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Solutions for a cultivated planet

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Increasing population and consumption are placing unprecedented demands on agriculture and natural resources. Today, approximately a billion people are chronically malnourished while our agricultural systems are concurrently degrading land, water, biodiversity and climate on a global scale. To meet the world's future food security and sustainability needs, food production must grow substantially while, at the same time, agriculture's environmental footprint must shrink dramatically. Here we analyse solutions to this dilemma, showing that tremendous progress could be made by halting agricultural expansion, closing 'yield gaps' on underperforming lands, increasing cropping efficiency, shifting diets and reducing waste. Together, these strategies could double food production while greatly reducing the environmental impacts of agriculture.

Contemporary agriculture faces enormous challenges[1–3]. Even with recent productivity gains, roughly one in seven people lack access to food or are chronically malnourished, stemming from continued poverty and mounting food prices[4,5]. Unfortunately, the situation may worsen as food prices experience shocks from market speculation, bioenergy crop expansion and climatic disturbances[6,7]. Even if we solve these food access challenges, much more crop production will probably be needed to guarantee future food security. Recent studies suggest that production would need to roughly double to keep pace with projected demands from population growth, dietary changes (especially meat consumption), and increasing bioenergy use[1–4,8,9], unless there are dramatic changes in agricultural consumption patterns.

Compounding this challenge, agriculture must also address tremendous environmental concerns. Agriculture is now a dominant force behind many environmental threats, including climate change, biodiversity loss and degradation of land and freshwater[10–12]. In fact, agriculture is a major force driving the environment beyond the "planetary boundaries" of ref. 13.

Looking forward, we face one of the greatest challenges of the twenty-first century: meeting society's growing food needs while simultaneously reducing agriculture's environmental harm. Here we consider several promising solutions to this grand challenge. Using new geospatial data and models, we evaluate how new approaches to agriculture could benefit both food production and environmental sustainability. Our analysis focuses on the agronomic and environmental aspects of these challenges, and leaves a richer discussion of associated social, economic and cultural issues to future work.

The state of global agriculture

Until recently, the scientific community could not measure, monitor and analyse the agriculture–food–environment system's complex linkages at the global scale. Today, however, we have new data that characterize worldwide patterns and trends in agriculture and the environment[14–17].

Agricultural extent

According to the Food and Agriculture Organization (FAO) of the United Nations, croplands cover 1.53 billion hectares (about 12% of Earth's ice-free land), while pastures cover another 3.38 billion hectares (about 26% of Earth's ice-free land) (Supplementary Fig. 1). Altogether, agriculture occupies about 38% of Earth's terrestrial surface—the largest use of land on the planet[14,18]. These areas comprise the land best suited for farming[19]: much of the rest is covered by deserts, mountains, tundra, cities, ecological reserves and other lands unsuitable for agriculture[20].

Between 1985 and 2005 the world's croplands and pastures expanded by 154 million hectares (about 3%). But this slow net increase includes significant expansion in some areas (the tropics), as well as little change or a decrease in others (the temperate zone[18]; Supplementary Table 1). The result is a net redistribution of agricultural land towards the tropics, with implications for food production, food security and the environment.

Crop yields

Global crop production has increased substantially in recent decades. Studies of common crop groups (including cereals, oilseeds, fruits and vegetables) suggest that crop production increased by 47% between 1985 and 2005 (ref. 18). However, considering all 174 crops tracked by the UN FAO and ref. 15, we find global crop production increased by only 28% during that time[18].

This 28% gain in production occurred as cropland area increased by only 2.4%, suggesting a 25% increase in yield. However, cropland area that was harvested increased by about 7% between 1985 and 2005—nearly three times the change in cropland area, owing to increased multiple cropping, fewer crop failures, and less land left fallow. Accounting for the increase in harvested land, average global crop yields increased by only 20% between 1985 and 2005, substantially less than the often-cited 47% production increase for selected crop groups. (Using the same methods as for the 20% result, we note that yields increased by 56% between 1965 and 1985, indicating that yields are now rising less quickly than before.)

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Aggregate measures of production can mask trends in individual crops or crop groups (Supplementary Fig. 2a). For example, cereal crops decreased in harvested area by 3.6% between 1985 and 2005, yet their total production increased by 29%, reflecting a 34% increase in yields per hectare. Oil crops, on the other hand, showed large increases in both harvested area (43%) and yield (57%), resulting in a 125% increase in total production[18]. While most crops increased production between 1985 and 2005, fodder crops did not: on average, they saw an 18% production drop as a 26% loss in harvested area overrode an 11% increase in yields.

Using geospatial data[15], we can examine how yield patterns have changed for key commodities (for example, maize in Supplementary Fig. 2b). These geographic patterns show us where productivity gains have been successful, where they have not, and where further opportunities for improvement lie.

Crop use and allocation

The allocation of crops to nonfood uses, including animal feed, seed, bioenergy and other industrial products, affects the amount of food available to the world. Globally, only 62% of crop production (on a mass basis) is allocated to human food, versus 35% to animal feed (which produces human food indirectly, and much less efficiently, as meat and dairy products) and 3% for bioenergy, seed and other industrial products.

A striking disparity exists between regions that primarily grow crops for direct human consumption and those that produce crops for other uses (Fig. 1). North America and Europe devote only about 40% of their croplands to direct food production, whereas Africa and Asia allocate typically over 80% of their cropland to food crops. Extremes range from the Upper Midwestern USA (less than 25%) to South Asia (over 90%).

As we face the twin challenges of feeding a growing world while charting a more environmentally sustainable path, the amount of land (and other resources) devoted to animal-based agriculture merits critical evaluation. For example, adding croplands devoted to animal feed (about 350 million hectares) to pasture and grazing lands (3.38 billion hectares), we find the land devoted to raising animals totals 3.73 billion hectares—an astonishing ~75% of the world's agricultural land. We further note that meat and dairy production can either add to or subtract from the world's food supply. Grazing systems, especially on pastures unsuitable for other food production, and mixed crop–livestock systems can add calories and protein to the world and improve economic conditions and food security in many regions. However, using highly productive croplands to produce animal feed, no matter how efficiently, represents a net drain on the world's potential food supply.

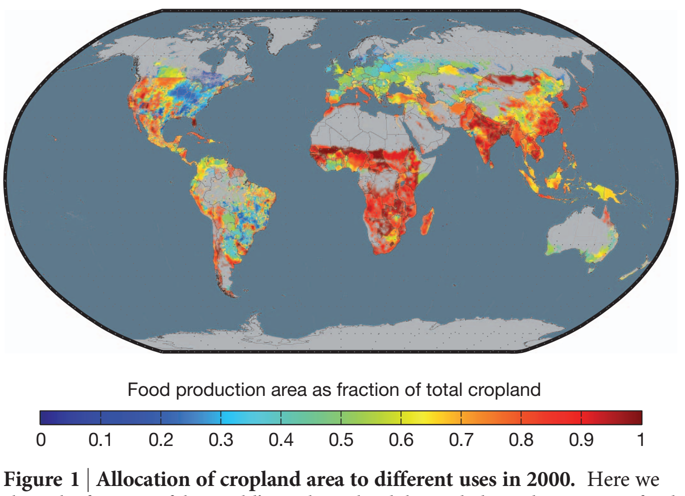

Figure 1 | Allocation of cropland area to different uses in 2000. Here we show the fraction of the world's total cropland that is dedicated to growing food crops (crops that are directly consumed by people) versus all other crop uses, including animal feed, fibre, bioenergy crops and other products. Averaged across the globe, 62% of total crop production (on a mass basis) is allocated to human food, 35% for animal feed (which produces human food indirectly, and less efficiently, as meat and dairy products) and 3% for bioenergy crops, seed, and other industrial products. There are striking disparities between regions that primarily grow crops for human consumption (such as Africa, South Asia, East Asia), and those that mainly produce crops for other uses (such as North America, Europe, Australia). Food production and allocation data were obtained from FAOSTAT[18], and were then applied to the spatial cropland maps of refs 14 and 15. All data are for a seven-year period centred on 2000.

Global environmental impacts of agriculture

The environmental impacts of agriculture include those caused by expansion (when croplands and pastures extend into new areas, replacing natural ecosystems) and those caused by intensification (when existing lands are managed to be more productive, often through the use of irrigation, fertilizers, biocides and mechanization). Below, we use new data and models[17,21,22] to examine both.

Agricultural expansion has had tremendous impacts on habitats, biodiversity, carbon storage and soil conditions[10,11,23,24]. In fact, worldwide agriculture has already cleared or converted 70% of the grassland, 50% of the savanna, 45% of the temperate deciduous forest, and 27% of the tropical forest biome[14,25].

Today, agriculture is mainly expanding in the tropics, where it is estimated that about 80% of new croplands are replacing forests[26]. This expansion is worrisome, given that tropical forests are rich reservoirs of biodiversity and key ecosystem services[27]. Clearing tropical forests is also a major source of greenhouse gas emissions and is estimated to release around 1.1×10^{15} grams of carbon per year, or about 12% of total anthropogenic CO_2 emissions[28]. Slowing or halting expansion of agriculture in the tropics—which accounts for 98% of total CO_2 emissions from land clearing[29]—will reduce carbon emissions as well as losses of biodiversity and ecosystem services[27].

Agricultural intensification has dramatically increased in recent decades, outstripping rates of agricultural expansion, and has been responsible for most of the yield increases of the past few decades. In the past 50 years, the world's irrigated cropland area roughly doubled[18,30,31], while global fertilizer use increased by 500% (over 800% for nitrogen alone)[18,32,33]. Intensification has also caused water degradation, increased energy use, and widespread pollution[32,34,35].

Of particular concern is that some 70% of global freshwater withdrawals (80–90% of consumptive uses) are devoted to irrigation[36,37]. Furthermore, rain-fed agriculture is the world's largest user of water[13,38]. In addition, fertilizer use, manure application, and leguminous crops (which fix nitrogen in the soil) have dramatically disrupted global nitrogen and phosphorus cycles[39–41], with associated impacts on water quality, aquatic ecosystems and marine fisheries[35,42].

Both agricultural expansion and intensification are also major contributors to climate change. Agriculture is responsible for 30–35% of global greenhouse gas emissions, largely from tropical deforestation, methane emissions from livestock and rice cultivation, and nitrous oxide emissions from fertilized soils[29,43–46].

We can draw important conclusions from these trends. First, the expansion of agriculture in the tropics is reducing biodiversity, increasing greenhouse gas emissions, and depleting critical ecosystem services. Yet this expansion has done relatively little to add to global food supplies; most production gains have been achieved through intensification. Second, the costs and benefits of agricultural intensification vary greatly, often depending on geographic conditions and agronomic practices. This suggests that some forms (and locations) of intensification are better than others at balancing food production and environmental protection[11,47].

Enhancing food production and sustainability

Until recently, most agricultural paradigms have focused on improving production, often to the detriment of the environment[10,11,47]. Likewise, many environmental conservation strategies have not sought to improve food production. However, to achieve global food security and environmental sustainability, agricultural systems must be transformed to address both challenges (Fig. 2).

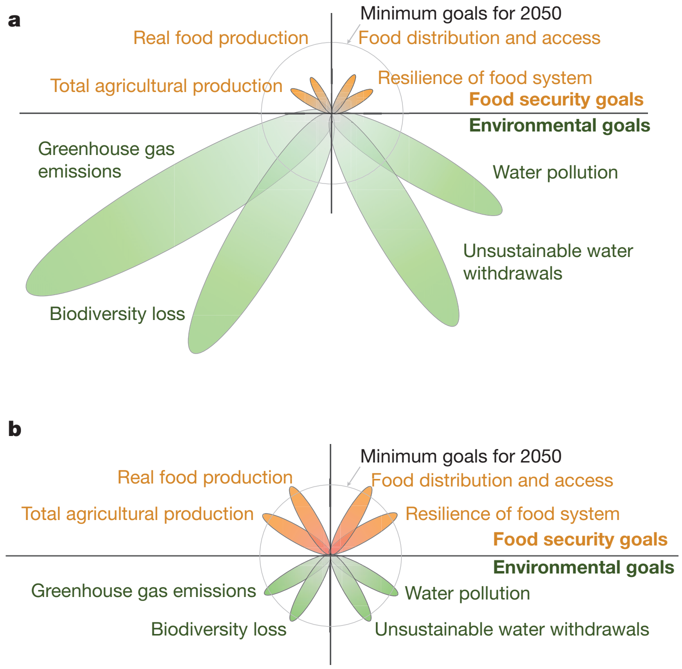

Figure 2 | Meeting goals for food security and environmental sustainability by 2050. Here we qualitatively illustrate a subset of the goals agriculture must meet in the coming decades. At the top, we outline four key food security goals: increasing total agricultural production, increasing the supply of food (recognizing that agricultural yields are not always equivalent to food), improving the distribution of and access to food, and increasing the resilience of the whole food system. At the bottom, we illustrate four key environmental goals agriculture must also meet: reducing greenhouse gas emissions from agriculture and land use, reducing biodiversity loss, phasing out unsustainable water withdrawals, and curtailing air and water pollution from agriculture. Panel **a** sketches out a qualitative assessment of how current agricultural systems may be measured against these criteria compared to goals set for 2050. Panel **b** illustrates a hypothetical situation in which we meet all of these goals by 2050.

First, the transformation of agriculture must deliver sufficient food and nutrition to the world. To meet the projected demands of population growth and increasing consumption, we must roughly double food supplies in the next few decades[1–3]. We must also improve distribution and access, which will require further changes in the food system.

The transformation of agriculture should also (1) cut greenhouse gas emissions from land use and farming by at least 80% (ref. 48); (2) reduce biodiversity and habitat losses; (3) reduce unsustainable water withdrawals, especially where water has competing demands; and (4) phase out water pollution from agricultural chemicals. Other environmental issues must also be addressed, but these four undergird the relationship between agriculture and the environment and should be addressed as necessary first steps.

An influential series of recent reports has suggested possible solutions to our interwoven food security and environmental challenges[1,2,6]. Below, we consider the potential strengths and weaknesses of four proposed strategies.

Stop expanding agriculture

The expansion of agriculture into sensitive ecosystems has far-reaching effects on biodiversity, carbon storage and important environmental services[10,11,33]. This is particularly true when tropical forests are cleared for agriculture[27,49,50], estimated to cause 5–10 million hectares of forest loss annually[18,51]. Slowing (and, ultimately, ceasing) the expansion of agriculture, particularly into tropical forests, will be an important first step in shifting agriculture onto a more sustainable path.

But will ending the expansion of agriculture negatively affect food supplies? Our analysis suggests that the food production benefits of tropical deforestation are often limited, especially compared to the environmental damages accrued. First of all, many regions cleared for agriculture in the tropics have low yields compared with their temperate counterparts. The authors of ref. 21 considered crop production and carbon emissions resulting from deforestation and demonstrated that the balance of production gains to carbon losses was often poor in tropical landscapes (Supplementary Fig. 3). Regions of tropical agriculture that do have high yields—particularly areas of sugarcane, oil palm and soybeans—typically do not contribute much to the world's total calorie or protein supplies, especially when crops are used for feed or biofuels. Nevertheless, such crops do provide income, and thereby contribute to poverty alleviation and food security to some sectors of the population.

Although ceasing the expansion of agriculture into tropical forests might have a negative—but probably small—impact on global crop production, losses can be offset elsewhere in the food system. Agricultural production potential that is 'lost' by halting deforestation could be offset by reducing losses of productive farmland and improving yields on existing croplands. Though the 'indirect land use' effects of biofuel production are thought to increase pressure on tropical forests[52], it may also be true that increasing food production in non-tropical zones might reduce pressures on tropical forests.

Economic drivers hold great sway over deforestation[53–55]. Ecologically friendly economic incentives could play an important part in slowing forest loss: the proposed Reducing Emissions from Deforestation and Degradation (REDD) programme, market certification, and ecotourism all provide opportunities to benefit economically from forest protection[56].

Close yield gaps

Increasing food production without agricultural expansion implies that we must increase production on our existing agricultural lands. The best places to improve crop yields may be on underperforming landscapes, where yields are currently below average.

Recent analyses[57,58] have found large yield variations across the world, even among regions with similar growing conditions, suggesting the existence of 'yield gaps' (Supplementary Fig. 4a). Here we define a yield gap as the difference between crop yields observed at any given location and the crop's potential yield at the same location given current agricultural practices and technologies.

Much of the world experiences yield gaps (Supplementary Fig. 4a) where productivity may be limited by management. There are significant opportunities to increase yields across many parts of Africa, Latin America and Eastern Europe, where nutrient and water limitations seem to be strongest (Supplementary Fig. 4b). Better deployment of existing crop varieties with improved management should be able to close many yield gaps[59], while continued improvements in crop genetics will probably increase potential yields into the future.

Closing yield gaps could substantially increase global food supplies. Our analysis shows that bringing yields to within 95% of their potential for 16 important food and feed crops could add 2.3 billion tonnes (5×10^{15} kilocalories) of new production, a 58% increase (Fig. 3). Even if yields for these 16 crops were brought up to only 75% of their potential, global production would increase by 1.1 billion tonnes (2.8×10^{15} kilocalories), a 28% increase. Additional gains in productivity, focused on increasing the maximum yield of key crops, are likely to be driven by genetic improvements[60,61]. Significant opportunities may also exist to improve yield and the resilience of cropping systems by improving 'orphan crops' (such crops have not been genetically improved or had much investment) and preserving crop diversity, which have received relatively little investment to date.

To close global yield gaps, the interwoven challenges of production and environment must again be addressed: conventional approaches to intensive agriculture, especially the unbridled use of irrigation and fertilizers, have been major causes of environmental degradation. Closing yield gaps without environmental degradation will require new approaches, including reforming conventional agriculture and adopting lessons from organic systems and precision agriculture. In addition, closing yield gaps will

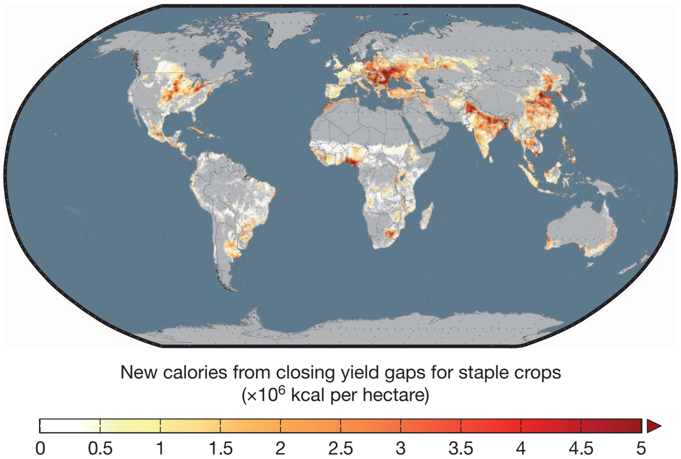

Figure 3 | Closing global yield gaps. Many agricultural lands do not attain their full yield potential. The figure shows the new calories that would be made available to the world from closing the yield gaps for 16 major crops: barley, cassava, groundnut, maize, millet, potato, oil palm, rapeseed, rice, rye, sorghum, soybean, sugarbeet, sugarcane, sunflower and wheat. This analysis shows that bringing the world's yields to within 95% of their potential for these 16 important food and feed crops could add 2.3 billion tonnes (5×10^{15} kilocalories) of new crop production, representing a 58% increase. These improvements in yield can be largely accomplished by improving the nutrient and water supplies to crops in low-yielding regions; further enhancement of global food production could be achieved through improved crop genetics. The methods used to calculate yield gaps and limiting factors are described in the Supplementary Information.

require overcoming considerable economic and social challenges, including the distribution of agricultural inputs and seed varieties and improving market infrastructure.

Increase agricultural resource efficiency

Moving forward, we must find more sustainable pathways for intensification that increase crop production while greatly reducing unsustainable uses of water, nutrients and agricultural chemicals.

Irrigation is currently responsible for water withdrawals of about 2,800 km^3 per year from groundwater, lakes and rivers. Irrigation is used on about 24% of croplands and is responsible for delivering 34% of agricultural production[17]. In fact, without irrigation, global cereal production would decrease by an estimated 20% (ref. 17), so more land would be required to produce the same amount of food.

However, the benefits and impacts of irrigation are not evenly distributed. Water needed for crop production varies greatly across the world (Supplementary Fig. 5). We find that, when irrigated, 16 staple crops use an average of 0.3 litres per kilocalorie (not including water losses). However, these water requirements are skewed: 80% of irrigated crops require less than 0.4 litres per kilocalorie, while the remaining 20% require 0.7 litres per kilocalorie or more.

Where water is scarce, good water and land management practices can increase irrigation efficiency. For example, curtailing off-field evaporative losses from water storage and transport and reducing on-field losses through mulching and reduced tillage will increase the value of irrigation water.

Chemical fertilizers, manure and leguminous crops have also been key to agricultural intensification. However, they have also led to widespread nutrient pollution and the degradation of lakes, rivers and coastal oceans. In addition, the release of nitrous oxide from fertilized fields contributes to climate change. Excess nutrients also incur energy costs associated with converting atmospheric nitrogen and mining phosphorus[22,62].

Even though excess nutrients cause environmental problems in some parts of the world, insufficient nutrients are a major agronomic problem in others. Many yield gaps are mainly due to insufficient nutrient availability (Supplementary Fig. 4b). This 'Goldilocks' problem of nutrients (that is, there are many regions with too much or too little fertilizer but few that are 'just right') is one of the key issues facing agriculture today[63].

Building on recent analyses of crop production, fertilizer use and nutrient cycling[15,22,64,65], we examine patterns of agricultural nitrogen and phosphorus balance across the world. Specifically, we show areas of excess nutrients resulting from imbalances between nutrient inputs (fertilizers, legumes and atmospheric deposition), harvest removal and environmental losses (Supplementary Fig. 6). We further analyse the efficiency of nutrient use by comparing applied nutrients to yield for 16 major crops (Supplementary Fig. 6c, d).

Our analysis reveals 'hotspots' of low nutrient use efficiency (Supplementary Fig. 6c, d) and large volumes of excess nutrients (Supplementary Fig. 6e, f). Nutrient excesses are especially large in China[66], Northern India, the USA and Western Europe. We also find that only 10% of the world's croplands account for 32% of the global nitrogen surplus and 40% of the phosphorus surplus. Targeted policy and management in these regions could improve the balance between yields and the environment. Such actions include reducing excessive fertilizer use, improving manure management, and capturing excess nutrients through recycling, wetland restoration and other practices.

Taken together, these results illustrate many opportunities to improve the water and nutrient efficiency of agriculture without reducing food production. Targeting particular 'hotspots' of low efficiency, measured as the disproportionate use of water and nutrient inputs relative to production, could significantly reduce the environmental problems of intensive agriculture. Furthermore, agroecological innovations in crop and soil management[1,67] show great promise for improving the resource efficiency of agriculture, maintaining the benefits of intensive agriculture while greatly reducing harm to the environment.

Increase food delivery by shifting diets and reducing waste

While improving crop yields and reducing agriculture's environmental impacts will be instrumental in meeting future needs, it is also important to remember that more food can be delivered by changing our agricultural and dietary preferences. Simply put, we can increase food availability (in terms of calories, protein and critical nutrients) by shifting crop production away from livestock feed, bioenergy crops and other non-food applications.

In Supplementary Fig. 7, we compare intrinsic food production (calories available if all crops were consumed by humans) and delivered food production (calories available based on today's allocation of crops to food, animal feed, and other products, assuming standard conversion factors) for 16 staple crops. By subtracting these two figures, we estimate the potential to increase food supplies by closing the 'diet gap': shifting 16 major crops to 100% human food could add over a billion tonnes to global food production (a 28% increase), or the equivalent of 3×10^{15} food kilocalories (a 49% increase) (Fig. 4).

Of course, the current allocation of crops has many economic and social benefits, and this mixed use is not likely to change completely. But even small changes in diet (for example, shifting grain-fed beef consumption to poultry, pork or pasture-fed beef) and bioenergy policy (for example, not using food crops as biofuel feedstocks) could enhance food availability and reduce the environmental impacts of agriculture.

A large volume of food is never consumed but is instead discarded, degraded or consumed by pests along the supply chain. A recent FAO study[68] suggests that about one-third of food is never consumed; others[69] have suggested that as much as half of all food grown is lost; and some perishable commodities have post-harvest losses of up to 100% (ref. 70). Developing countries lose more than 40% of food post-harvest or during processing because of storage and transport conditions. Industrialized countries have lower producer losses, but at the retail or consumer level more than 40% of food may be wasted[68].

In short, reducing food waste and rethinking dietary, bioenergy and other agricultural choices could substantially improve the delivery of calories and nutrition with no accompanying environmental harm. While wholesale conversions of the human diet and the elimination of

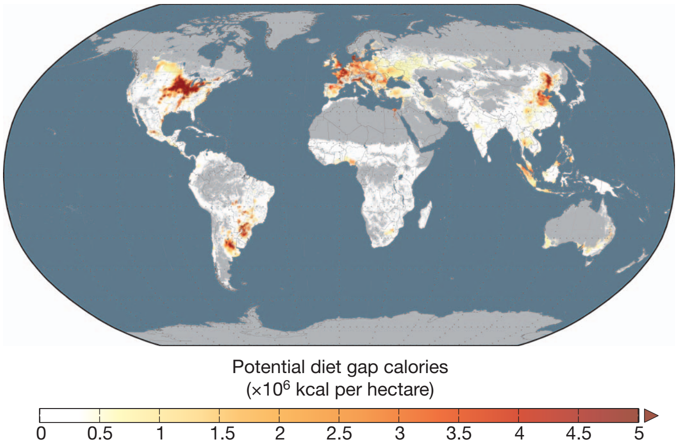

Figure 4 | Closing the diet gap. We estimate the potential to increase food supplies by closing the 'diet gap': shifting 16 major crops to 100% human food and away from the current mix of uses (see Fig. 1) could add over a billion tonnes to global food production (a 28% increase for those 16 crops), the equivalent of $\sim 3 \times 10^{15}$ kilocalories more food to the global diet (a 49% increase in food calories delivered).

food waste are not realistic goals, even incremental steps could be extremely beneficial. Furthermore, targeted efforts—such as reducing waste in our most resource-intensive foods, especially meat and dairy—could be designed for optimal impact.

Searching for practical solutions

Today, humans are farming more of the planet than ever, with higher resource intensity and staggering environmental impacts, while diverting an increasing fraction of crops to animals, biofuels and other non-food uses. Meanwhile, almost a billion people are chronically hungry. This must not continue: the requirements of current and future generations demand that we transform agriculture to meet the twin challenges of food security and environmental sustainability.

Our analysis demonstrates that four core strategies can—in principle—meet future food production needs and environmental challenges if deployed simultaneously. Adding them together, they increase global food availability by 100–180%, meeting projected demands while lowering greenhouse gas emissions, biodiversity losses, water use and water pollution. However, all four strategies are needed to meet our global food production and environmental goals; no single strategy is sufficient.

We have described general approaches to solving global agricultural challenges, but much work remains to translate them into action. Specific land use, agricultural and food system tactics must be developed and deployed. Fortunately, many such tactics already exist, including precision agriculture, drip irrigation, organic soil remedies, buffer strips and wetland restoration, new crop varieties that reduce needs for water and fertilizer, perennial grains and tree-cropping systems, and paying farmers for environmental services. However, deploying these tactics effectively around the world requires numerous economic and governance challenges to be overcome. For example, reforming global trade policies, including eliminating price-distorting subsidies and tariffs, will be vital to achieving our strategies.

In developing improved land use and agricultural practices, we recommend following these guidelines:

(1) Solutions should focus on critical biophysical and economic 'leverage points' in agricultural systems, where major improvements in food production or environmental performance may be achieved with the least effort and cost.

(2) New practices must also increase the resilience of the food system. High-efficiency, industrialized agriculture has many benefits, but it is vulnerable to disasters[71], including climatic disturbances, new diseases and economic calamities.

(3) Agricultural activities have many costs and benefits, but methods of evaluating the trade-offs are still poorly developed[72]. We need better data and decision support tools to improve management decisions[73], productivity and environmental stewardship.

(4) The search for agricultural solutions should remain technology-neutral. There are multiple paths to improving the production, food security and environmental performance of agriculture, and we should not be locked into a single approach a priori, whether it be conventional agriculture, genetic modification or organic farming.

The challenges facing agriculture today are unlike anything we have experienced before, and they require revolutionary approaches to solving food production and sustainability problems. In short, new agricultural systems must deliver more human value, to those who need it most, with the least environmental harm.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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Author Information Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Readers are welcome to comment on the online version of this article at www.nature.com/nature. Correspondence and requests for materials should be addressed to J.A.F. (jfoley@umn.edu).

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Supplementary Materials – Figures

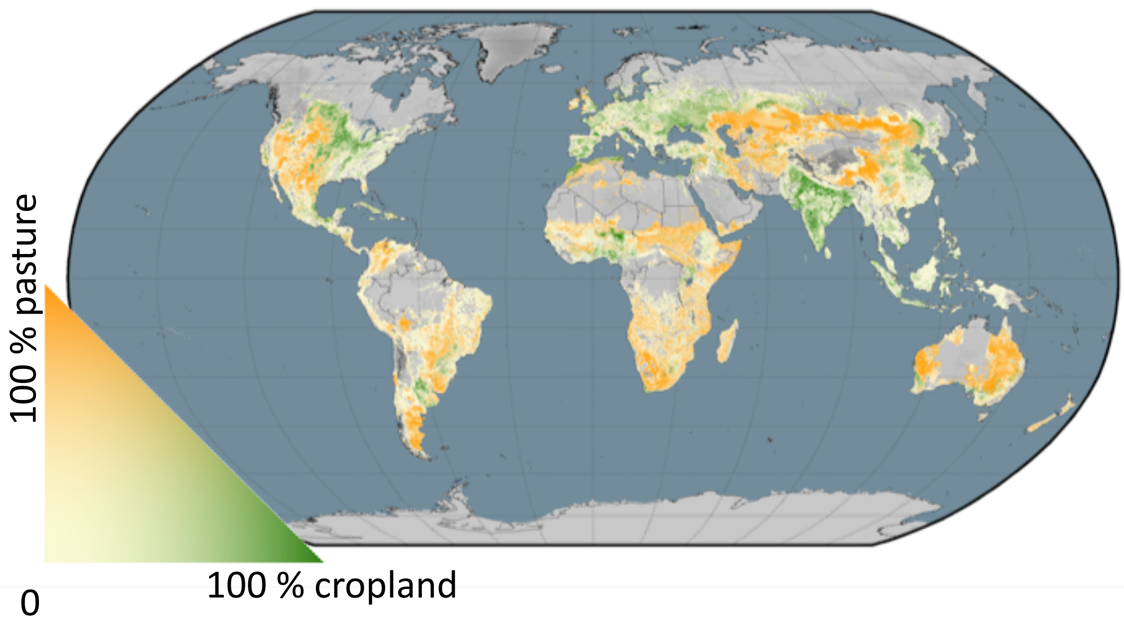

Figure S1. Extent of Global Agricultural Lands. This map illustrates the global extent of croplands (green) and pastures (brown), as estimated from satellite- and census-based data by Ramankutty *et al.*[1]. According to U.N. FAO statistics, croplands currently extend over 1.53 billion hectares (~12% 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].

Fig S2a

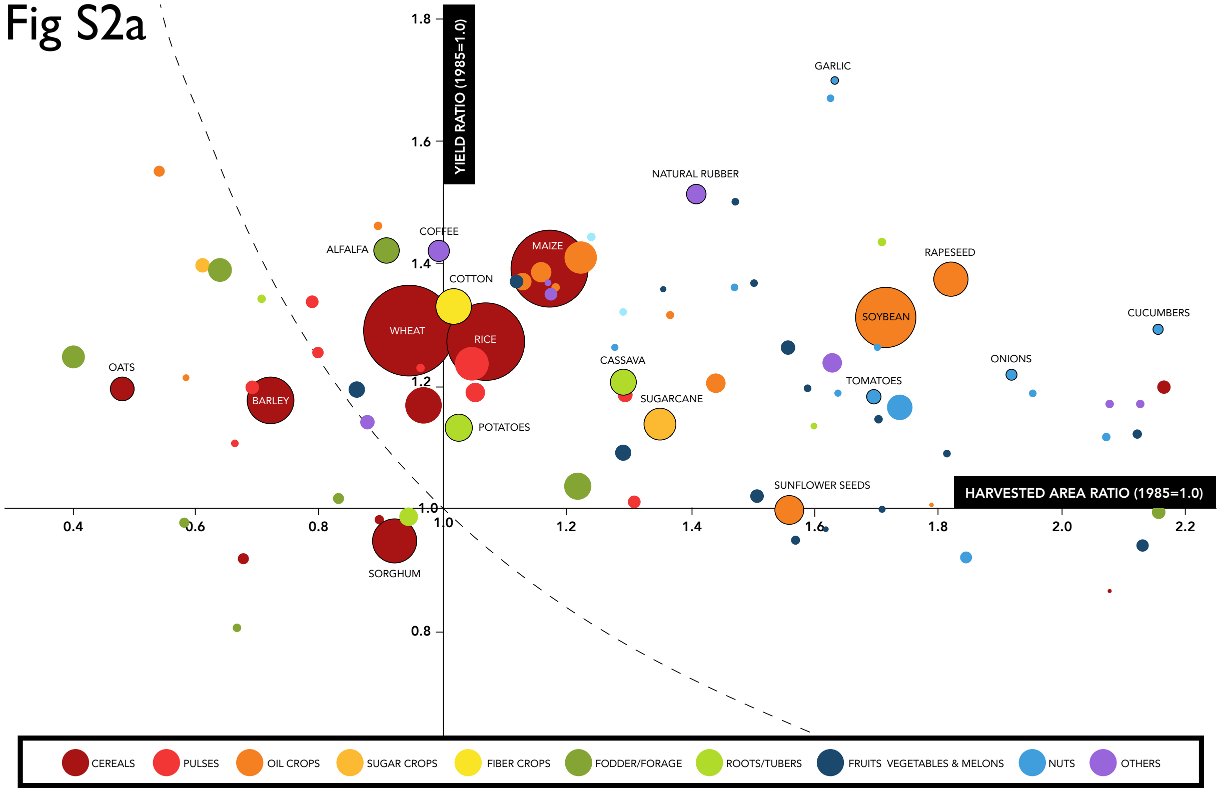

Figure S2. Trends in Global Crop Production, 1985–2005. In Figure S2a, we illustrate recent changes in yield and harvested area for 174 crops. The vertical axis shows changes in yield, expressed as a ratio of yields reported in 2005 and 1985. The horizontal axis reports relative changes in harvested 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.

Fig S2b

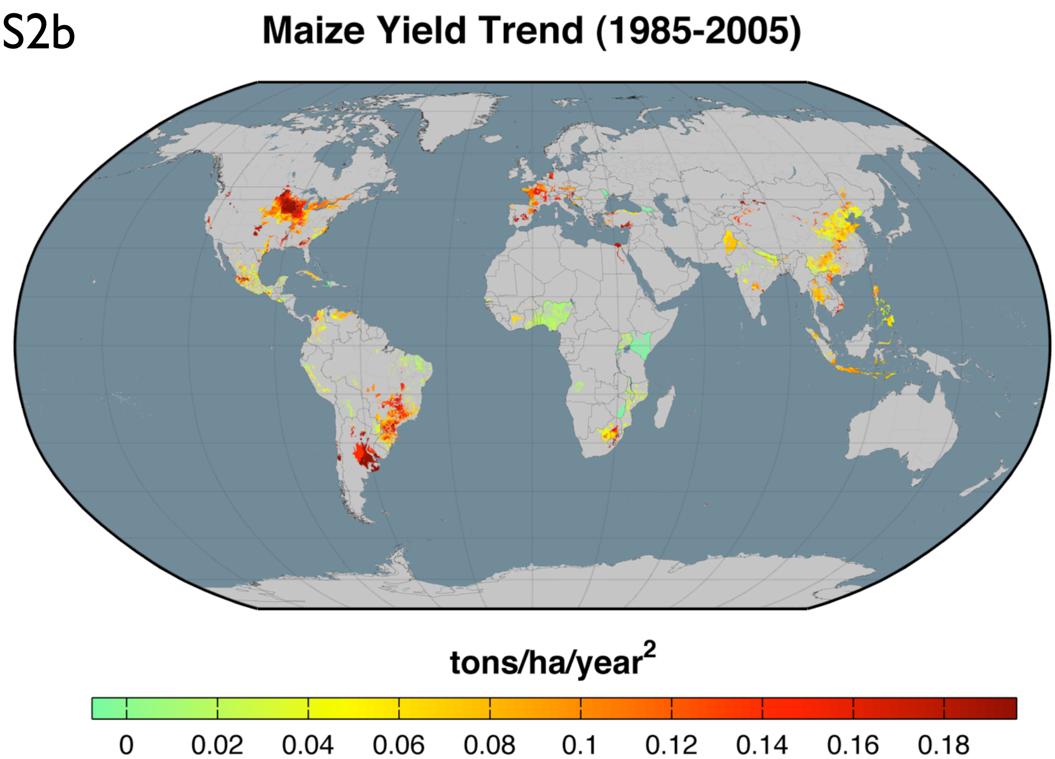

Figure S2b shows a detailed map of yield trends (tonnes/ha/year^2) for maize for 1985–2005. The plot shows statistically significant ($p < 0.1$) trends based on a linear regression of estimated annual yield values between 1985 and 2005. The data used in this calculation are based on Monfreda *et al.*[3],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

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Fig S3

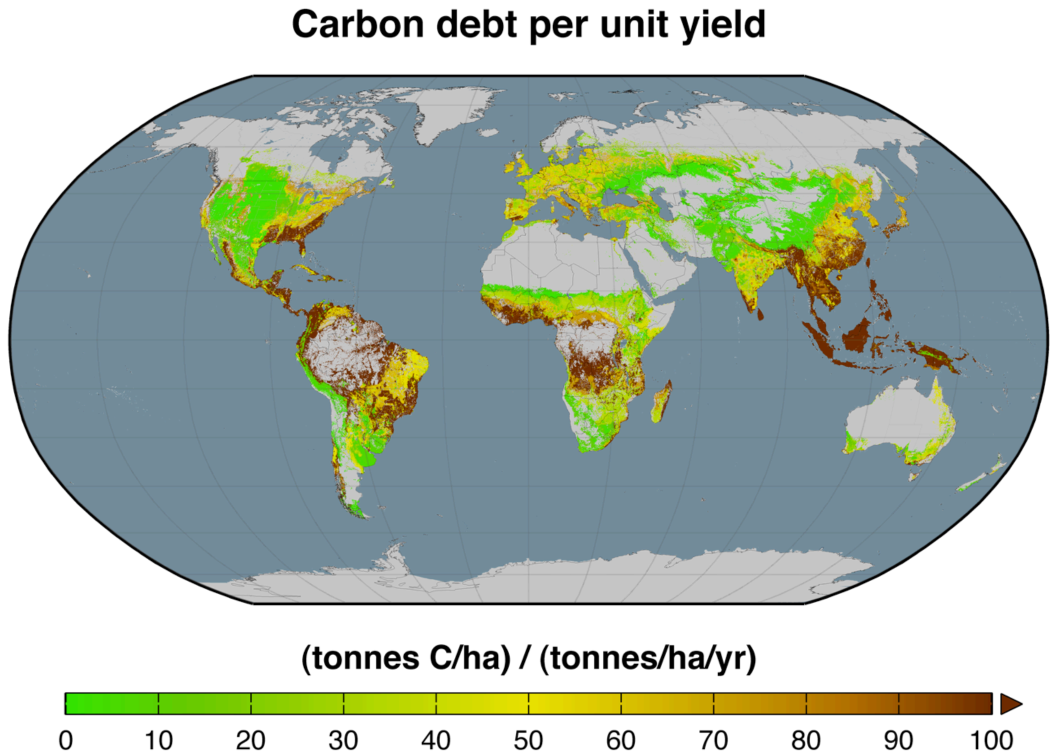

Figure S3. Ratio of Current Agricultural Yields to the Historical Carbon Debt of the World's Croplands. Here we consider the trade-off between growing more food through agricultural expansion and the emissions of carbon dioxide into the atmosphere from clearing additional land for crops. West *et al.*[4] 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.

Fig S4a

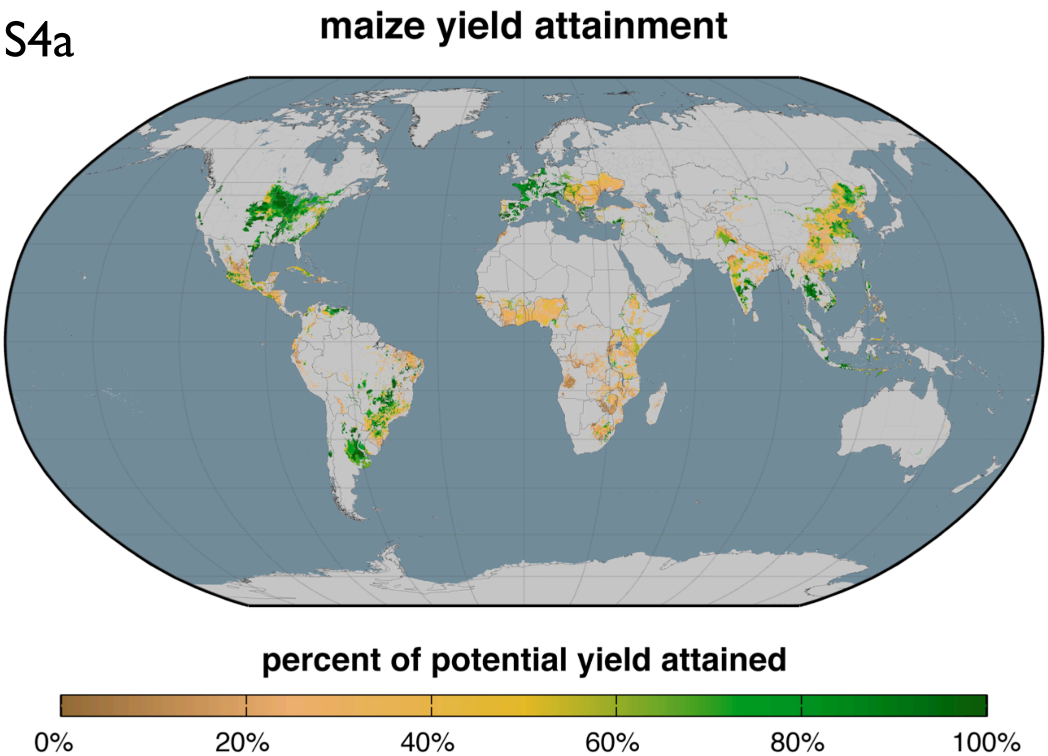

Fig S4b

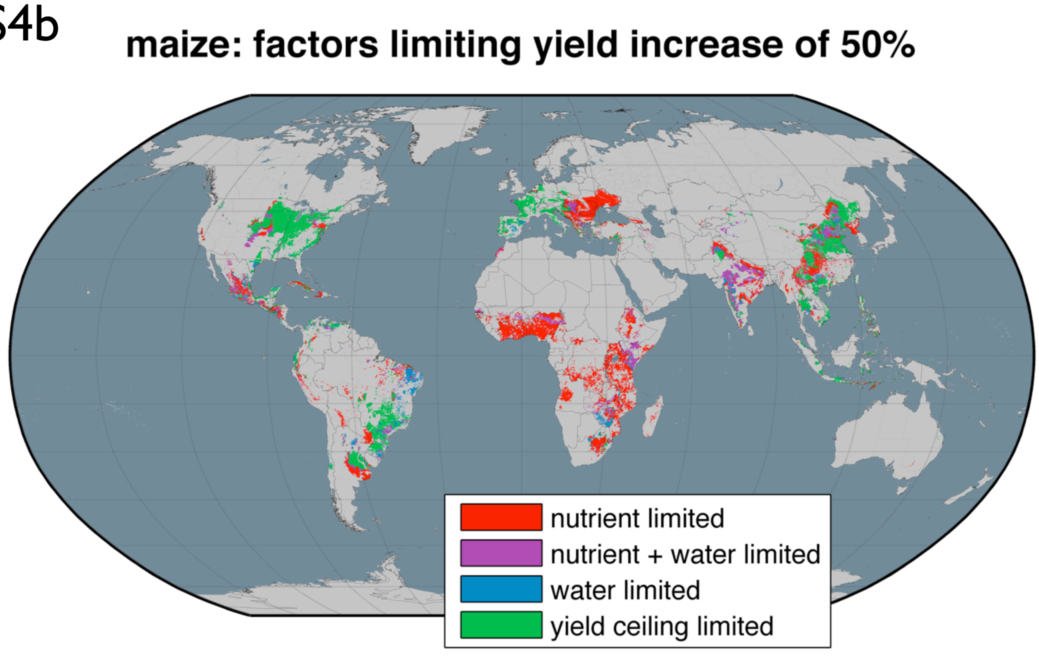

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Figure S4. Global Yield Gap Analysis. In Figure S4a, we show the global patterns of "yield attainment" for maize – the ratio of yields reported for any given location compared to the near-maximum (95th percentile) yields reported for maize, controlling 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

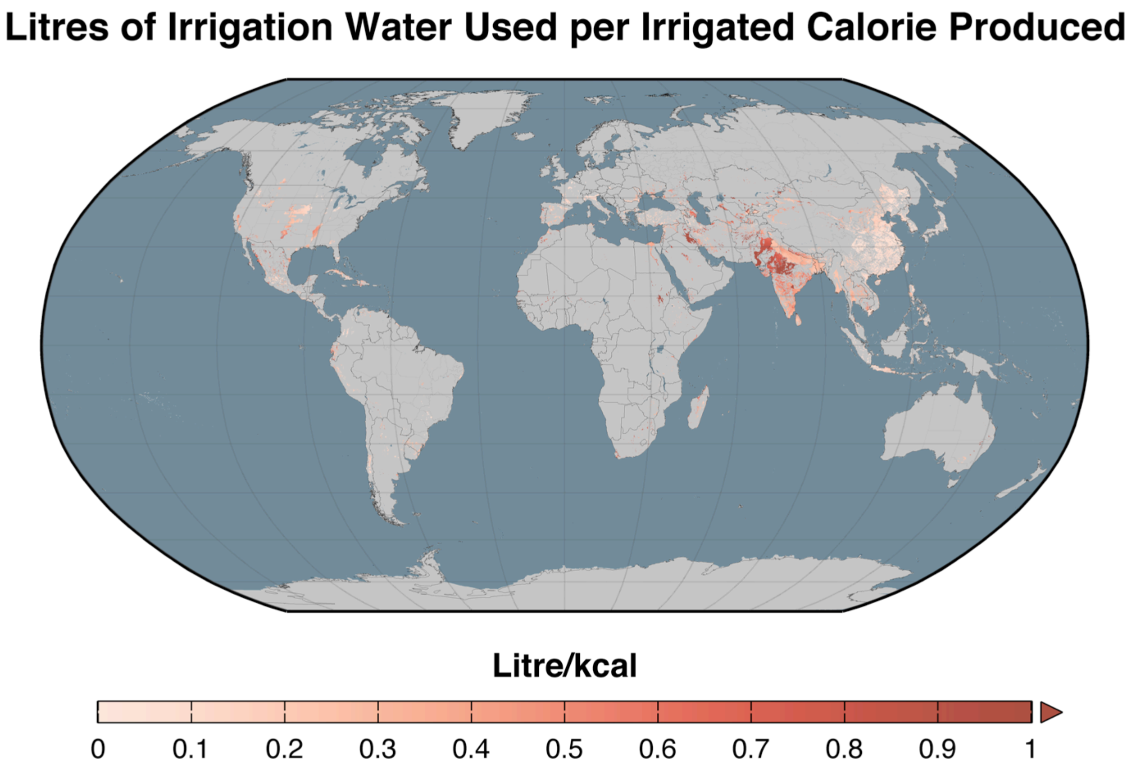

Figure S5. Irrigation Use Efficiency Across the Globe. Irrigation is one of our best tools for improving crop yields. However, the use and yield benefits of irrigation water are not distributed evenly across the globe. Here we show irrigation water required per kilocalorie of crop yield (irrigation water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

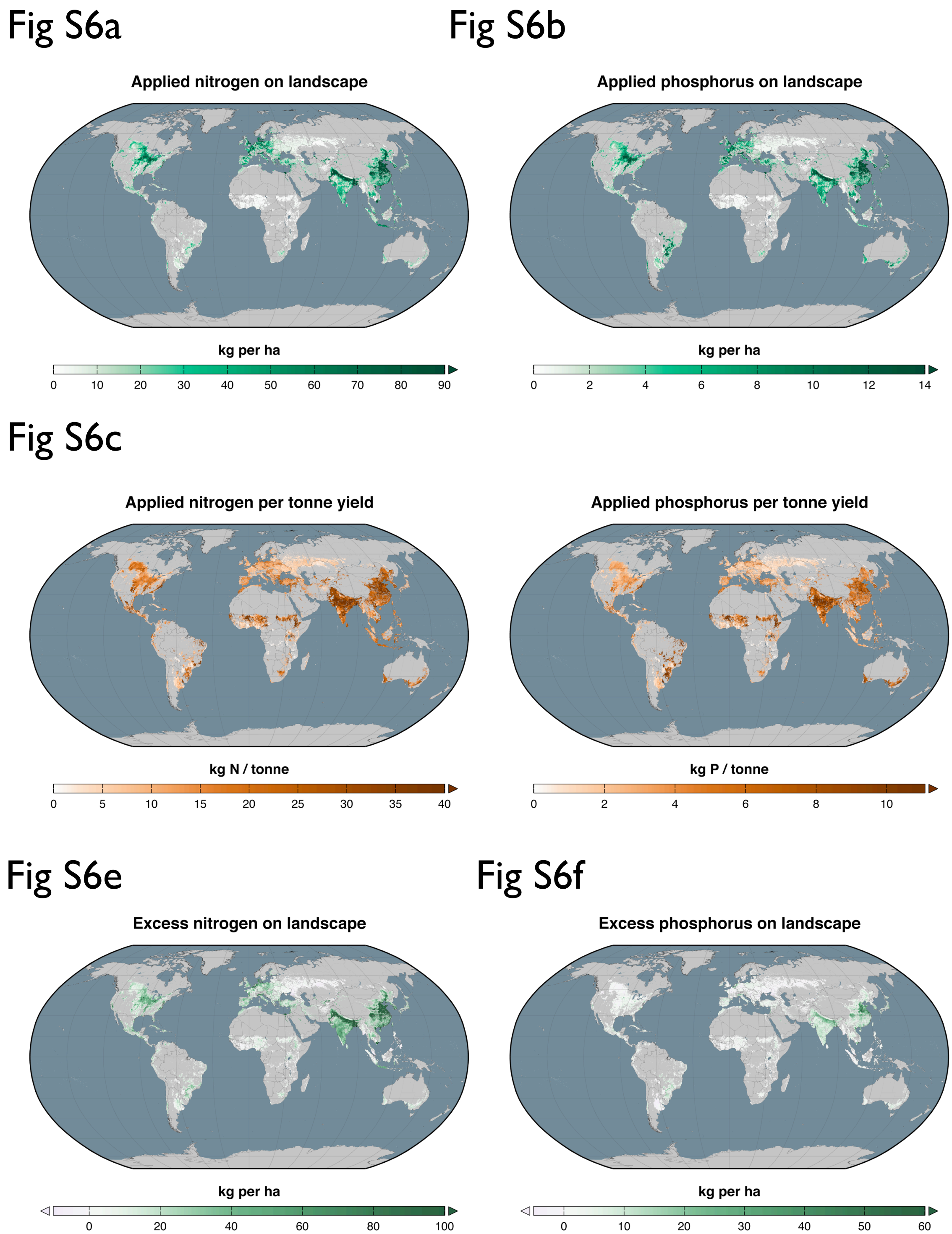

Figure S6. Nutrient Applications, Nutrient Use Efficiency, and Excess Nutrients on the Globe. Building on recent geospatial datasets and analyses of crop production and nutrient cycling (Monfreda *et al.*[3]; Potter *et al.*[7]; Liu *et al.*[8]; MacDonald *et al.*[9]) and utilising updated fertilizer 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.

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Fig S7a

Intrinsic Calorie Production

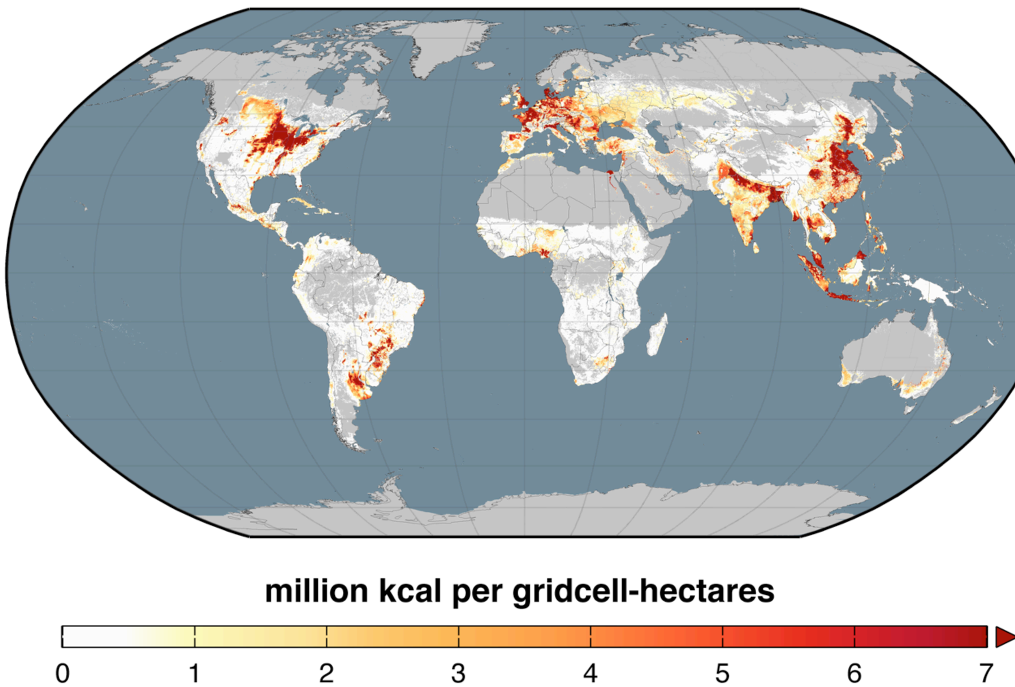

Fig S7b

Deliverable Food Calories

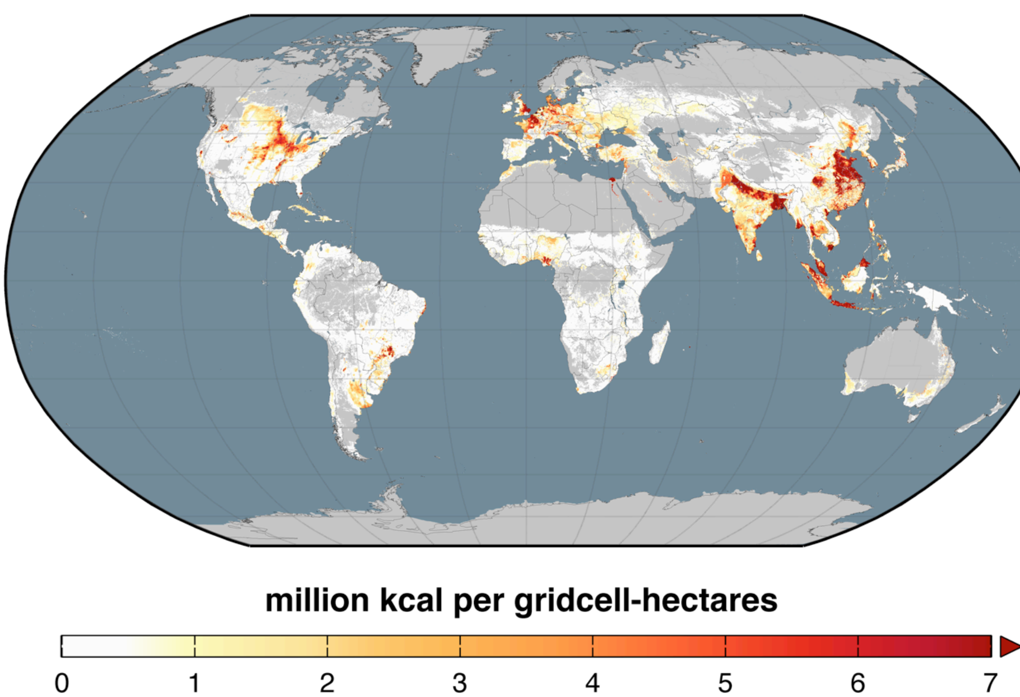

Figure S7. Differences Between Intrinsic and Delivered Food Production. Here we compare global crop yields for 16 staple crops (barley, cassava, groundnut, maize, millet, potato, oil palm, rapeseed, rice, rye, sorghum, soybean, sugarbeet, sugarcane, sunflower, and wheat) in terms of their *intrinsic 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].

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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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