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Supplementary Materials for

Leverage points for improving global food security and the environment

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Materials and Methods

Yield gap and increasing production calculations

Yield gaps were calculated based on methods defined in previous studies (*3*, *13*, *32*), which groups spatially-explicit yield data in Monfreda (*30*) in 100 equal-area climate "bins." Bins are crop-specific and are defined based on annual precipitation and growing-degree days. Climate data were from WorldClim (*33*). Crop-specific yield potentials for each bin are defined as the 95th percentile of the range of yields within a bin. The yield gap is calculated as the difference between the potential yields and the agricultural census reported yields in Monfreda (*30*). Next, we calculated 50% of the potential yield value for each crop and scenario used in this analysis. We then identified all areas for each of the 17 crops that had yields at or less than 50% of the potential values. The total production gains from this scenario were calculated by multiplying the scenario yields by the harvested area for each crop and summing the gains over all crops.

To account for differences in water content in the economic yield, the concentration of production gains (such as 50% of all production gains in this scenario are concentrated in ~5% of the total harvested area) were analyzed based on kilocalories. The results were then converted back to economic yield and are reported that way in Table 2a. Estimates of the number of additional people whose daily calorie needs could be met is based on the assumption that 1 X 10^{15} kcals can feed 1 billion people (*34*).

Increasing yields in low-performing regions will likely require a mix of strategies. Several field trials in low-yielding regions conclude that nutrients and water, not genetics, are the limiting factors for increasing yields (*35*, *36*). However, additional fertilizer may have limited response when applied to very degraded soils (*36*, *37*). For example, cases of yield tripling in parts of Africa were achieved by nutrient and water management coupled with higher-yielding crop varieties (*38*, *39*). In addition, closing these yield gaps may require a broader mix of strategies to address the major limitations to yield improvements, including access to credit and markets, insufficient technology, availability of better seeds, pest and weed control, soil nutrients, and water (*36*).

Nutrient balance and nitrous oxide (N_2O) emission calculations

Nutrient balance calculations

Nutrient inputs were compiled from several sources. Crop-specific fertilizer application rates for nitrogen and phosphorus were from Mueller et al. (*13*). Manure application rates were estimated using methods consistent with Potter et al. (*40*) and Foley et al. (*3*). Manure quantity is derived from livestock density, and distributed proportionally to the mix of cropland and pasture. Consistent with Bouwman et al. (*41*) we assume that 36% of manure is volatilized and thus not an input in the nutrient balance equations. Manure available to croplands varies regionally and, consistent with Liu et al. (*42*), we assume the following application rates of 66% in western Europe and Canada, 87% in the USA, and 90% elsewhere. Next, the available manure quantities were distributed across agricultural lands based on the relative proportion of croplands and pastures. Nitrogen input from fixation by legumes (only soybean included in this analysis) was estimated using a range of observed fixation rates (*43*), scaled to yield. Rates of atmospheric deposition were global estimates developed for the IPCC AR4 (*44*).

Nutrient balance was calculated using a simple mass balance model described in West (*45*). This approach is similar to recent global estimates of nitrogen (*42*) and phosphorus (*46*). Nutrient removal at harvest was estimated using nutrient density data (*47*) for the dry fraction of harvested material. We define the difference of input and harvested amounts as "excess nutrients."

We compared our estimates of applied and excess nitrogen and phosphorus to several other studies using a larger set of crops (140) than the main 17 crops reported throughout this paper. Liu et al. (*42*) used a similar approach of distributing manure across croplands and, as such our estimates of total applied nitrogen are very similar (134Tg here, vs. 136Tg in Liu et al. (*42*)). We find that 56% of the nitrogen applied to 175 crops (75Tg) is in excess of the amount removed at harvest. We calculated total applied phosphorus using the same assumptions of manure distribution. We find that total phosphorus (manure and fertilizer) applied to 175 crops is 25Tg and the excess is 14Tg (56%). Therefore, the 17 crops account for 73% of the applied and 68% of the excess nitrogen across all croplands. Similarly, the 17 crops account for 68% of the applied and 58% of the excess phosphorus across all croplands.

Our estimates of applied and excess and nitrogen and phosphorus are ~20-25% lower than previous studies (*40*, *46*, *48*). The difference is primarily because the other studies mentioned estimate applied nutrients based on total manure production (not distributed using methods here or Liu et al. (*42*)). Because we distributed the manure across croplands and pastures (instead of using total manure production), the results here likely better reflect nutrient balances on croplands.

In addition, estimates of excess nutrients reflect a snapshot, based on a single year circa 1997-2003. However, accumulation or depletion of soil nutrients could have occurred over longer periods, which would exacerbate nutrient imbalances. This is especially true for phosphorus, which can have a long-term legacy of historical overuse (*49*). Sattari et al. (*50*) show the role of this residual soil phosphorus pool for crop production in Europe. As such, our estimates of excess nutrients are likely conservative.

Avoidable nitrogen and phosphorus calculations

We used a crop- and climate-specific yield response model (*13*) to calculate the amount of fertilizer application that could be reduced yet still get the same yields. We refer to this potential as "avoidable" nitrogen and phosphorus. Similar to the yield gap methodology described above, the yields for each crop are divided into 100 climate bins of equal harvested area. Within each climate bin, the yield response model uses Mitscherlich-Baule curves to describe the saturating relationship between yield and additional inputs of nitrogen, phosphorus, and potassium. Additionally, yields on rain-fed lands plateau at model-derived rain-fed yield ceilings.

We used the model to estimate the minimum amount of nitrogen and phosphorus needed to obtain current yields. Since the model is based on current yields and management practices, this approach estimates "best in class" application rates that minimize excess nitrogen and phosphorus. Avoidable nitrogen and phosphorus was only estimated for those crops with high-resolution yield and fertilizer data throughout the growing area. The model was only used for crops where the r^2 is >= 0.33 for within-bin variability and >= 0.66 for global variability explained. As such, it was not used for millet, sorghum, rye, sugarcane, soybean, rapeseed, cassava, and groundnut.

Nitrous oxide emission calculations

We used the IPCC Tier-1 (*22*) methodology for estimating nitrous oxide emissions from croplands, which assumes that 1% of nitrogen inputs are emitted as N_2O. The same inputs listed above for the nitrogen nutrient balance were used to calculate N_2O emissions.

Water consumption calculations
We used crop-specific geospatial data sets of water consumption from Siebert and Döll (*6*). We restricted our analysis to precipitation-limited areas, defined here as places where annual potential evapotranspiration exceeds precipitation. Precipitation data were from WorldClim (*33*). Potential evapotranspiration was calculated using Thornthwaite's (*51*) method. Irrigated grasslands were excluded from the analysis for calculating the percentage of global water consumption for each crop. Country-scale water productivity was calculated using methods described in Brauman et al. (*26*).

Diet gap and waste calculations
The diet gap is the difference between total calorie production and available calories after conversion to meat (or lost to other non-food uses, such as biofuels). Methods for calculating this diet gap follow Cassidy et al. (*28*), which estimated the diet gap for the year ~2000 (average of 1997-2003). Average crop calorie content values compiled by Tilman et al. (*11*) were used to convert tonnes to potential calories. Crop allocation was derived from the FAO Food Balance Sheets (*29*). Calorie conversion from feed to meat was based on efficiency rates in Smil (*52*) and Cassidy et al. (*28*). Details on how carcass weight, distiller grains, and other factors affect available calories are described in Cassidy et al. (*28*).

Similar methods were used to calculate the effects of food waste on available calories. We estimated consumer-level food waste and associated land requirements in China, India, and the United States to illustrate the effects of waste and diet on global food security and land requirements. We used national food availability data in FAO's Food Balance Sheets (*29*) and regional consumer-level food waste percentages (on a weight basis) (*31*) to estimate total food waste in major food categories for each country. Total per capita kilocalories values were included in the table to include oils, sweeteners, and other food categories that were difficult to connect to specific crops and their respective yields. We account for domestic versus exporting country yields in the case of wheat, rice, and vegetables. For simplicity in Table 1, we combined wheat, rice, and vegetables into "cereals and vegetables" since all three had very similar percentages of consumer waste.

Feed calories embodied in livestock were calculated using conversion factors (described above) (*28*) and adjusted to cropland-derived feed intake only based on Bouwman et al. (*53*). We excluded the approximate fraction of livestock produced from grazing forage and other non-cropland sources based on regional feed source fractions from Bouwman et al. (*53*).The embodied feed calories in meat were included in the calculations for the loss of available calories from meat waste. These calculations were used to compare the relative impact of wasting wheat and beef in the main text.

Crop harvested area requirements (hectares $kcal^{-1}$) for each country were derived using FAOSTAT national weighted-average feed crop yields. For meat, we assumed that feed was derived from domestic feed crops based on crop allocation data from Cassidy et al. (*28*).

Crop allocation trend calculations
Consistent with Cassidy *et al.* (*28*) we used the end-use data in the FAO Food Balance Sheets for 41 crops to determine the allocation of calories from 1961-2009. These 41 crops represent 90% of total calorie production globally. We found that the fraction of total crop calories produced decreased from 57% in 1961 to 51% in 2009. Of particular note, the 'other' use-category has consistently accounted for 11-13% of agricultural calories. However, beginning in the 2000s, the rapid scale-up of biofuel production caused 'other' utilization to increase to 16%. During this

same period, the fraction of calories allocated to biofuel production increased from 1% to 4% (*28*). It is important to note that the crop allocation estimates are not the same as the diet gap. The diet gap calculates calories delivered to the food system, which includes the calories from animal products from feed (including distiller grains from biofuel stocks).

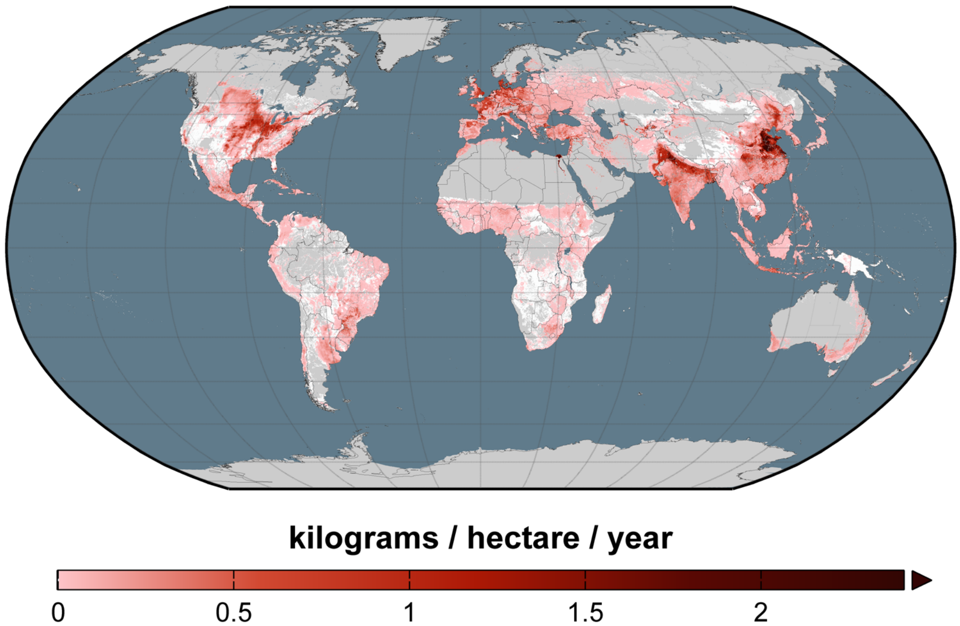

Figure S1. Nitrous oxide (N_2O) emissions from major crops.
Nitrous oxide emissions from croplands were estimated using the IPCC Tier-1 approach (*22*), which assumes that 1% of nitrogen inputs are emitted as N_2O. Inputs included crop-specific fertilizer application data (*13*), NO_x deposition (*44*), and livestock manure (defined in supporting materials text). This figure depicts N_2O emissions for the 17 crops included in this study, and does not include N_2O emissions from other crops, pastures, or non-agricultural areas.

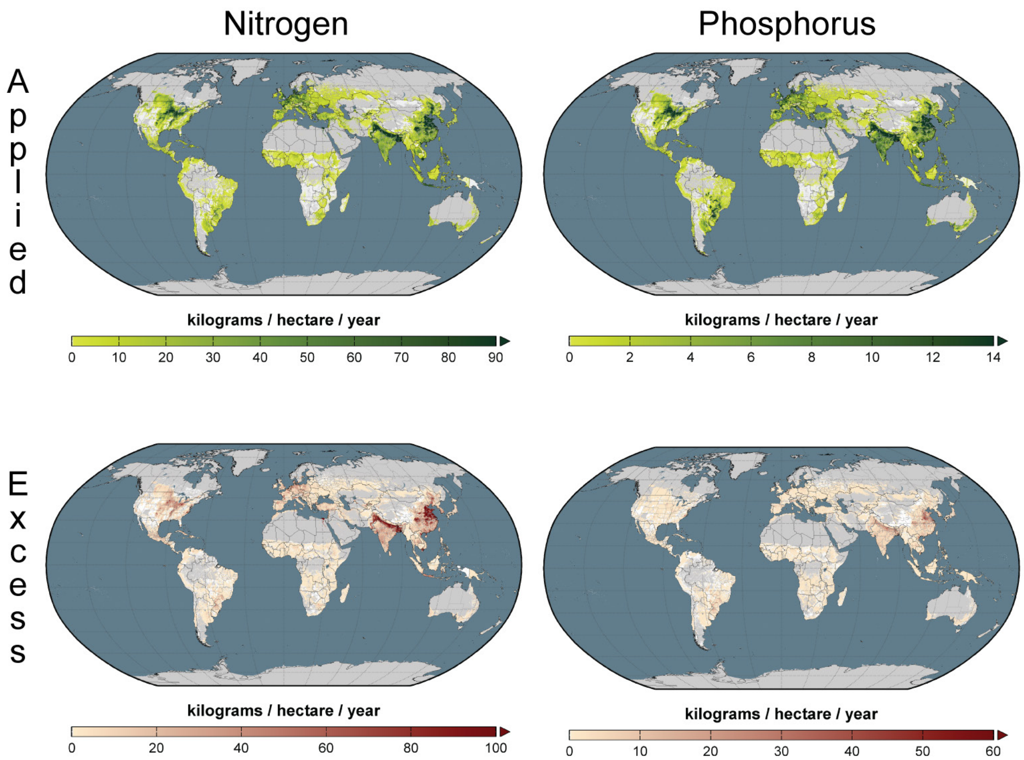

Figure S2. Applied and excess nitrogen and phosphorus in croplands.
Nitrogen and phosphorus inputs and excess were calculated for 17 crops using a simple mass balance model. To account for both the rate and spatial extent of croplands, the data are presented as kg per ha of the landscape. Approximately 60% of nitrogen and 48% of phosphorus applied to the 17 crops are in excess of the nutrient content of the harvested material annually. Fifty percent of the excess nitrogen and phosphorus is concentrated in only 24% and 21% of the cropland area, respectively. The global leverage points are a few countries and crops. China, India, and the USA account for ~66% of the global excess nitrogen and phosphorus. Analyzed from a crop perspective, wheat, rice, and maize account for ~58-60% of the global excess of these two nutrients.

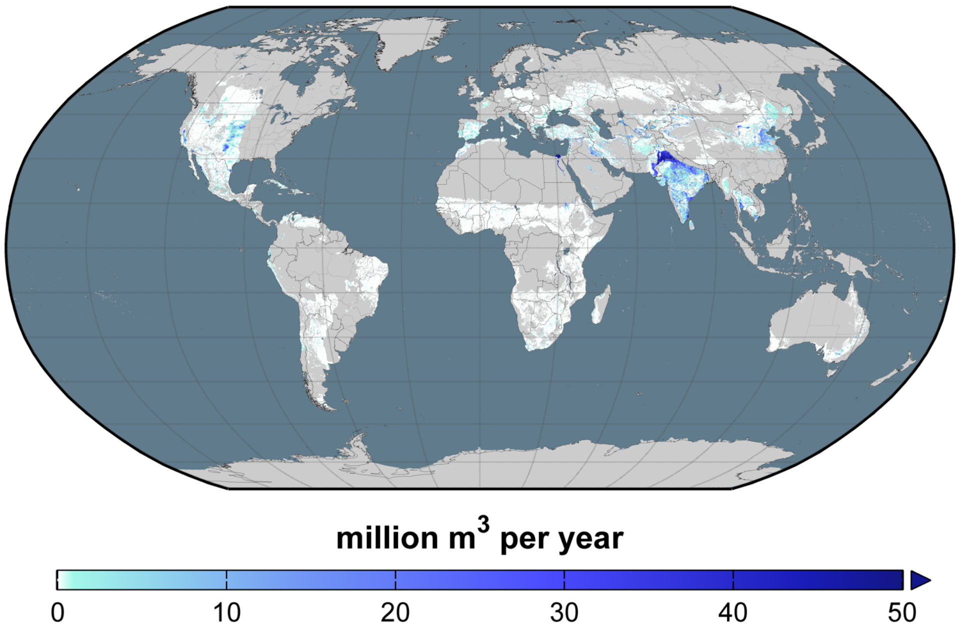

Figure S3. Water consumption of 17 major crops in precipitation-limited areas.
We estimated water consumption for 17 major crops using crop-specific irrigation data developed by Siebert and Döll (*6*). The figure shows the total irrigation water consumption each five arc-minute grid cell ($m^3\ yr^{-1}$). For the 17 crops analyzed, India, Pakistan, China, and USA account for 65% of all irrigation water used in precipitation-limited areas, with India alone accounting for 32%. Rice and wheat together comprise 59% of the total irrigated area and consume 55% of irrigation water. Maize, cotton, and sugarcane use an additional 27% of total irrigation water. Despite covering only 3% of cropland area globally, sugarcane and cotton are highly water intensive crops, with mean water use that is 2.4 and 1.6 times, respectively, the amount used for each hectare of wheat.

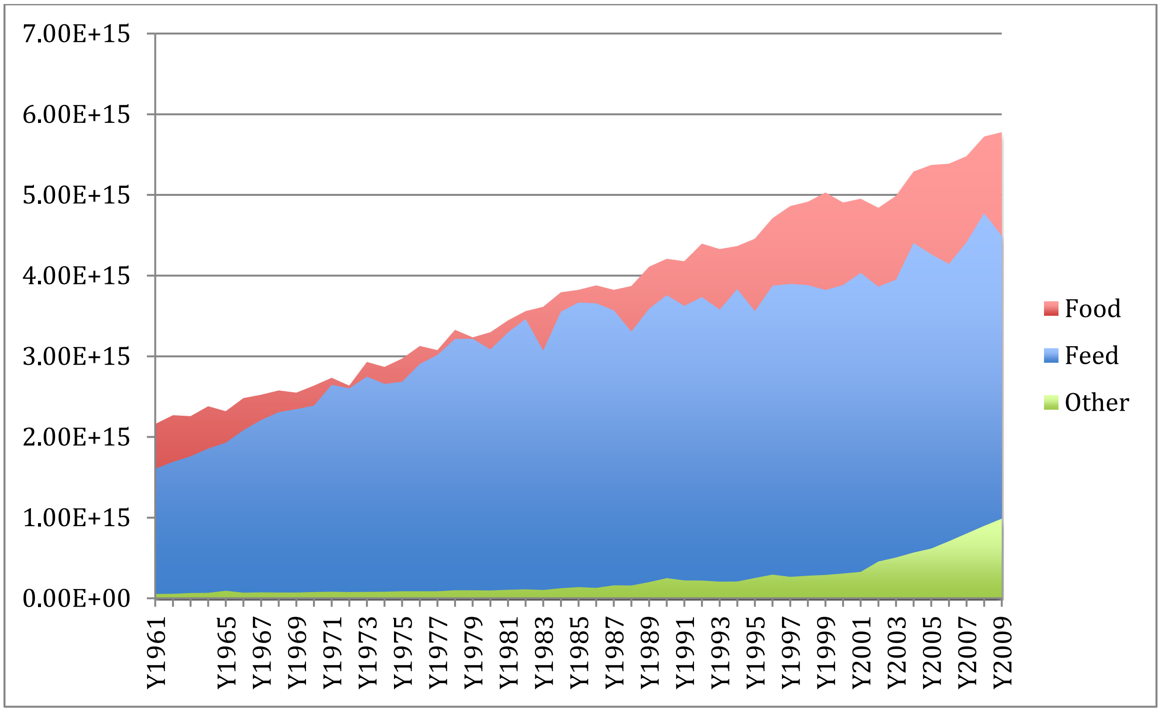

Figure S4. Trends in calorie use for food, feed, fuel, and other uses (1961-2010). We used the end-use data in the FAO Food Balance Sheets for 41 crops to determine the allocation of calories from 1961-2010. These 41 crops represent more than 90% of total calorie production globally. We found that non-food utilization has intensified over time, increasing from 43% of calories in 1961 to 49% in 2009. Of particular note, the 'other' use-category has consistently accounted for 11-13% of agricultural calories. However, beginning in the 2000s, the rapid scale-up of biofuel production caused 'other' utilization to increase to 16%.

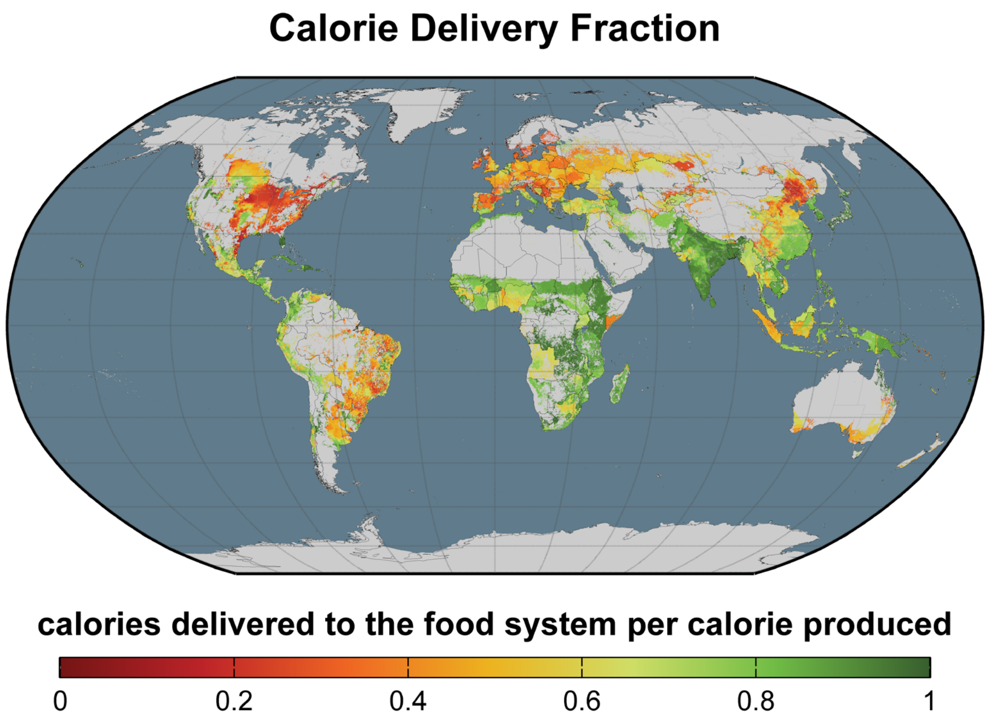

Figure S5. Allocation of food and feed and its effect on the diet gap.
Crop allocation to animal feed and biofuels reduces calories available to people. These crop allocations were used to determine the potential calories and the subset of calories that are available to people after loss through conversion from feed to animal products and biofuels. We refer to the difference between potential and delivered calories as a "diet gap." We estimate that the USA, China, Western Europe, and Brazil account for 26%, 17%, 11%, and 6% of the global diet gap, respectively. Changing crop allocation to directly feed people in these four regions alone could provide enough calories to meet the basic needs of 2.4 billion people. Maize represents the largest potential gain, accounting for 41% of the global diet gap. Maize in the USA accounts for 19% of the global diet gap, enough calories for 760 million people; maize in China represents 9% of the diet gap. *Figure based on data from Cassidy et al.* (*28*).

Table S1. Production and resource use for 17 crops included in this analysis.
Data in these columns is relative to total production of all crops. Cropland harvested area and yield were derived from Monfreda *et al*. (*30*), which combines sub-national agricultural statistics from ~12,500 political units and satellite data from 1997-2004. Calorie conversions were based on Tilman *et al*. (*11*). Yield attainment was calculated based on 100 crop-specific climate zones, following methods defined elsewhere (*13,32*). Data in these columns is relative to total production of all crops. For example, wheat is ~14% of total cropland harvested area and the 17 crops combined account for ~58% of total harvested area.

Crop	Harvested Area	Share of cropland	Average yield	Production	Share of production	Avg. Yield attainment	Total Calories	Share of Calories
name	**hectares**	**percent**	**tons/ hectare**	**tons, dry weight**	**percent**	**percent**	**kilocalories**	**percent**
Barley	53,885,256	3.6%	2.5	119,270,376	3.5%	57.0%	4.5E+14	4.3%
Cassava	15,228,750	1.0%	10.5	51,244,490	1.5%	56.6%	1.7E+14	1.6%
Cotton	30,285,146	2.0%	1.7	47,756,934	1.4%	60.6%	-	-
Groundnut	22,049,138	1.5%	1.4	29,324,293	0.9%	58.4%	1.2E+14	1.2%
Maize	135,164,352	9.0%	4.4	533,870,509	15.8%	53.3%	2.1E+15	20.7%
Millet	33,271,542	2.2%	0.8	22,904,950	0.7%	55.7%	8.8E+13	90.0%
Oil Palm	9,523,223	0.6%	12.5	95,404,721	2.8%	56.5%	6.4E+14	6.2%
Potato	19,176,720	1.3%	15.8	85,010,530	2.5%	50.8%	2.1E+14	2.1%
Rapeseed	24,397,368	1.6%	1.5	26,596,791	0.8%	67.7%	1.8E+14	1.7%
Rice	150,229,776	10.0%	3.9	520,925,042	15.4%	61.7%	1.6E+15	15.8%
Rye	9,339,490	0.6%	2.2	17,692,098	0.5%	46.4%	6.4E+13	60.0%
Sorghum	38,747,392	2.6%	1.4	48,754,604	1.4%	54.3%	1.9E+14	1.8%
Soybean	74,263,088	5.0%	2.2	150,059,393	4.4%	73.0%	5.9E+14	5.7%
Sugar Beet	6,082,875	0.4%	38.9	28,401,377	0.8%	57.0%	1.7E+14	1.6%
Sugarcane	19,571,416	1.3%	64.3	188,672,569	5.6%	63.4%	3.7E+14	3.5%
Sunflower	20,365,756	1.4%	1.2	23,072,455	0.7%	62.3%	7.3E+13	70.0%
Wheat	208,329,088	13.9%	2.7	504,459,734	14.9%	54.0%	1.9E+15	18.0%
Sum of crops	869,976,000	58.2%	5.0	2,493,420,865	73.7%	58.2%	9.0E+15	86.5%

Table S2A. Production gains (tons) from closing the yield gap in low-performing areas to 50% of potential yields
The potential gains summarized below illustrate what is possible if yields in low-performing areas were increased to 50% of their potential. Values of zero indicate that either all croplands within the region have yields greater than 50% of potential yields or it is not grown there.

Crop	Global	Africa	Asia	Europe	Northern America	Oceania	South and Central America
Name	Tons				Tons		
Barley	12,350,252	1,886,045	5,541,629	20,907,765	957,767	317,796	442,772
Cassava	13,269,162	22,032,142	3,935,706	0	0	7,389	3,606,363
Cotton	4,084,580	1,032,529	3,973,150	3,950	3,054,538	114,506	556,034
Groundnut	2,197,121	2,402,638	2,357,777	6,103	26,144	13,619	341,947
Maize	68,392,695	22,947,909	47,254,559	23,416,717	2,546,479	30,339	18,036,845
Millet	2,694,085	2,168,897	2,382,445	143,574	254	3,391	13
Oil palm	20,117,299	8,983,926	0	0	0	0	175,473
Potato	54,346,926	4,223,562	31,787,230	47,536,227	556,760	179	3,714,104
Rapeseed	1,140,789	6,710	2,052,184	596,457	96,528	615,085	3,642
Rice	27,449,230	7,528,967	58,574,868	108,216	27	493	3,096,864
Rye	4,330,479	572	478,961	6,039,274	205,992	1,080	5,006
Sorghum	6,567,348	5,106,752	2,473,714	33,486	598,972	995,233	857,564
Soybean	2,475,716	402,784	5,961,590	507,216	352,373	1,563	92,184
Sugar beet	21,287,985	34,758	12,611,781	35,892,263	3,415	0	671
Sugarcane	54,574,809	8,418,403	63,075,516	0	0	18,404	26,160,096
Sunflower	1,933,318	104,947	807,853	2,044,041	46,562	9,774	18,550
Wheat	60,748,341	6,334,863	51,085,336	43,192,456	13,972,863	10,818,522	9,284,398
Sum of crops	357,960,135	89,124,393	133,353,901	86,271,884	5,919,822	4,411,035	30,405,380

Table S2B. Calorie gains (kilocalories) from closing the yield gap in low-performing areas to 50% of potential yields
The potential gains summarized below illustrate what is possible if yields in low-performing areas were increased to 50% of their potential. Values of zero indicate that either all croplands within the region have yields greater than 50% of potential yields or it is not grown there. Calories associated with cotton are seed oil.

Crop name	Global kilocalories	Africa	Asia	Europe	Northern America	Oceania	South and Central America
		Kilocalories					
Barley	4.1E+13	5.1E+12	1.2E+13	2.2E+13	6.2E+11	1.9E+11	9.6E+11
Cassava	1.4E+13	1.0E+13	1.7E+12	-	-	2.1E+09	2.3E+12
Cotton	1.7E+13	4.9E+12	4.4E+12	3.0E+10	6.0E+12	7.8E+10	1.3E+12
Groundnut	8.4E+12	5.4E+12	2.6E+12	4.6E+10	2.3E+10	1.2E+10	3.2E+11
Maize	2.4E+14	7.9E+13	7.1E+13	4.5E+13	1.1E+12	3.9E+10	4.9E+13
Millet	9.3E+12	5.4E+12	3.9E+12	7.6E+10	4.6E+07	1.3E+09	4.6E+06
Oil Palm	1.1E+14	1.1E+14	-	-	-	-	6.8E+11
Potato	3.8E+13	2.0E+12	1.4E+13	2.0E+13	4.5E+10	1.5E+08	2.7E+12
Rapeseed	5.6E+12	1.8E+10	3.5E+12	1.4E+12	8.9E+10	6.2E+11	3.9E+09
Rice	7.7E+13	1.8E+13	5.3E+13	1.4E+11	4.9E+07	4.2E+08	6.4E+12
Rye	1.4E+13	2.2E+10	6.4E+11	1.3E+13	2.9E+11	1.1E+10	1.9E+10
Sorghum	2.3E+13	1.4E+13	6.1E+12	6.8E+10	3.0E+11	1.3E+12	9.6E+11
Soybean	8.9E+12	9.0E+11	7.2E+12	6.7E+11	1.2E+11	1.3E+09	4.1E+10
Sugar Beet	1.5E+13	1.7E+10	3.4E+12	1.1E+13	6.4E+08	-	2.0E+09
Sugarcane	1.6E+13	3.7E+12	7.9E+12	-	-	5.2E+08	4.3E+12
Sunflower	5.8E+12	1.8E+11	1.6E+12	3.9E+12	6.4E+10	5.9E+09	4.7E+09
Wheat	2.0E+14	1.9E+13	9.7E+13	5.5E+13	1.2E+13	1.2E+13	3.9E+12
Sum of Crops	8.5E+14	2.7E+14	2.9E+14	1.7E+14	2.1E+13	1.5E+13	6.8E+13

Table S2C. Distribution of kilocalorie gains from meeting half the goal of closing the yield gap to 50% of potential yields.
Half of the potential gains (4.3 X 10^{14} kcals) from closing the yield gap to 50% of potential yields are concentrated in only 5% of the total harvested area of the 17 crops analyzed here. The table below summarizes the distribution of gains by continent. Values of zero indicate that either all croplands within the region have yields greater than 50% of potential yields or it is not grown there. Calories associated with cotton are seed oil.

Crop	Global	Africa	Asia	Europe	Northern America	Oceania	South and Central America
name	kilocalories	Kilocalories					
Barley	8.2E+12	3.8E+11	2.4E+12	4.9E+12	1.0E+10	6.2E+08	5.1E+11
Cassava	6.3E+12	4.6E+12	8.3E+11	-	-	-	8.6E+11
Cotton	1.7E+13	4.9E+12	4.4E+12	3.0E+10	7.8E+10	6.0E+12	1.3E+11
Groundnut	4.7E+11	3.4E+11	6.0E+10	4.0E+10	1.8E+08	2.8E+09	3.0E+10
Maize	1.6E+14	4.6E+13	4.4E+13	3.6E+13	1.0E+11	-	3.1E+13
Millet	-	-	-	-	-	-	-
Oil Palm	1.1E+14	1.1E+14	-	-	-	3.0E+05	6.6E+11
Potato	2.4E+13	3.9E+11	9.4E+12	1.2E+13	6.7E+09	5.1E+07	2.1E+12
Rapeseed	6.7E+11	2.4E+08	3.6E+11	3.0E+11	2.7E+09	1.2E+07	1.3E+07
Rice	1.5E+13	5.5E+12	7.8E+12	1.1E+10	0.0E+00	1.0E+10	1.9E+12
Rye	3.7E+12	2.2E+10	2.2E+11	3.4E+12	3.9E+10	5.9E+11	4.5E+09
Sorghum	6.3E+12	5.1E+12	4.0E+11	1.3E+08	3.6E+10	-	2.2E+11
Soybean	1.2E+09	-	1.2E+09	-	-	-	-
Sugar Beet	1.2E+13	1.7E+10	2.7E+12	9.4E+12	6.4E+08	-	2.0E+09
Sugarcane	9.8E+12	3.5E+12	4.8E+12	-	-	-	1.5E+12
Sunflower	1.4E+10	-	1.4E+10	-	3.1E+07	4.0E+10	-
Wheat	6.8E+13	6.0E+12	4.3E+13	1.7E+13	4.7E+11	4.4E+10	9.7E+11
Sum of Crops	4.4E+14	1.8E+14	1.2E+14	8.4E+13	7.5E+11	6.7E+12	4.0E+13

Table S3A. Annual nitrogen use for 17 crops included in this analysis. Nitrogen balance was calculated using a simple mass balance model. The 17 crops analyzed here account for 73% of the applied and 68% of the excess across all croplands. Percentage values below are relative to the 17 major crops included in this analysis. Negative excess values indicate a nutrient deficit (more harvested than applied). Avoidable N, the estimated percentage of applied N that could be reduced yet still maintain current yields, is only reported for crops that the model performed well. Cotton is included in this analysis because of its intensive use of nutrients.

Crop	Average Nitrogen Application	Total Nitrogen Inputs	Share of Nitrogen Inputs	Average Excess Nitrogen	Total Excess Nitrogen	Share of Excess Nitrogen	Average Avoidable Nitrogen	Share of N2O
Name	**kilograms per hectare**	**kilograms**	**percent**	**kilograms per hectare**	**kilograms**	**percent**	**percent**	**percent**
Barley	68.4	3.9E+09	4.0%	31.7	1.7E+09	3.4%	10.5%	4.5%
Cassava	27.2	4.6E+08	0.5%	16.3	2.5E+08	0.5%	-	0.5%
Cotton	119.8	3.7E+09	3.9%	80.9	2.5E+09	4.8%	18.2%	4.3%
Groundnut	62.3	2.5E+09	2.6%	65.0	1.4E+09	2.8%	-	1.7%
Maize	123.8	1.7E+10	18.0%	64.3	8.8E+09	17.2%	28.5%	20.2%
Millet	31.2	1.1E+09	1.2%	21.3	7.1E+08	1.4%	-	1.3%
Oil Palm	69.6	7.0E+08	0.7%	-41.5	-4.0E+08	-0.8%	5.4%	0.8%
Potato	119.4	2.4E+09	2.5%	108.9	2.1E+09	4.1%	32.9%	2.8%
Rapeseed	130.7	3.4E+09	3.4%	95.2	2.3E+09	4.6%	-	3.8%
Rice	126.0	2.0E+10	20.4%	80.8	1.2E+10	24.2%	13.9%	22.8%
Rye	58.6	6.0E+08	0.6%	24.2	2.3E+08	0.4%	-	0.7%
Sorghum	44.9	1.8E+09	1.9%	26.5	1.0E+09	2.0%	-	2.1%
Soybean	50.2	2.4E+09	13.9%	54.0	4.0E+09	7.9%	-	4.7%
Sugar Beet	125.3	8.0E+08	0.8%	121.0	7.4E+08	1.5%	18.5%	0.9%
Sugarcane	118.0	2.4E+09	2.5%	105.0	2.1E+09	4.1%	-	2.8%
Sunflower	48.5	1.1E+09	1.1%	11.7	2.4E+08	0.5%	39.8%	1.2%
Wheat	98.6	2.1E+10	22.1%	51.6	1.1E+10	21.2%	20.0%	24.7%
Sum of Crops	95.0	9.7E+10	100%	58.0	5.1E+10	100.0%	-	100.0%

Table S3B. Annual phosphorus use for 17 crops included in this analysis. Phosphorus balance was calculated using a simple mass balance model. The 17 crops analyzed here account for 68% applied and 58% excess across all croplands. Percentage values below are relative to the 17 major crops included in this analysis. Negative excess values indicate a nutrient deficit (more harvested than applied). Avoidable P, the estimated percentage of applied P that could be reduced yet still maintain current yields, is only reported for crops that the model performed well. Cotton is included in this analysis because of its intensive use of nutrients.

Crop	Average Phosphorus Application	Total Phosphorus Application	Share of Phosphorus Application	Average Excess Phosphorus	Total Excess Phosphorus	Share of Excess Phosphorus	Average Avoidable Phosphorus
Name	**kilograms per hectare**	**kilograms**	**percent**	**kilograms per hectare**	**kilograms**	**percent**	**percent**
Barley	13.6	7.2E+08	4.2%	5.7	3.1E+08	3.8%	25.3%
Cassava	8.7	1.3E+08	0.7%	3.9	6.1E+07	0.8%	-
Cotton	23.2	6.8E+08	3.9%	13.1	4.0E+08	5.0%	14.1%
Groundnut	20.7	4.4E+08	2.6%	17.5	3.9E+08	4.8%	-
Maize	20.4	2.7E+09	15.5%	8.6	1.2E+09	14.7%	20.2%
Millet	8.7	2.8E+08	1.6%	6.1	2.0E+08	2.5%	-
Oil Palm	12.5	1.2E+08	0.7%	-13.9	-1.3E+08	-1.5%	26.2%
Potato	27.0	5.0E+08	2.9%	23.4	4.5E+08	5.4%	11.4%
Rapeseed	23.3	5.7E+08	3.3%	14.7	3.6E+08	4.2%	-
Rice	24.7	3.6E+09	21.2%	15.5	2.4E+09	28.8%	22.0%
Rye	10.5	9.9E+07	0.6%	5.6	5.3E+07	0.6%	-
Sorghum	10.7	4.0E+08	2.3%	5.7	2.2E+08	2.8%	-
Soybean	22.6	1.7E+09	9.8%	9.8	7.3E+08	8.4%	-
Sugar Beet	26.8	1.6E+08	0.9%	24.2	1.5E+08	1.8%	31.2%
Sugarcane	27.5	5.3E+08	3.1%	22.9	4.6E+08	5.4%	-
Sunflower	9.3	1.9E+08	1.1%	-10.0	-2.0E+08	-2.4%	17.6%
Wheat	21.2	4.4E+09	25.4%	5.9	1.2E+09	15.0%	13.3%
Sum of Crops	20.1	1.7E+10	100%	9.4	8.2E+09	100.0%	-

Table S4. Irrigation use for 17 crops included in this analysis.
The relative share of irrigation water consumption is based on total consumption for all crops in the Siebert and Doll (*6*) data set (irrigated grasslands were not included). The 17 crops analyzed here account for 92% of irrigation water consumption of all irrigation water consumed for agriculture and 95% of all irrigated cropland, globally. Percent values in the table are relative to the 17 crops analyzed. Cotton is included in this analysis because of its intensive use of nutrients.

Crop	Irrigated Area	Irrigated Area	Water Consumption from Irrigation	Global Irrigation Intensity	Share of Irrigation Water Consumption
Name	hectares	percent	km3	mm/year	percent
Barley	4,190,767	2%	10	247	2%
Cassava	6,408	0%	0	427	0%
Cotton	14,315,201	8%	79	549	11%
Groundnut	2,535,378	1%	7	259	1%
Maize	20,535,658	12%	71	345	10%
Millet	1,540,590	1%	4	253	1%
Oil Palm	5,012	0%	0	506	0%
Potato	2,646,403	2%	11	425	2%
Rapeseed	3,230,314	2%	8	234	1%
Rice	48,919,404	28%	206	421	30%
Rye	266,890	0%	1	340	0%
Sorghum	3,041,256	2%	11	352	2%
Soybean	2,764,542	2%	9	329	1%
Sugar Beet	1,227,728	1%	8	664	1%
Sugarcane	7,473,721	4%	61	810	9%
Sunflower	1,071,954	1%	4	364	1%
Wheat	58,550,000	34%	200	341	29%
Sum of Crops	172,322,608	100%	688	399	100%

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