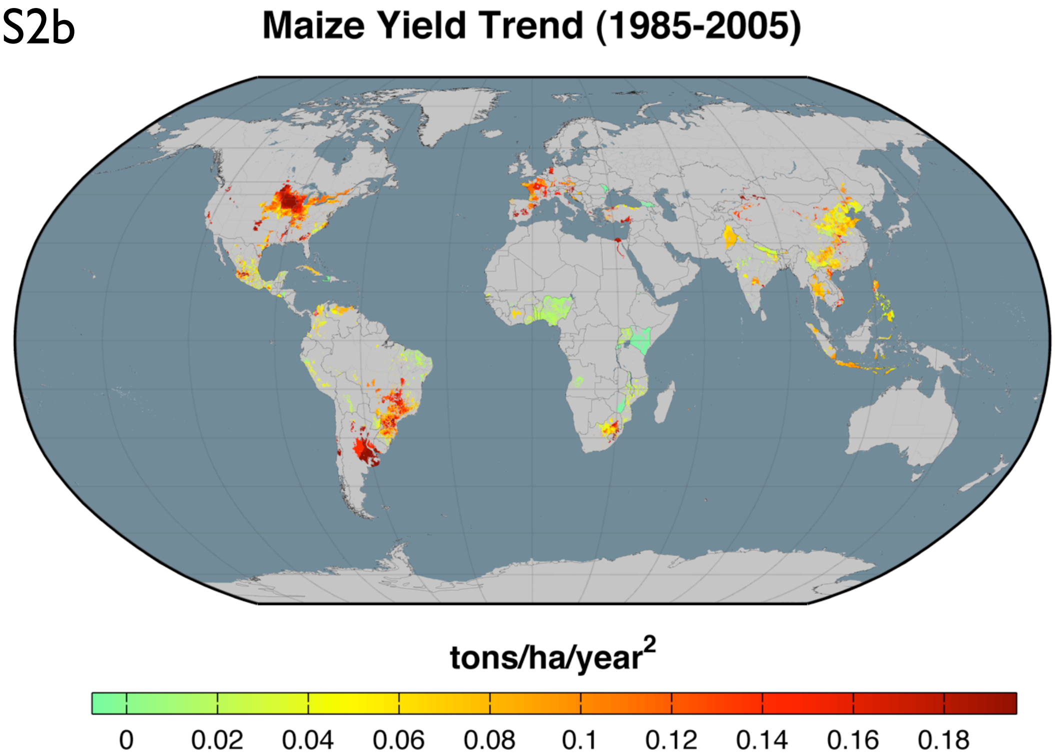

Figure S2b shows a detailed map of yield trends (tonnes/ha/year^2) for maize for 1985–2005. The plot shows statistically significant ($p < 0.1$) trends based on a linear regression of estimated annual yield values between 1985 and 2005. The data used in this calculation are based on Monfreda *et al.*[3], extended with additional data to cover the entire period.

Fig S3

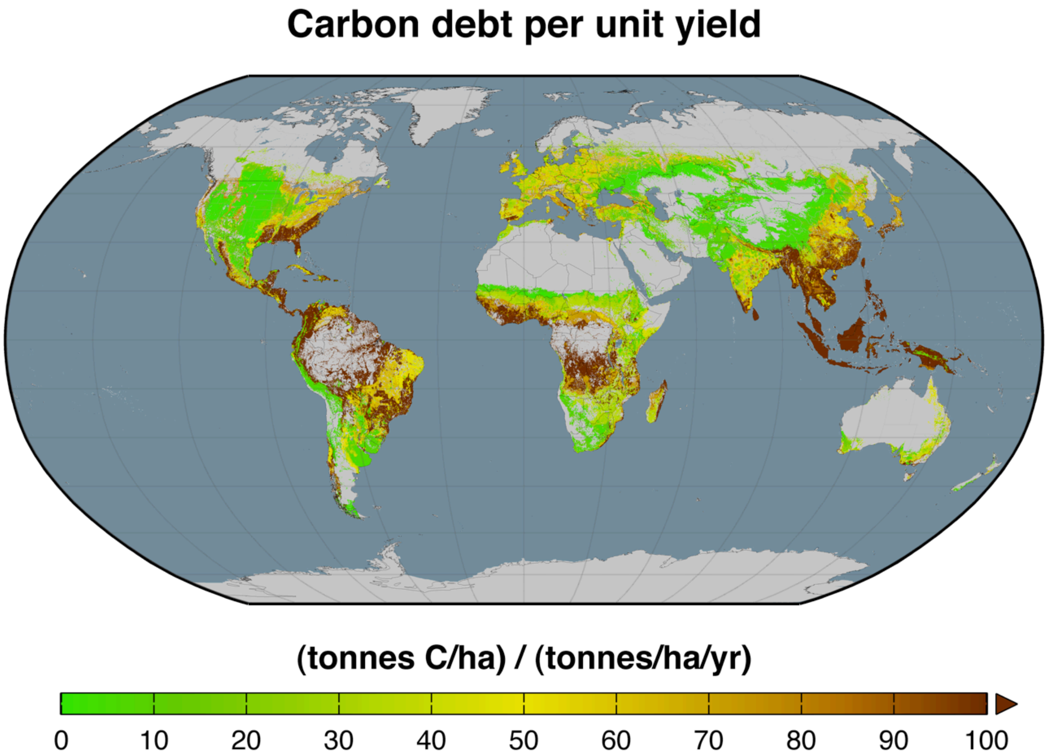

Figure S3. Ratio of Current Agricultural Yields to the Historical Carbon Debt of the World's Croplands. Here we consider the trade-off between growing more food through agricultural expansion and the emissions of carbon dioxide into the atmosphere from clearing additional land for crops. West *et al.*[4] reported that tropical lands typically provide average crop yields ~50% lower than those in temperate regions – with the notable exception of oil palm, sugarcane, and South American soybeans – yet release nearly two times more carbon for each unit of land cleared. The ratio of low yields to high carbon losses illustrates the difficult trade-offs of many tropical areas and highlights the environmental dangers of relying on tropical cropland expansion to meet future food demands.

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Fig S4a

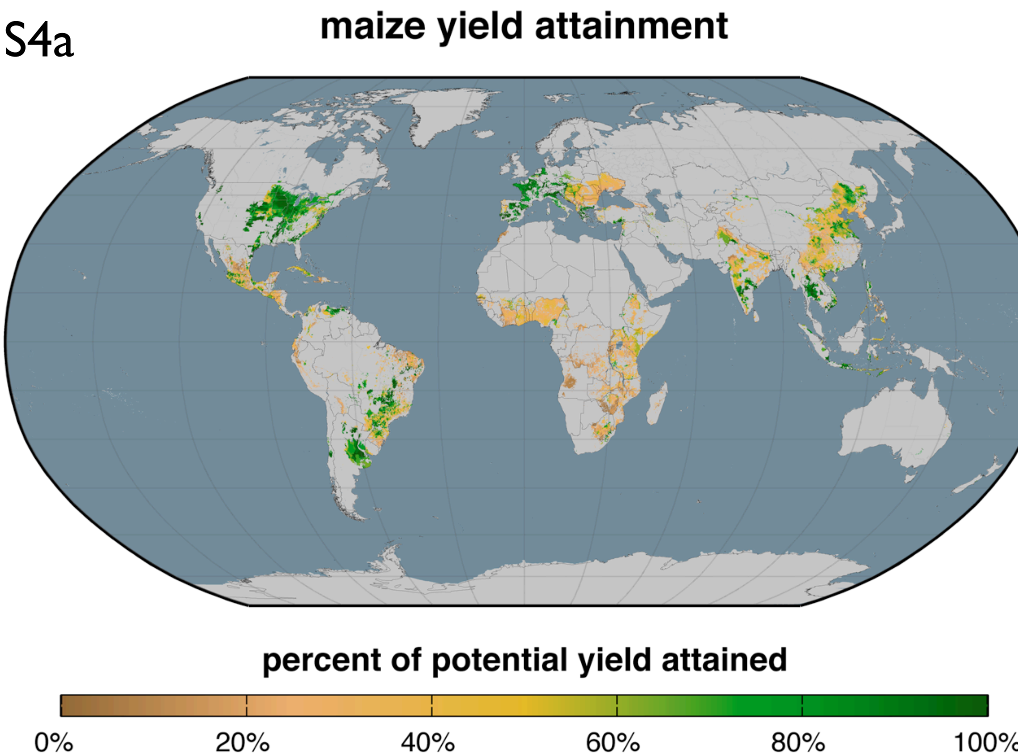

Fig S4b

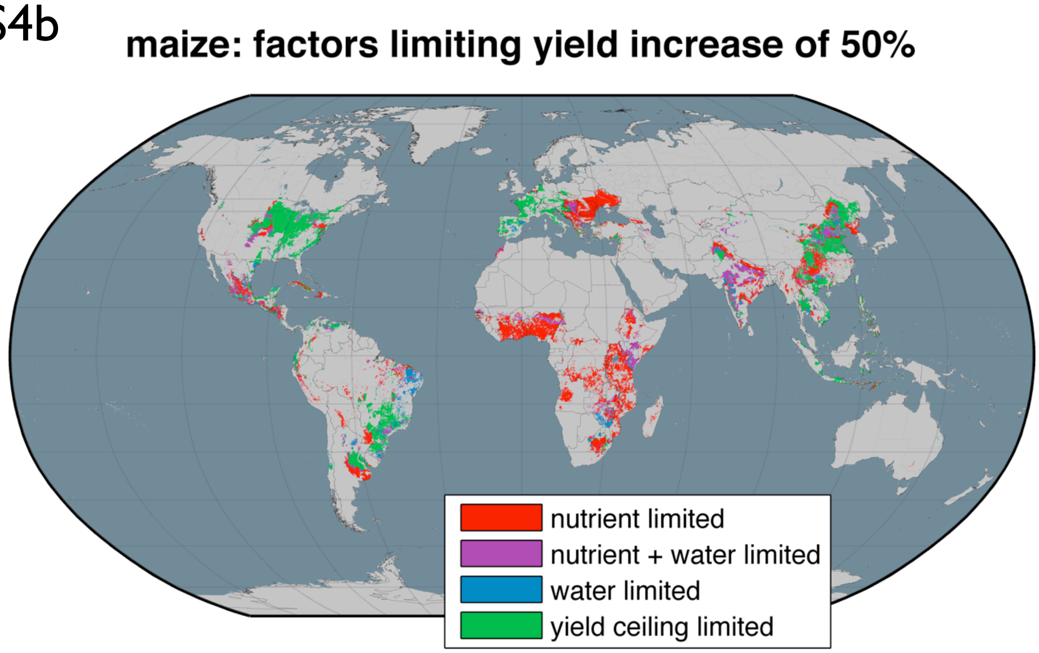

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Figure S4. Global Yield Gap Analysis. In Figure S4a, we show the global patterns of "yield attainment" for maize – the ratio of yields reported for any given location compared to the near-maximum (95th percentile) yields reported for maize, controlling for global variations in climate and soil conditions (adapted from methods of Licker *et al.*[5]). For a given location, a ratio of 50% shows that crop yields are only reaching half of their potential compared with other regions with the same climatic conditions and soils.

Figure S4b shows which factors most limit maize production – nutrients, water, or crop yield ceilings associated with today's genetics and seed quality. These limiting factors are quantified using simple relationships between agricultural inputs and yield (see Supplemental Information). In much of the world, the lack of nutrients and water are key limiting factors, whereas in regions of high productivity yields are likely limited by crop genetics.

Fig S5

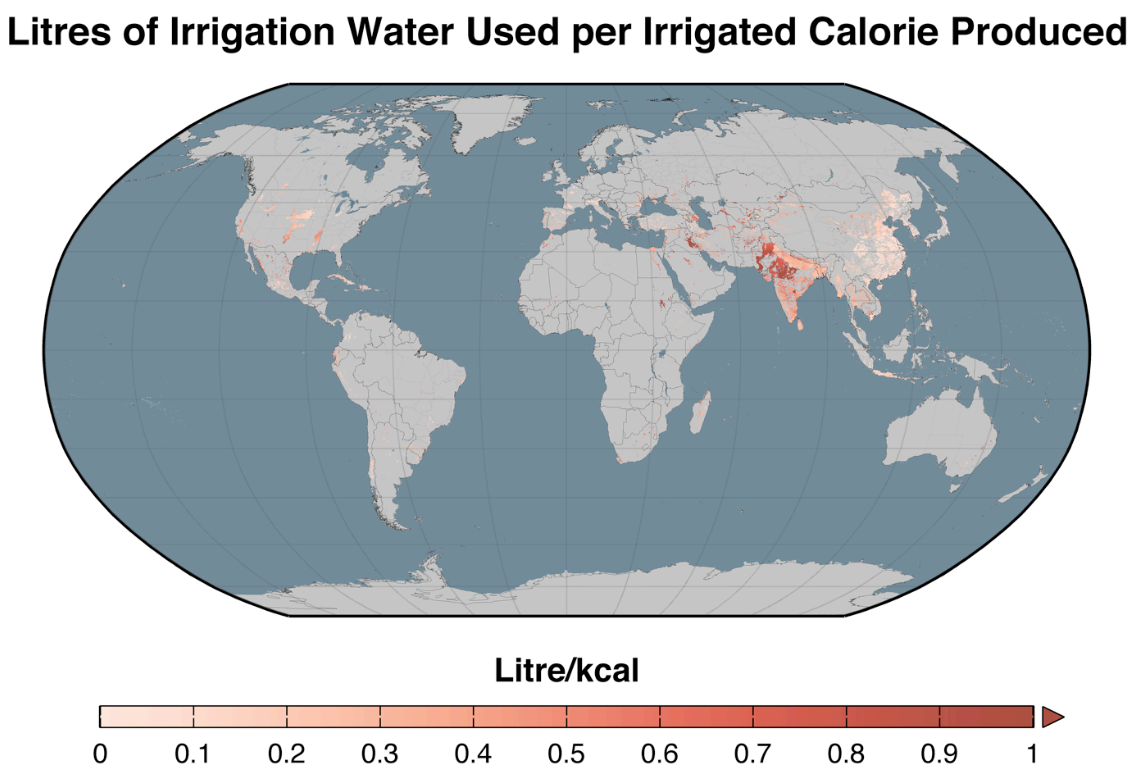

Figure S5. Irrigation Use Efficiency Across the Globe. Irrigation is one of our best tools for improving crop yields. However, the use and yield benefits of irrigation water are not distributed evenly across the globe. Here we show irrigation water required per kilocalorie of crop yield (irrigation water requirements and yields of irrigated crops from Siebert and Döll[6].

Use of irrigation water varies greatly across the world: the 16 staple crops analyzed here (barley, cassava, groundnut, maize, millet, potato, oil palm, rapeseed, rice, rye, sorghum, soybean, sugarbeet, sugarcane, sunflower, and wheat) require an average of ~0.3 liters of irrigation per kilocalorie of production. In this figure, we see that even higher water use (over 1 liter per kilocalorie) is required in northern India and portions of the Middle East.

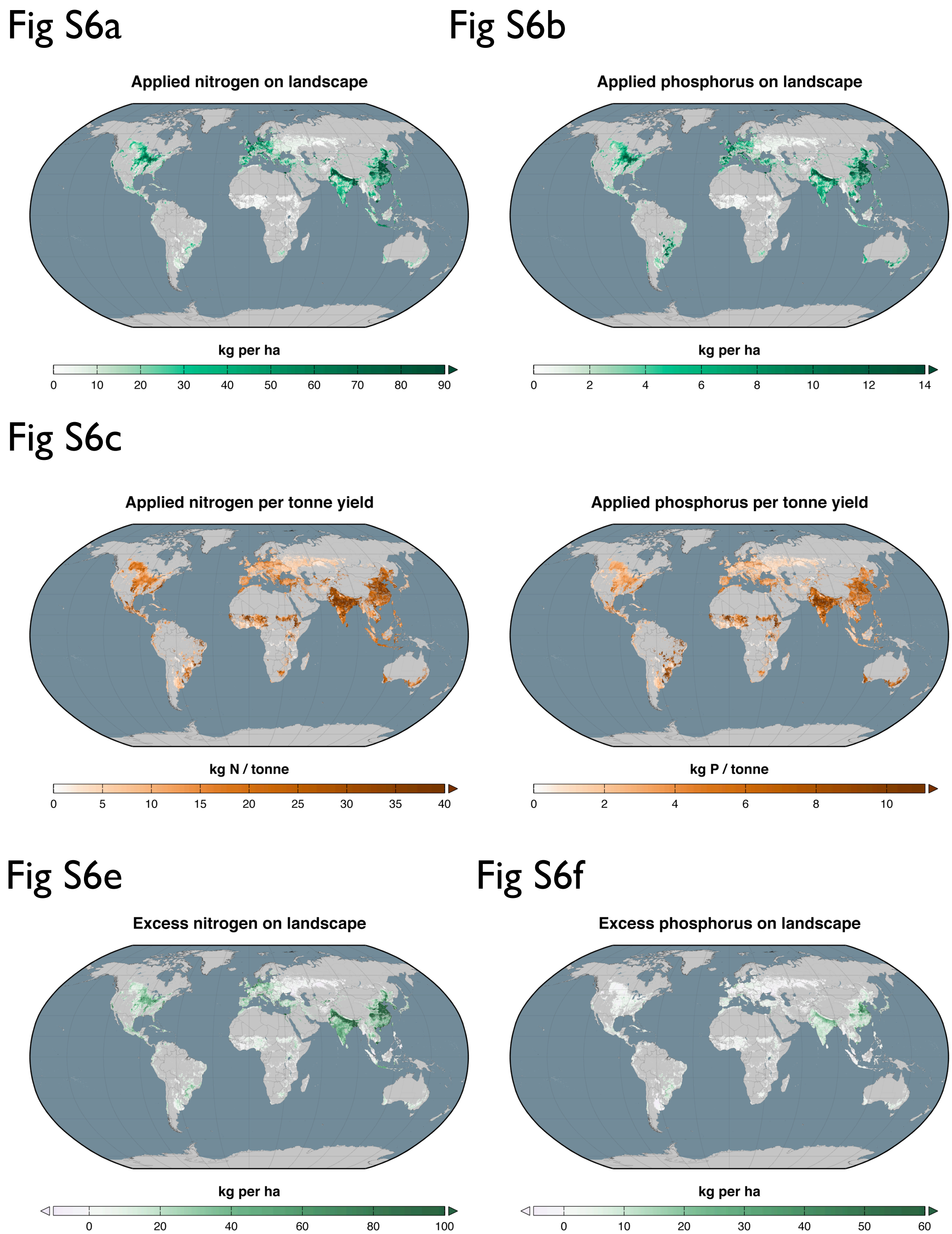

Figure S6. Nutrient Applications, Nutrient Use Efficiency, and Excess Nutrients on the Globe. Building on recent geospatial datasets and analyses of crop production and nutrient cycling (Monfreda *et al.*[3]; Potter *et al.*[7]; Liu *et al.*[8]; MacDonald *et al.*[9]) and utilising updated fertilizer and manure datasets we illustrate global patterns of nutrient inputs (Figure S6a,b), nutrient use efficiency (yield per unit nutrient input, Figure S6c,d), and estimated levels of excess nutrients (Figure S6e,f).

This analysis shows that there are “hot spots” of low nutrient use efficiency (Figure S6c,d) and large volumes of excess nutrients (Figure S6e,f). Nutrient excesses are especially large in China, Northern India, USA, and Western Europe. Furthermore, 10% of the world’s croplands account for 32% of the global nitrogen surplus and 40% of the global phosphorus surplus.

Fig S7a

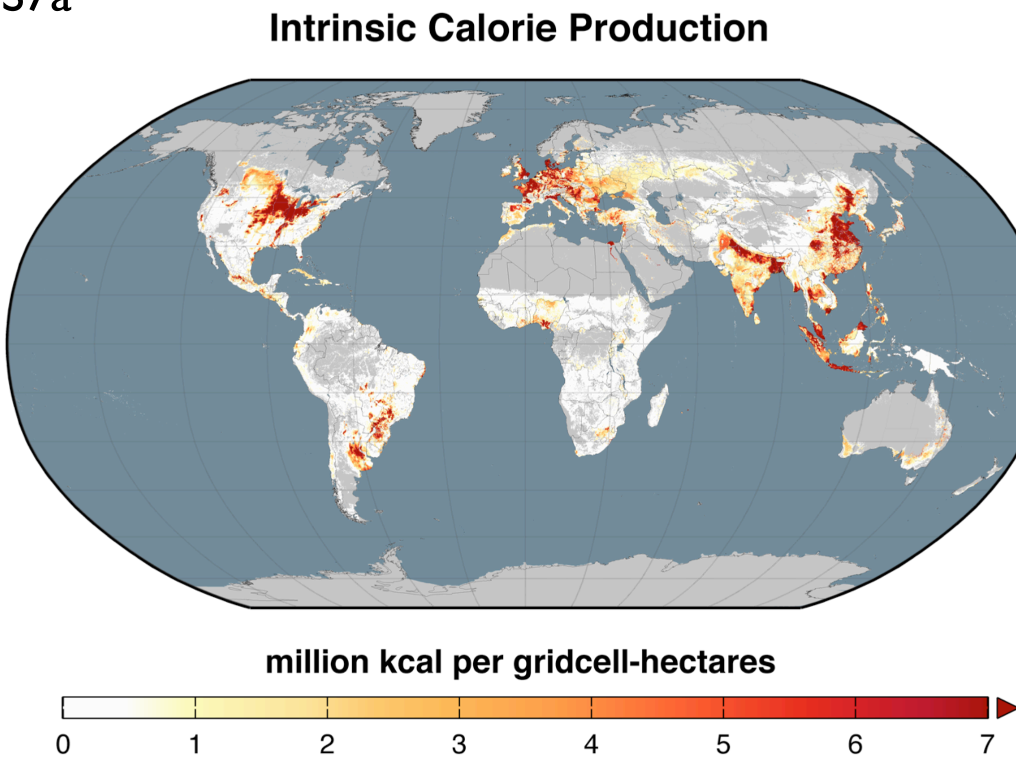

Fig S7b

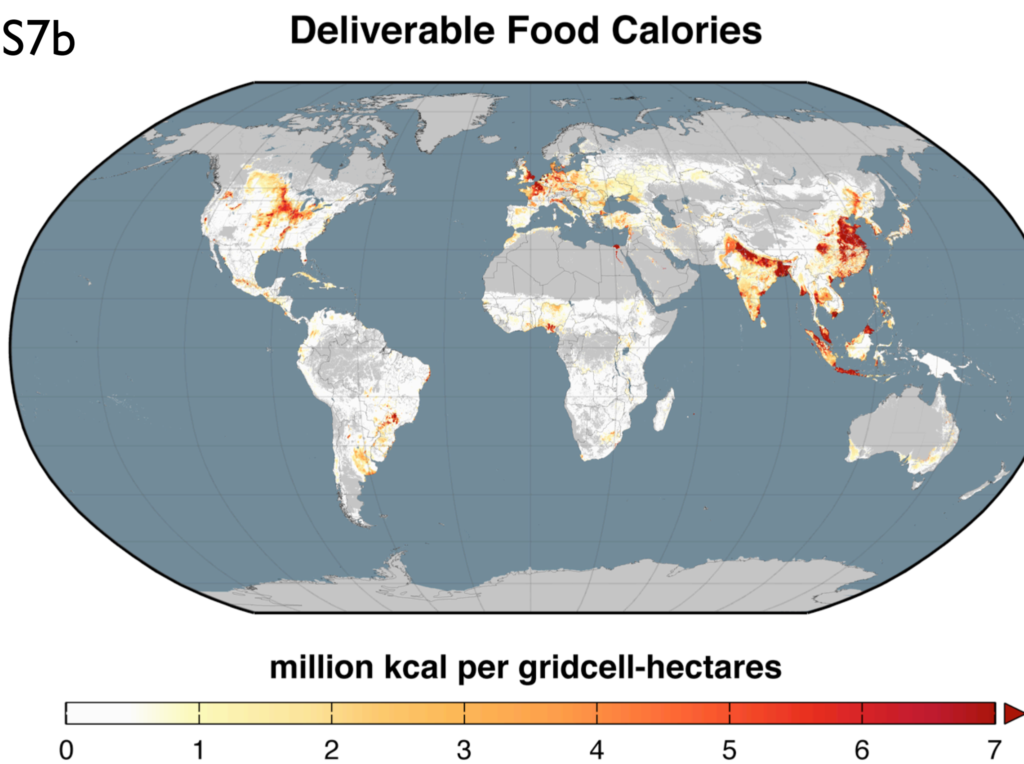

Figure S7. Differences Between Intrinsic and Delivered Food Production. Here we compare global crop yields for 16 staple crops (barley, cassava, groundnut, maize, millet, potato, oil palm, rapeseed, rice, rye, sorghum, soybean, sugarbeet, sugarcane, sunflower, and wheat) in terms of their *intrinsic food production* (Figure S7a, calories that would be available if all crops were consumed by humans directly) and their *delivered food production* (Figure S7b, calories available based on today's allocation of crops to food, animal feed, and other products, assuming standard conversion factors).

Supplementary Materials – Methods

Geospatial Yield Data

National and sub-national cropland area, maize harvested area and production information was collected for the spatial units delineated by Monfreda *et al.*[3] from crop census reports, agricultural yearbooks and FAOSTAT data[2]. We then combined these data with spatial maps of cropland areas from Monfreda *et al.*[3], to put the estimates on a 5 minute latitude-longitude spatial grid (approximately 9 km by 9 km at the equator).

We then averaged the harvested area and production numbers for each 5 minute grid cells to generate 7-year averaged harvested area and production estimates for ~1985 to ~2005 in 5-year time steps. Yield was estimated as the ratio of production and harvested area. Finally, we linearly regressed the yields from circa 1985 to 2005 to determine the trends of maize yields at 5 min spatial resolution.

Yield Gaps and Limiting Factors Calculations

To calculate yield gaps, we build on the work of Licker *et al.*[5] and group yield variations from Monfreda *et al.*[3] into 100 equal-area "bins" of similar climate (annual precipitation and growing degree-day) characteristics. Crop-specific potential yields for the yield gap analyses are defined as the 95th percentile yield within a climate bin. Comparing observed yields to potential yields defines the yield gap or "potential yield attainment" of each grid cell.

Management practices that limit maize yield increases (Figure 6b) are calculated using simple climate-specific input-yield models. For each climate bin, we quantify the saturating relationship (Mitscherlich-Baule functional form[10]) between yields and nitrogen fertilizer application, phosphate fertilizer application, potash fertilizer application (fertilizer data from Nathaniel D. Mueller, personal communication July 6, 2011), and percent irrigated area (Portmann *et al.*[11]) using a nonlinear least-squares algorithm. Yield plateaus (Y_{max}) for the Mitscherlich-Baule response are defined as the 98th percentile yields in a bin. The y-intercepts for nutrient response (defined by b_N, b_P, and b_K) are tied to the 2nd percentile yields in a bin, while y-intercepts for irrigation are allowed to vary with rainfed yield potentials in each climate bin. Following von Liebig's "law of the minimum"[10], yield can be limited by any one of the inputs (Eqn. S1).

$$Y_{mod} = \min\left(Y_{max}\left(1 - b_N e^{(-c_N N)}\right), Y_{max}\left(1 - b_P e^{(-c_P P)}\right), Y_{max}\left(1 - b_K e^{(-c_K K)}\right), Y_{max}\left(1 - b_{IRR} e^{(-c_{IRR} IRR)}\right)\right) \quad \text{Eqn. S1}$$

Using our empirically derived input-yield relationships, we model yields and assess what factors – nutrients, nutrients and irrigation, irrigation, or yield ceiling (90% of bin-specific potential yields) – limit a 50% yield increase within each climate bin.

Nutrient Inputs and Nutrient Balance Calculations

For Figure 8, applied nitrogen and phosphorus fertilizer rates are expressed in terms of kg per hectare of land (cropland and non-agriculture land). Total nutrient consumption is calculated as the sum of crop-specific chemical-fertilizer application rates (Nathaniel D. Mueller, personal communication July 6, 2011) multiplied across crop areas from Monfreda *et al.*[3]. The sum of nutrient consumption across all crops is harmonized with FAO national-level nutrient consumption statistics.

Manure application rates are calculated from the manure production dataset of Potter *et al.*[7]. We assume stable-produced manure is available to be applied to croplands, and that stable-produced manure is produced in proportion to cultivated agricultural land in a grid cell (the ratio of cropland area / cropland and pasture area from Ramankutty *et al.*[1]). Available manure is then subject to cropland application rates of 66% in Western Europe and Canada, 87% in the U.S., and 90% elsewhere (following Liu *et al*.[8]). Manure nitrogen loss from volatilization is estimated as a constant 36% loss (following Bouwman *et al.*[12]).

Excess nutrients are calculated as a simple mass balance described in West *et al.*, which is similar to recent efforts to estimate nutrient balances (Liu *et al.*[8], MacDonald *et al.*[9]). Chemical fertilizer and manure data sets are inputs for both nitrogen and phosphorous models. The nitrogen has additional inputs from nitrogen deposition (Dentener *et al.*[13]) and nitrogen fixation by legumes. Nitrogen fixation is scaled as a function of yields using a range of *Nfix* values from the literature (Smil[14]) and yields (Monfreda *et al.*[3]). Nutrient removal from harvest is estimated as the product of yield (Monfreda *et al.*[3]), dry fraction (Monfreda *et al.*[3]), and nutrient density (USDA[15]).

Diet Gap Calculations

The “diet gap” is the difference between calories produced and calories that become available for human consumption. We analyze sixteen staple crops: barley, cassava, groundnut, maize, millet, potato, oil palm, rapeseed, rice, rye, sorghum, soybean, sugarbeet, sugarcane, sunflower, and wheat. The proportion of crop production allocated to food, feed, and other products is determined using FAOSTAT data for crop production, use and trade[2]. To account for trade, crop production is separated into production that was consumed domestically, and production that was exported. Crop production that was consumed domestically is multiplied by country specific crop use proportions. Crop production that was exported is multiplied by global average crop use proportions.

Delivered food calories are the sum of the calories that directly go to the food system, as well as the calories that have been converted from animal feed to meat. The calories available from crop production directly allocated to food are the product of food production in tonnes and average calorie content of the given crop, as determined by FAOSTAT Food Balance Sheets[2]. We use grain to edible meat conversions to convert feed to animal protein[16]. The feed to animal protein calorie conversion is dependent on the density of cattle, chicken and pig meat produced within a country[2].

Supplementary Materials – Tables

Table S1. Changes in Global Agricultural Land Between 1985 to 2005

Global agriculture changes 1985 to 2005 (Million hectares and % change) Numbers may not add up exactly due to rounding						
	Cropland		Pasture		Agricultural	
	Ha	% change	Ha	% change	Ha	% change
Global	35.89	2.41	117.78	3.61	153.67	3.23
North America	-13.12	-0.88	-3.30	-0.10	-16.42	-0.35
Latin America	21.41	1.44	23.13	0.71	44.54	0.94
Europe-Central Asia	-45.34	-3.04	19.80	0.61	-25.54	-0.54
Africa	45.90	3.08	19.93	0.61	65.83	1.38
Oceania	-1.48	-0.10	-40.20	-1.23	-41.67	-0.88
Asia	28.51	1.91	98.42	3.01	126.93	2.67
East Asia	7.06	0.47	22.49	0.69	29.55	0.62
Southeast Asia	15.04	1.01	0.51	0.02	15.55	0.33
South Asia	3.27	0.22	-9.07	-0.28	-5.80	-0.12
West Asia	3.14	0.21	84.49	2.59	87.63	1.84

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