Scope of the Challenge and Menu of Potential Solutions

This World Resources Report addresses a fundamental question: How can the world adequately feed nearly 10 billion people by the year 2050 in ways that help combat poverty, allow the world to meet climate goals, and reduce pressures on the broader environment? Chapters 1–4 of this report assess the scope of the challenge and outline the menu of possible solutions for a sustainable food future.

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CHAPTER 1

A RECIPE FOR CHANGE

The challenge of creating a sustainable food future involves balancing several competing needs. By 2050, the world must feed many more people, more nutritiously, and ensure that agriculture contributes to poverty reduction through inclusive economic and social development, all while reducing greenhouse gas (GHG) emissions, loss of habitat, freshwater depletion and pollution, and other environmental impacts of farming. Pursuing any one of these goals to the exclusion of the others will likely result in failure to achieve any of them.

First, the world needs to meet growing food demand. Food demand will grow in part because the world's population will grow. The United Nations projects a 40 percent population growth in just 40 years, from nearly 7 billion in 2010—the base year for many of the calculations in this report—to 9.8 billion by 2050.[1] In addition, at least 3 billion people are likely to enter the global middle class by 2030.[2] History shows that more affluent consumers demand more resource-intensive food, such as meat, vegetables, and vegetable oils.[3] Yet at the same time, approximately 820 million of the world's poorest people remain undernourished even today because they cannot afford or do not have access to an adequate diet.[4]

Strategies can attempt to reduce the demand for food by the affluent in socially beneficial ways, but failing to produce enough food to meet overall global demand is not an acceptable option because, when food availability falls short, the world's rich outcompete the poor and hunger increases.[5] Based on current trends, both crop and livestock production will need to increase at substantially faster rates than they have increased over the past 50 years to fully meet projected food demand.[6]

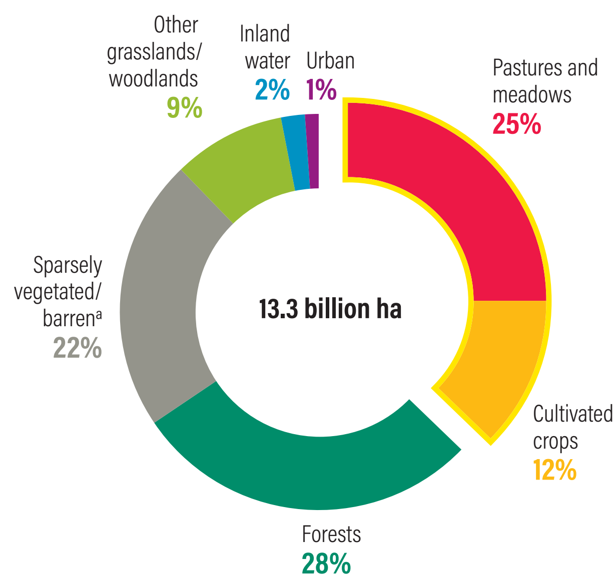
Second, the world needs agriculture to contribute to inclusive economic and social development to help reduce poverty. More than 70 percent of the world's poor live in rural areas, where most depend on agriculture for their principal livelihood.[7] Growth originating in the agricultural sector can often reduce poverty more effectively than growth originating in other economic sectors, in part by providing employment and in part by lowering the cost of food.[8] Although agriculture directly accounts for only about 3.5 percent of gross world product, that figure is approximately 30 percent in low-income countries.[9] Agriculture is at least a part-time source of livelihoods for more than 2 billion people.[10] Women make up an estimated 43 percent of the agricultural workforce worldwide, and they constitute an even higher share of agricultural workers in East Asia, Southeast Asia, and sub-Saharan Africa.[11] Because increasing women's income has disproportionate benefits for alleviating hunger,[12] assisting women farmers is a particularly effective way to reduce poverty and enhance food security.

Third, the world needs to reduce agriculture's impact on the environment and natural resources. Agriculture's impacts are especially large in three environmental areas:

Land-based Ecosystems

Since the invention of agriculture 8,000–10,000 years ago, growing crops and raising livestock have been the primary causes of ecosystem loss and degradation.[13] Today, more than one-third of the planet's landmass, and almost half of the world's vegetated land, is used to produce food (Figure 1-1).[14] By one estimate, "worldwide agriculture has already cleared or converted 70 percent of grassland, 50 percent of the savanna, 45 percent of the temperate deciduous forest, and 27 percent of tropical forests."[15] Yet agriculture continues to expand and is the dominant driver of deforestation and associated impacts on biodiversity.[16]

Figure 1-1 | Thirty-seven percent of Earth's landmass (excluding Antarctica) is used for food production



Note: Numbers may not sum to 100% due to rounding.
[a] Permanent ice cover, desert, etc. When excluding deserts, ice, and inland water bodies, nearly 50 percent of land is used to produce food.
Source: FAO (2011b).

Climate

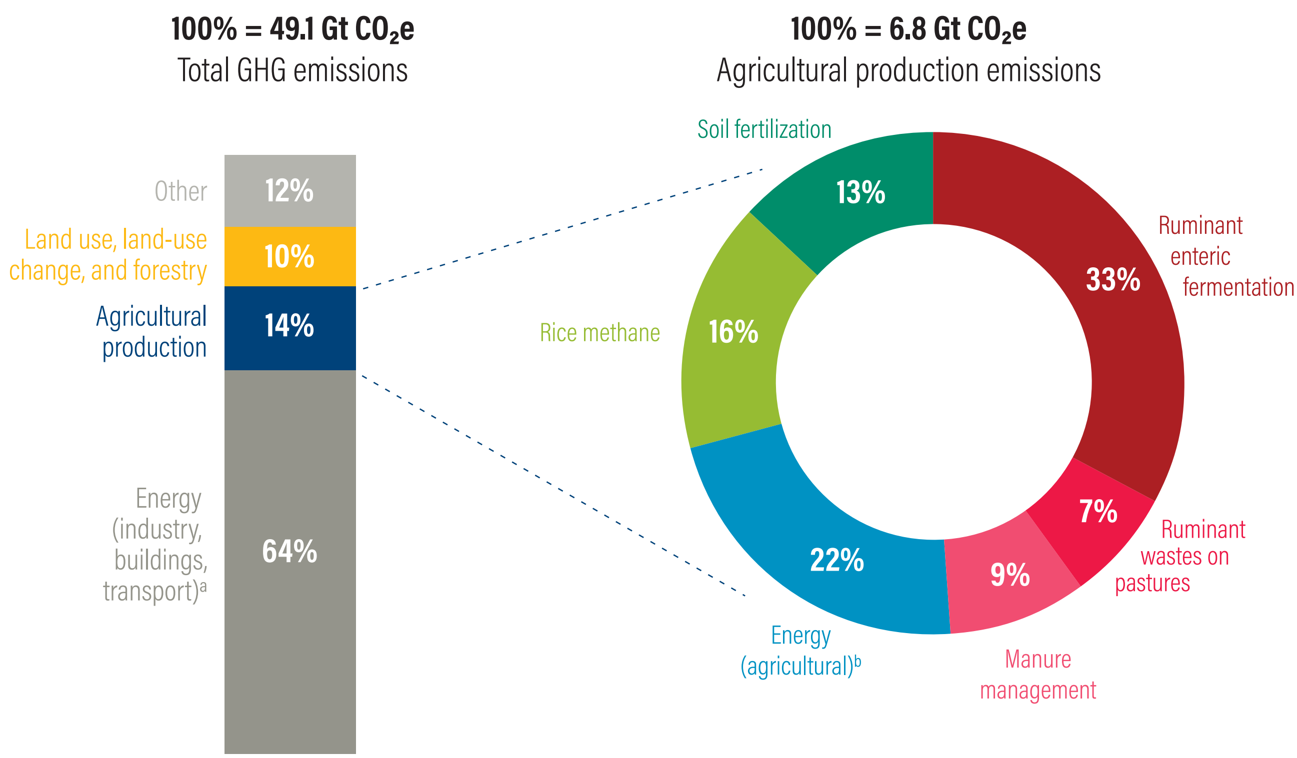
Agriculture and associated land-use change such as deforestation accounted for nearly one-quarter of global greenhouse gas (GHG) emissions in 2010 (Figure 1-2). Of these, agricultural production contributed more than one-half.[17]

Agriculture's role in the challenge of climate change is also intimately connected to its impacts on ecosystems. Native vegetation and soils contain vast quantities of carbon, and conversion to agriculture causes the loss of nearly all the carbon in the vegetation and, in the case of cropland, roughly one-quarter of the carbon in the top meter of soils.[18] By 2000, conversion of natural ecosystems accounted for roughly one-third of the increased carbon dioxide in the atmosphere since preindustrial times.[19] Agriculture-related emissions, including those from loss of carbon in cleared and drained peatlands, now amount to roughly five gigatons (Gt) of CO_2e per year. Total emissions from loss of land-based carbon are equivalent to about 10 percent of human-caused emissions from all sources.[20] If we estimate on the basis of gross conversion, which ignores the carbon impact of forest regrowth, the estimates of emissions from land-use change would be substantially higher.[21]

Water

Agriculture accounts for 70 percent of all fresh water withdrawn from rivers, lakes, and aquifers, and for 80 to 90 percent of fresh water consumption by human activities (Figure 1-3).[22] Agriculture is also the primary source of nutrient runoff, which creates "dead zones" and toxic algal blooms in coastal waters and aquatic ecosystems.[23]

Figure 1-2 | Agriculture accounts for about one-quarter of global GHG emissions (~2010)



Note: Numbers may not sum to 100% due to rounding.

[a] Excludes emissions from agricultural energy sources described above.

[b] Includes emissions from on-farm energy consumption as well as from manufacturing of farm tractors, irrigation pumps, other machinery, and key inputs such as fertilizer. It excludes emissions from the transport of food.

Sources: GlobAgri-WRR model (agricultural production emissions); WRI analysis based on UNEP (2012); FAO (2012a); EIA (2012); IEA (2012); and Houghton (2008) with adjustments.

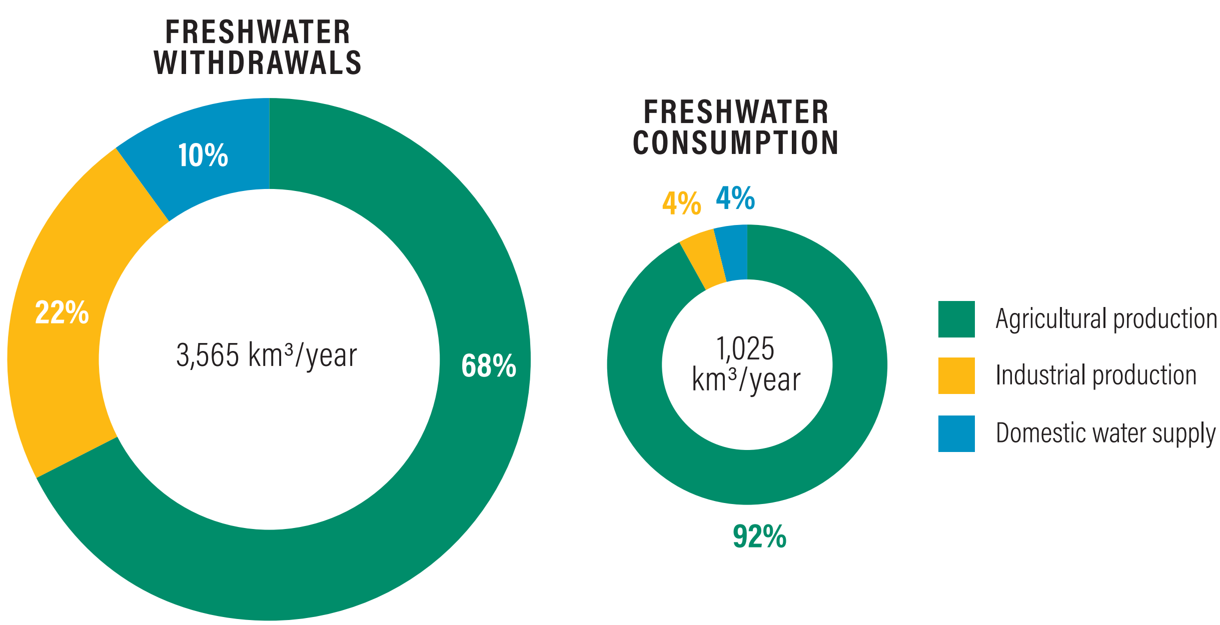
Addressing Food Supply, Development and Poverty Reduction, and Environmental Protection

Because of feedback effects, addressing any one of these needs in isolation would probably undermine the chances of meeting all three. For example, the world could focus on raising food production by converting forests and savannas to croplands and grazing lands, but this approach would increase agriculture-related GHG emissions from the loss of carbon in plants and soils. The climate effects of such an approach would likely have large adverse effects on agricultural output due to higher average temperatures, extended heat waves, flooding, shifting precipitation patterns, and saltwater inundation or intrusion of coastal fields (Figures 1-4 and 1-5).[24] Reducing agriculture's impact on climate and the broader environment in a manner that fails to meet food needs or provide economic opportunities would probably undermine the political support for that environmental protection. Trying to increase food production in ways that boost prices or displace smallholders without alternative opportunities could undermine the economic development necessary to support improved agriculture.

Agriculture's past performance is evidence of the enormity of the challenge. Between 1962 and 2006, the Green Revolution[25] drove increased yields with scientifically bred varieties of grains, synthetic fertilizers, and a doubling of irrigated area.[26] A "livestock revolution" increased meat and dairy yields per animal and per hectare through improved feeding, breeding, and health care.[27] Even these vast yield increases were not enough to prevent net cropland and pastureland expansion of roughly 500 million hectares (Mha), according to data from the Food and Agriculture Organization of the United Nations (FAO).[28] And although this period witnessed reductions in global poverty rates, roughly 820 million people remained chronically undernourished in 2017.[29]

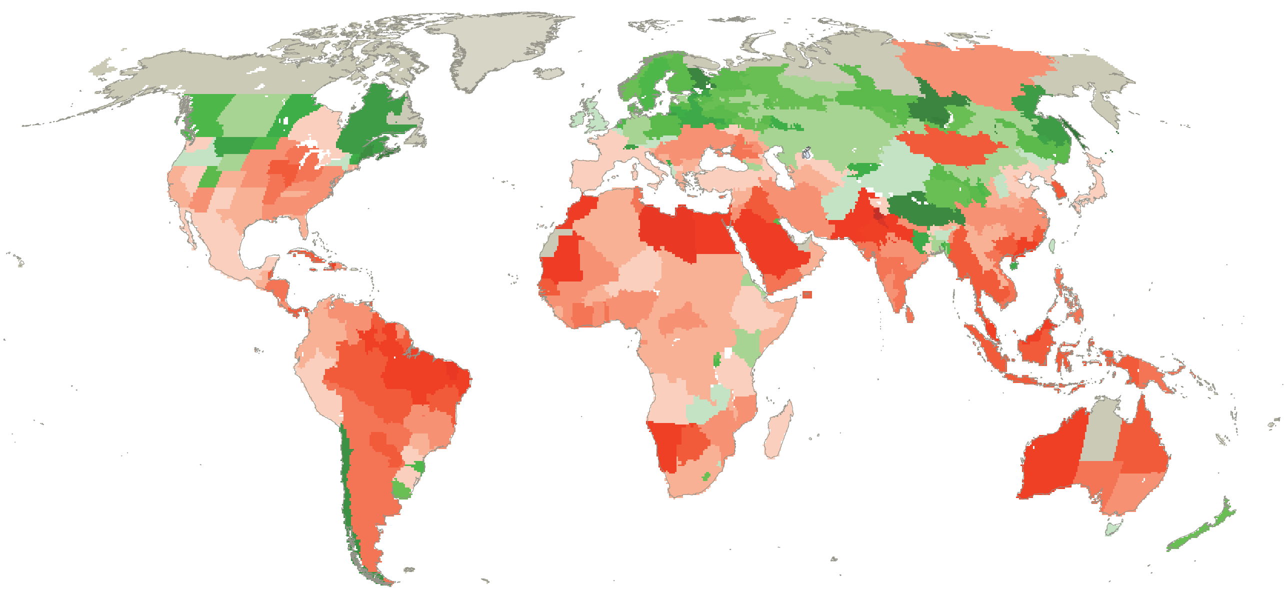
To balance by midcentury the three great needs—meeting food demand, supporting development, and protecting the earth's natural resources—the world's food system must exceed previous achievements in increasing food production while reducing poverty, avoiding land conversion, and mitigating agriculture-related GHG emissions.

Figure 1-3 | Agriculture accounts for the vast majority of global freshwater withdrawals and consumption



Note: Figures measure only "blue water" demand and do not consider rainfed agriculture ("green water"). Consumption figures are averaged for the years 1996–2005; withdrawal figures are for the year 2000.
Sources: Hoekstra and Mekonnen (2012) (consumption); OECD (2012) output from IMAGE model (withdrawals).

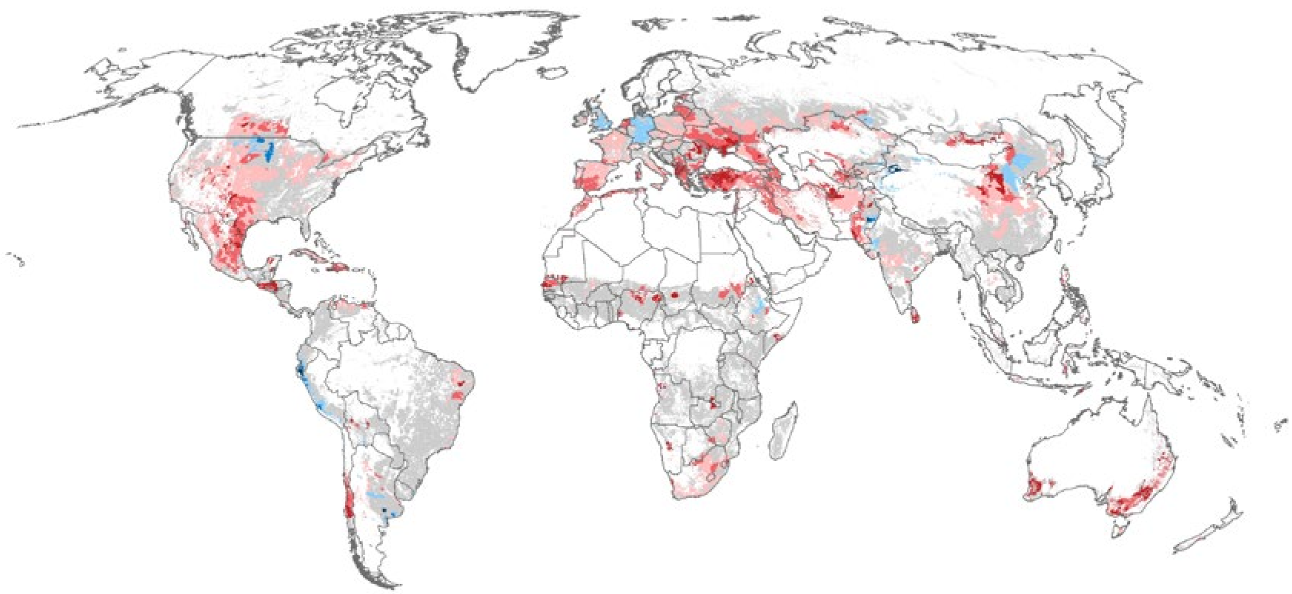
Figure 1-4 | Climate change is projected to have net adverse impacts on crop yields (3°C warmer world)



No data | -50% | **Percentage change in yield** | +100%

Note: Maps are for illustrative purposes and do not imply the expression of any opinion on the part of WRI concerning the legal status of any country or territory, or concerning the delimitation of frontiers or boundaries.
Source: World Bank (2010).

Figure 1-5 | Water stress will increase in many agricultural areas by 2040 due to growing water use and higher temperatures



> 2.8x decrease | 2x decrease | 1.4x decrease | Near baseline level | 1.4x increase | 2x increase | > 2.8x increase

Projected changes in water stress, 2010–40

Note: Areas in white do not contain cropland or pasture. Based on a business-as-usual scenario using shared socioeconomic pathway SSP2 and climate scenario RCP8.5. Maps are for illustrative purposes and do not imply the expression of any opinion on the part of WRI concerning the legal status of any country or territory, or concerning the delimitation of frontiers or boundaries.
Sources: Gassert et al. (2015); cropland and pasture from Ramankutty et al. (2008).

CHAPTER 2

A TALE OF THREE GAPS

We quantify the challenge of creating a sustainable food future in terms of the need to close three "gaps": in food production, agricultural land area, and greenhouse gas mitigation. To measure the size of these gaps, we use a new model, GlobAgri-WRR, developed in a partnership between WRI, CIRAD, INRA, and Princeton University.

Creating a sustainable food future requires closing three interrelated "gaps" by 2050:

The Food Gap

The food gap, as we define it, is the difference between the crop calories produced in 2010 and those that the world will likely require in 2050 based on projected demand. This gap can be closed both through measures that decrease the rate of growth in demand and measures that increase supply. The more the gap can be closed through demand-reduction measures, the smaller will be the challenge of increasing food production. And as that challenge decreases, so does the risk that the world will fail to meet food needs, which would most harshly affect the poor. In this report, we explore both demand-reduction measures and the potential to boost food supply to fill the remaining gap.

The Land Gap

The land gap is the difference between the projected area of land needed to produce all the food the world will need in 2050 and the amount of land in existing agricultural use in 2010. The food gap could be closed by expanding agricultural land—but at the cost of increased harm to ecosystems and further releases of their stored carbon. To avoid huge additional land clearing, the target is to hold agricultural land area—both cropland and grazing land—to the area used in 2010, the base year for our analysis.

The Greenhouse Gas (GHG) Mitigation Gap

The GHG mitigation gap is the difference between agriculture-related GHG emissions projected in 2050 and an emissions target for agriculture and related land-use change in 2050 necessary to stabilize the climate at acceptable temperatures. The emissions include both emissions from agricultural production and from land-use change. The GHG mitigation gap can be closed by demand measures, by measures to increase production on existing land, and by changes in production processes.

To measure the size of each gap, we use a new model, GlobAgri-WRR (Box 2-1 and Appendix A). Although the food gap is simply the difference between demand in 2050 and demand in 2010, the land and GHG mitigation gaps can usefully be understood in different ways, which leads us to develop a few versions of the gap. Primarily, we use the GlobAgri-WRR model to project what land-use demands and emissions are likely to be in 2050 under a "business-as-usual" or "baseline" trajectory. In general, crop and pasture yields grow, farmers increase their efficiency in the use of many inputs, and these gains hold down the growth in agricultural land area and emissions. Using different ways of estimating historical yield trends, GlobAgri-WRR also projects an "alternative" baseline, and the land or GHG mitigation gaps represent the difference between these baselines and the land-use and emissions targets that must be achieved for a sustainable food future.

Our definition of the baseline projection, and therefore of the land and mitigation gaps, already assumes great progress and effort by farmers, governments, businesses, and individuals. Their efforts contributed to the historical rates of progress, and so this future baseline implicitly assumes similar efforts. It is easy to overlook how much work is necessary to achieve even this baseline.

To help keep in mind the level of ambition required in the baseline projection, we also create a "no productivity gains after 2010" projection, which assumes no improvement in the efficiency of production systems and no increase in average yields after 2010. We estimate how much agricultural land would expand and GHG emissions would rise by 2050 if all expected food demands were met under this "no gains" assumption. Using this projection, the land-use and GHG mitigation gaps in 2050 are much larger.

In effect, the gap quantified by this "no productivity gains after 2010" projection measures the total progress required between 2010 and 2050 to achieve a sustainable food future. By contrast, the gap using the business-as-usual baseline, which is largely based on past trends in productivity gains, indicates how much higher rates of progress must be than those achieved in the past.

BOX 2-1 | Overview of the GlobAgri-WRR Model (see Appendix A for a longer description)

GlobAgri-WRR is a version of the GlobAgri model developed jointly by the Centre de coopération internationale en recherche agronomique pour le développement (CIRAD) and Institut national de la recherche agronomique (INRA), WRI, and Princeton University. This global accounting and biophysical model quantifies food production and consumption from national diets and population, as well as land-use demands. The model also estimates GHG emissions from agriculture, including emissions from production (primarily methane and nitrous oxide), carbon dioxide emissions from the energy used to produce fertilizers and pesticides or to run farm machinery, and emissions from land-use change. Emissions modeled include everything up to the farm gate but do not include those from food processing, transportation, retail, or cooking.

GlobAgri links food consumption decisions in each country or region (see Appendix A for a list of countries and regions) to the production of the crops, meat, milk, and fish necessary to meet food demands after accounting for food loss and waste at each stage of the value chain from farm to fork. Its core data for production, consumption, and yields for base year 2010 are based on data from FAO (2019a). The model accounts for the multiple food, feed, and energy products that can be generated by each crop and reflects the estimates of both crop and food product calorie contents by region as estimated in FAO (2019a). It estimates land-use and GHG emissions related to agricultural production in each of the world's countries in light of crop yields, population, diets, production methods, and levels of food loss and waste—factors that can all be modified to examine future scenarios of agricultural production and food consumption. Much of the complexity of the model resulted from automated ways in which it reconciles different FAOSTAT data.

To analyze the alternative food production and consumption scenarios and the "menu items" presented in Courses 1–5, GlobAgri-WRR altered the relevant attribute while holding all other consumption and production factors constant. For example, to examine the consequences of shifting diets, the model assumes any additional or less food consumption per food category would be supplied at the same national crop yields, and using the same national livestock production systems, along with the same rates of food loss and waste as in the 2050 baseline. Thus, in Courses 1–5, GlobAgri-WRR calculates the impact of each menu item in isolation. With limited exceptions, the model also assumes that the role of imports and exports would remain the same. For example, if 20 percent of a crop in Country A is imported, then the same percentage would remain true under scenarios of altered demand for that crop, and countries also contribute the same share of the crop to global exports. The combined scenarios presented in the penultimate section of this report, *The Complete Menu*, alter several attributes at once (for instance, all demand-side attributes). Because the combined effects are not merely the sum of each individual menu item, we then allocate the total combined effect to individual menu items in combined mitigation scenarios. Assumptions underlying the 2050 baseline are presented in this chapter.

GlobAgri-WRR is designed to estimate land use and GHG emissions with specified levels of population, diets and other crop demands, specific trade patterns, and specified agricultural production systems in different countries. The model by itself does not attempt to analyze what policies and practices will achieve those systems, which are the focus of this broader report. For this reason, GlobAgri-WRR does not need to attempt to analyze economic feedback effects.

Other models attempt to estimate these kinds of economic effects and feedbacks. For example, if people in one country were to become richer and increase their food consumption, the prices of food would generally increase globally, which might result in some reductions in food consumption in other countries, and changes in production systems globally. Such models can in theory help us understand how to design policies to achieve specific consumption or production practices, but they are not necessary to analyze the land-use and emissions consequences of any specific set of consumption or production practices. One downside of such models is that they must make a large series of assumptions to operate because economists have not econometrically estimated many of the relationships programmed into these models. They include some of the most basic demand and supply responses of individual crops around the world to prices and almost no estimates of the extent to which a reduction in consumption of one food item simply shifts consumption to another. Future projections of economics are even more uncertain than modeling current behavior. Perhaps most important, the need to assign prices and supply and demand relationships among parameters requires a high level of biophysical simplification. By focusing only on noneconomic relationships, GlobAgri-WRR can incorporate a substantially higher level of biophysical detail.

Patrice Dumas (CIRAD) is the principal architect of the GlobAgri-WRR model, working in partnership with Tim Searchinger (Princeton University and WRI). Other researchers contributing to the core model include Stéphane Manceron and Chantal Le Mouël (INRA), and Richard Waite and Tim Beringer (WRI). A number of researchers from INRA and CIRAD provided important analyses that underpin the GlobAgri-WRR modeling in this report. They include Maryline Boval, Philippe Chemineau, Hervé Guyomard, Sadasivam Kaushik, David Makowsky, and Tamara Ben Ari.

A strength of the GlobAgri-WRR model is that it incorporates other biophysical submodels that estimate GHG emissions or land-use demands in specific agricultural sectors. GlobAgri-WRR therefore benefits from other researchers' work, incorporating the highest levels of detail available. Major contributions include a representation of the global livestock industry developed primarily by Mario Herrero (CSIRO) and Petr Havlík (IIASA), with extra contributions from Stefan Wirsenius (Chalmers University); a land-use model with lead developer Fabien Ramos, formerly of the European Commission Joint Research Centre (JRC); a nitrogen use model developed by Xin Zhang (originally of Princeton University and now of the University of Maryland); a global rice model with lead developer Xiaoyuan Yan of the Chinese Institute for Soil Science; and an aquaculture model with lead developers Mike Phillips of WorldFish and Rattanawan Mungkung of Kasetsart University. Each of these submodels had several contributors. For more on the GlobAgri-WRR model, see Appendix A.

Understanding the Food Gap

The food gap is the difference between the amount of food that must be produced in 2050 to ensure that everyone in the world obtains sufficient food and nutrition and the amount that was produced in 2010. We establish this target not because we believe that increasing food consumption by everyone will be appropriate. In fact, our report explores ways to cut excess food consumption by many. But underproducing food is not an acceptable option because those who overconsume will likely outcompete those who are hungry if food availability is insufficient and prices rise. The food gap identifies by how much food demand must be decreased and food production increased to avoid that result.

BOX 2-2 | Why and how we use calories as our measure of the food gap

Food comes from a wide variety of crops and animal products, and provides not only calories but also proteins, vitamins, minerals, fiber, and other nutritional benefits to people. There is no one perfect way to measure quantities of food or a "food gap." For instance, FAO's estimate in 2012 of a 70 percent food gap between 2006 and 2050, which many authors have cited, measured food by its "economic value." But because prices change over time, economic value does not provide a consistent unit of measure. Likewise, food "volume" is a weak measure because it includes water, which does not provide energy, and different foods have widely varying quantities of water. Moreover, "nutrients" are not amenable to a single uniform unit of measure because people need many different types of nutrients.

Although far from perfect, "calories" are consistent over time, avoid embedded water, and have a uniform unit of measure. Production and consumption data on calories are also globally available. Of course, the use of calories to measure the food gap might lead to distorted solutions if we considered solutions that increased calories at the expense of nutrients. For example, it might reward in our analysis the production of cereals with high yields and calorie content (or worse, food with added sugars) in place of fruits and vegetables, beans, and animal-based foods. To prevent this distortion, our "shifting diets" scenarios in Chapter 6 ensure not only adequate calories but also adequate protein for all populations, and include two scenarios that increase fruit and vegetable consumption and limit added sugars and red meat consumption in line with nutritional recommendations. We therefore use calories to provide a practical means of measuring the food gap only among nutritionally balanced alternatives.

How much more food will the world demand by 2050 under business-as-usual trends?

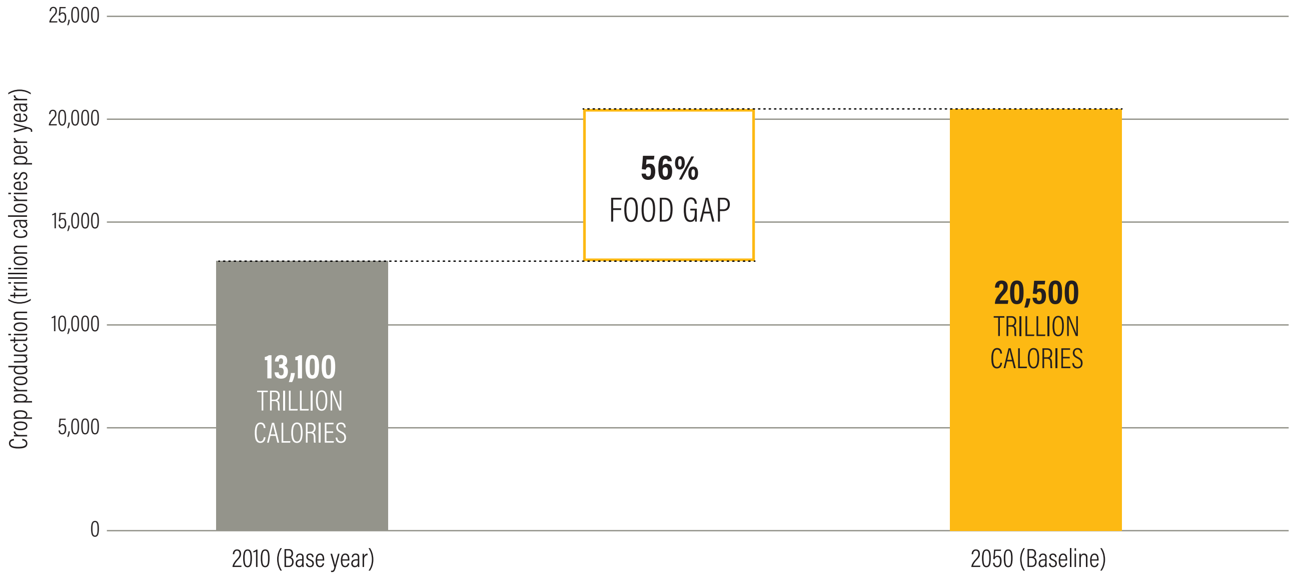
To project food demands in 2050, we start with a 2012 FAO projection of the diets that the average person in each country will consume in that year.[30] FAO based its projections on economic growth and income trends and culture in different countries. We adjust these projections per person moderately, adding fish consumption and including enough additional calories in sub-Saharan Africa and South Asia to ensure sufficient nutrition for everyone, after accounting for waste and unequal distribution.[31] Additionally, the United Nations has added more than half a billion people to its medium-level estimate of the global population in 2050 compared to the scenario used by FAO,[32] so we further adjust 2050 food demands to reflect this new estimate of 9.8 billion people.

By this method, we project that world food demand (measured in total calories) will rise by 55 percent between 2010 and 2050. This figure counts the caloric content (Box 2-2) of all food categories, including not just crops but also dairy, fish, and meat.

Another way to calculate the food gap is to look at the necessary increase in crop production alone to meet projected food demands in 2050. This crop gap excludes milk, meat, and fish but includes the growth in crops needed for animal feed to produce this milk, meat, and fish, as well as crop growth needed for direct human consumption. We also assume that the same share of crops must continue to meet industrial demands and must continue to supply biofuels at their 2010 share of global transportation fuel of 2.5 percent.[33] This growth in crop demand means that crop production (measured in total calories) would be 56 percent higher in 2050 than in 2010, almost the same size as the growth in total food demand. Overall, crop production would need to increase from 13,100 trillion kilocalories (kcal) per year in 2010 to 20,500 trillion kcal in 2050—a 7,400 trillion kcal per year crop calorie "gap"[34] (Figure 2-1).

To put the challenge in perspective, without measures to limit demand, the projected increase in crop calorie demand in the 44-year period between 2006 and 2050 is 11 percent higher than the increase achieved between 1962 and 2006, a period that encompassed the Green Revolution.[35]

Figure 2-1 | The world needs to close a food gap of 56 percent by 2050



Note: Includes all crops intended for direct human consumption, animal feed, industrial uses, seeds, and biofuels.
Sources: WRI analysis based on FAO (2019a); UNDESA (2017); and Alexandratos and Bruinsma (2012).

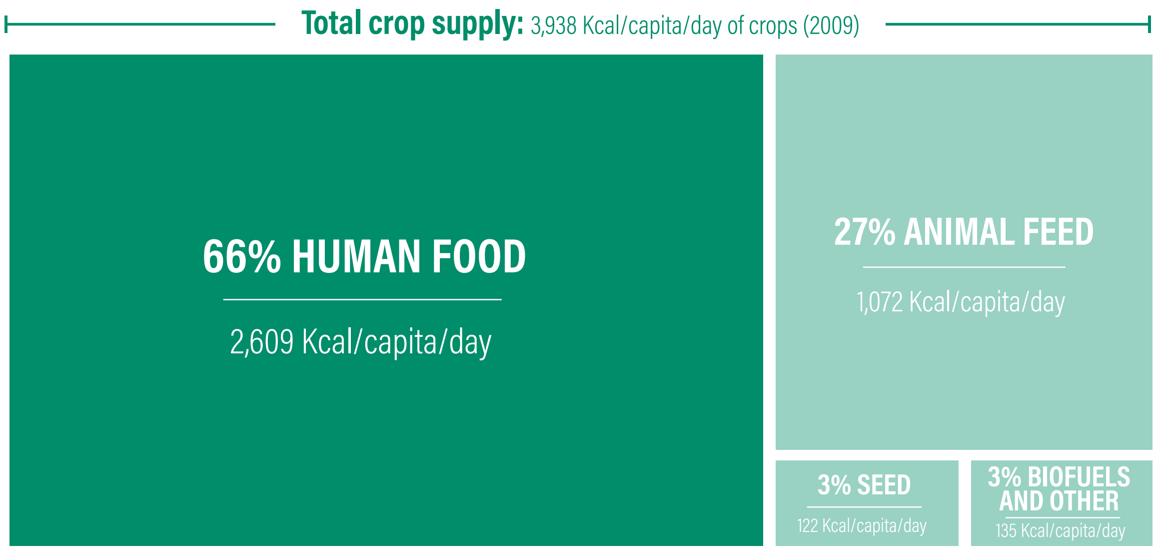
Is there really a "food gap"?

A common refrain in popular writings is that the world does not actually need more food because it already produces 1.5 times the quantity of calories needed to feed everyone on the planet today and therefore enough to feed 40 percent more people if food were evenly distributed (Figure 2-2).[36] Could we just redistribute the food?

It is true that the world's distribution of food is highly unequal. Approximately 820 million people worldwide are undernourished, even as more than 2 billion people are overweight or obese.[37] But the claim that the world already has enough food if evenly distributed must make a number of major assumptions. It assumes no food losses or waste. It also counts as available for food the one-third of all crop calories that are now used for animal feed, for seed, and in industrial uses such as biofuels. In effect, this claim assumes that the world becomes predominately vegan (except for milk and meat from grazing animals). It also assumes that people who switch away from meat and milk substitute the same maize, soybeans, and feed wheat that today are eaten by animals rather than the more likely combination of foods, including fruits, vegetables, and beans. This more realistic combination requires more land and tends to use more fertilizer and water per calorie than animal feed.[38]

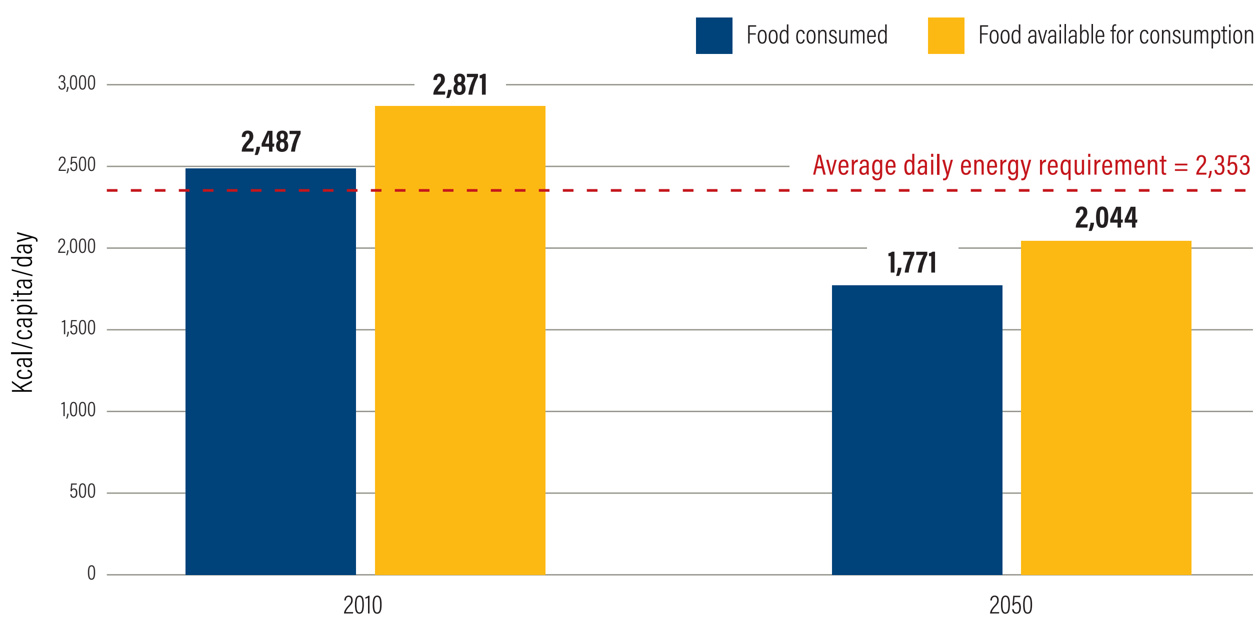
Realistically, we should focus on actual food consumption patterns, including meat and milk, and account for food losses and waste. Doing so yields a very different result. The amount of food consumed in 2010 (nearly 2,500 kcal per person per day), spread over the projected population in 2050, would provide only 1,771 kcal per person per day—nearly 600 kcal below FAO's recommended average daily energy requirement (ADER) (Figure 2-3).[39] Even if we assume away all postconsumer food waste, "available food" (see Box 2-3 for definitions) would still fall short of the target by 300 calories per person per day.[40]

Figure 2-2 | Claims that the world already produces more than enough food assume that people will eat animal feed and biofuel crops and that food loss and waste are eliminated



Note: Numbers may not sum to 100% due to rounding.
Source: Kummu et al. (2012) using FAO data.

Figure 2-3 | The amount of food consumed (or available) in 2010 would be insufficient to feed the world population in 2050



Note: Data reflect food for direct human consumption. They exclude food crops grown for animal feed, seeds, and biofuels. Consumption and availability figures shown are global averages.
Sources: WRI analysis based on GlobAgri-WRR model with source data from FAO (2019a); FAO (2011c); and UNDESA (2017) (medium fertility scenario).

Equally, planning needs to focus on the reality of food distribution. Assuming food to be equally distributed does not make it so, any more than assuming equal distribution of housing, cars, health care, or income. More equitable distribution of food without increased production would mean that the poor eat more but the wealthy must eat less, which explains why the goal is challenging. Failure to produce enough food to meet all demands in the hope that the rich would then volunteer to eat less would be irresponsible because the more likely result is that the rich would outcompete the poor for the available food.[41]

The only viable way to distribute food more equally is to explore realistic strategies that would persuade overconsumers and inefficient consumers to consume less. This report identifies some promising, if challenging, strategies. These strategies are not denials of the food gap but ways of closing the food gap—although even they would not eliminate the need to produce substantially more food.

Understanding the Land Gap

Our target for land is to avoid a net expansion of agricultural land beyond the area used in 2010.

This target is necessary to protect the natural ecosystems that provide the critical services underpinning agriculture, including climate and water regulation, soil stabilization, and pest control, among others. It is necessary also to protect biodiversity. Rates of species extinction have accelerated and have now reached 0.4–0.6 percent per year.[42] Agriculture has long been understood to be the single largest cause of biodiversity loss and is likely to remain so in the future absent major change.[43] Agricultural expansion is occurring in critical hotspots of biodiversity in Brazil, Indonesia, parts of Africa, and even parts of the United States and Canada occupied by rare grassland bird species.[44]

Agricultural expansion also has frequent adverse social consequences such as displacing or compromising native peoples who depend on local ecologies for ecosystem services such as water filtration, soil integrity, flood protection, and cultural identity.[45] And for reasons we elaborate below, this target is also necessary to close the GHG mitigation gap and stabilize the climate.

Using this target, how big is the land gap?

BOX 2-3 | Definitions

This report uses several terms to describe the status of food along the food supply chain:

- **Food production.** Food at the point when crops are ready for harvest, livestock ready for slaughter, and fish caught. This is food at the start of the production stage of the food supply chain.
- **Food availability.** Food at the point when it is ready to eat but not yet ingested. This includes food available for retail purchase and in restaurants.
- **Food consumption.** Food ingested by people. This number is lower than "food availability" because it subtracts consumer waste, that is, food that is not ultimately eaten.
- **Food supply chain.** The movement of food from farm, ranch, or boat to the consumer. The food supply chain consists of five stages: *production*—during or immediately after harvest or slaughter; *handling and storage*—after leaving the farm for handling, storage, and transport; *processing and packaging*—during industrial or domestic processing and/or packaging; *distribution and market*—during distribution to wholesale and retail markets; and *consumption*—in the home or business of the consumer, in restaurants, or through caterers.
- **Food loss.** The food lost from human consumption in the production, handling and storage, and processing part of the chain. Some of this food may be diverted to animal feed.
- **Food waste.** The food that does not get consumed by people after it reaches the retail or consumption stage.

How much more agricultural land would the world need in 2050 using today's production systems and yields?

To measure the full effort needed to avoid agricultural land expansion, we use GlobAgri-WRR to estimate the amount of land the world would need in 2050 to produce enough food to meet projected demand if today's production systems and efficiencies were to remain unchanged. Under this projection, which we term "no productivity gains after 2010," agricultural area would grow by 3.2 billion hectares beyond the roughly 5 billion hectares in use in 2010.

That level of expansion would eliminate the majority of the world's remaining forests and woody savannas. This figure thus represents the total amount of forest and savanna the world must save through improvements in food production systems and reductions in the rate of food demand growth.

How much more cropland would the world need based on business-as-usual trends?

Fortunately, by increasing yields from cropland, agriculture has consistently become more land-efficient over the past 50 years and is likely to continue to do so in the future. The area of cropland required will depend on yield gains. How much yields will grow is impossible to predict with certainty, in part because previous rates of yield growth reflected not just private initiative but also extensive government efforts and scientific advances, and these are uncertain in the coming decades. We rely on two alternative projection methods.

The main 2050 business-as-usual baseline we use relies on yield projections for 2050 by FAO. These projections are based on the professional judgment of FAO experts and external experts, who consider not only trend lines but also their knowledge of the technical potential of different regions.[46] Overall, although FAO projects very different rates of growth for individual crops compared to the past, on average, FAO projects that yields will grow between 2010 and 2050 at roughly the same linear rate as they did from 1961 to 2010. This projection means that the amount of land required to produce crops in 2050 will be roughly the same as if the global yield of each crop grew at the same rate it grew from 1962 to 2006.[47] We therefore consider this baseline consistent overall with trend lines since 1961. Based on these estimates, we project an average rate of crop yield growth across all crops of 48 percent between 2010 and 2050.[48]

Annual yields per hectare can also rise if farmers plant and harvest crops more frequently on each hectare of land each year, an increase in "cropping intensity"—or the ratio of harvested area divided by total cultivated area.[49] Farmers can either leave land fallow less often or plant more hectares with multiple crops each year. FAO projects a smaller rate of growth in cropping intensity in the next several decades compared to the past. The reason is that growing multiple crops per year often relies on irrigation, and farmers have less opportunity now to expand irrigation, given that the easier places to irrigate have already been exploited. We again rely on FAO's projection of cropping intensity in our baseline; globally, we project cropping intensity to rise from 85 percent in 2010 to 89 percent in 2050. In this projection we therefore do not increase cropping intensity in the future baseline as much as predicted by past trends.

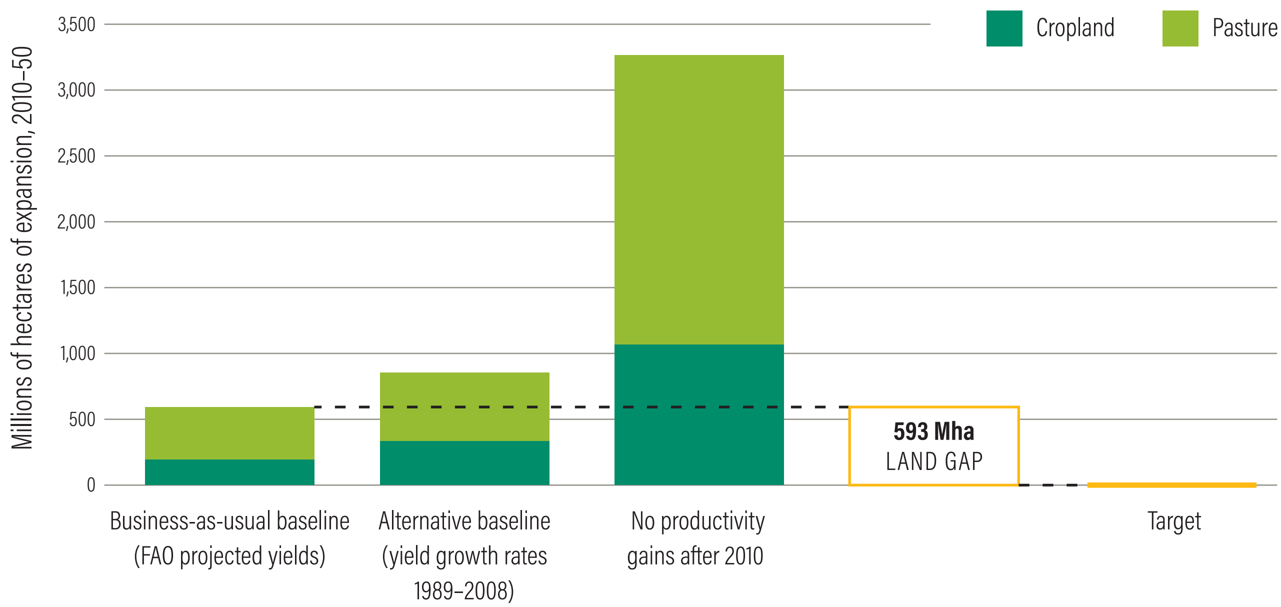
Using these FAO estimates of growth in yield and cropping intensity, GlobAgri-WRR projects a net increase in global cropland between 2010 and 2050 of 171 Mha. Using an analysis of aquaculture systems described more in Course 4, we also project an additional 20 Mha of aquaculture ponds, bringing the total land-use expansion to 191 Mha (Figure 2-4).

We also develop a less optimistic "alternative baseline" because FAO's projected yield gains are more optimistic than suggested by recent trend lines. During the second half of this historical time period—that is, from 1989 to 2008—crop yields grew at a slower linear rate than they did from 1962 to 1988 (i.e., fewer additional kilograms were produced per hectare each year).[50] Our "alternative baseline" projects future cropland needs based on yields we project ourselves using these more recent (i.e., 1989–2008) growth rates. Using this alternative baseline, we estimate that global area of cropland and aquaculture ponds would expand by 332 Mha between 2010 and 2050 (Figure 2-4).[51]

How much more pastureland would the world need under business-as-usual trends?

Although cropland expansion tends to receive more attention, expanding pastureland by clearing forests and woody savannas presents a potentially greater challenge. Globally, pasture occupies two or three times as much land as crops, depending on the criteria used to identify grazing land.[52] Between 1962 and 2009, according to FAO statistics, pastureland area expanded by 270 Mha—a slightly larger amount than cropland expansion during this period (220 Mha).[53] And in Latin America, pasture expansion has been the dominant cause of forest loss over the past several decades.[54]

Figure 2-4 | The world needs to close a land gap of 593 million hectares to avoid further agricultural expansion



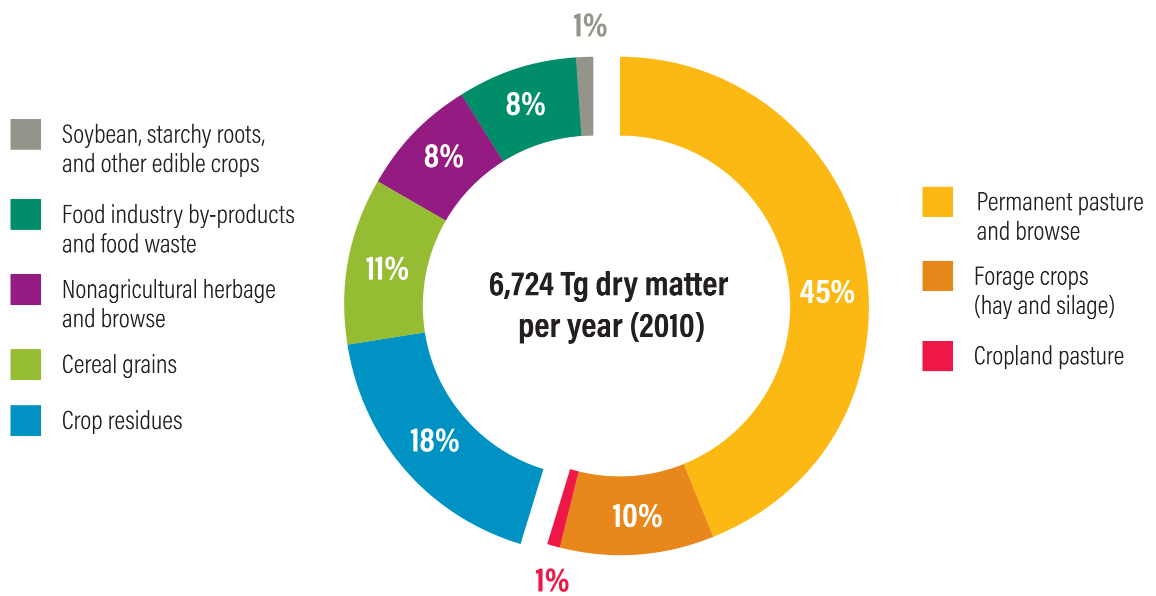
Note: "Cropland" increase includes a 20 Mha increase in aquaculture ponds under the two projected baselines and a 24 Mha increase in the "no productivity gains after 2010" projection.
Source: GlobAgri-WRR model.

Pasture area is projected to expand even more than cropland because of high projected growth in demand for milk and ruminant meat, whose production relies heavily on grasses and other forages. In the GlobAgri-WRR model, grasses provided one-half of all animal feed used by ruminants in 2010. In a separate analysis by Wirsenius et al. (2010), grasses provided more than half of all the feed of all livestock when including grass-based forages produced on cropland (Figure 2-5). Although we project that the share of global food crops used in ruminant animal feed will grow from 7 percent to 9 percent between 2010 and 2050,[55] the share of pasture and forage crops will probably expand because they are more nutritious than the next biggest category of ruminant feeds—food crop residues—which will decline.

Projecting the expansion of pastureland under business-as-usual trends, however, is even more difficult than cropland. Three factors determine the output per hectare of grazing land: increases in the efficiency of converting feed into meat and milk, increases in the quantity of grass grown and consumed by animals per hectare, and increases in the share of feeds that do not derive from pasture. Each of these factors contributes to more output per hectare of grazing land between 2010 and 2050 in our main business-as-usual scenario—dairy productivity per hectare rises by 53 percent, beef productivity by 62 percent, and sheep and goat meat productivity by 71 percent. Our 2050 pastureland baseline projects livestock efficiency improvements based on the recent trend lines in each of these three factors.[56]

Even with these productivity increases, we project a global increase in pasture area of 401 Mha in our baseline scenario (Figure 2-4). Our alternative baseline scenario assumes slower crop pasture yield growth and reduces the growth of ruminant livestock feed efficiency by 25 percent relative to the business-as-usual baseline. In this less optimistic projection, pasture area expands by 523 Mha. Because farmers already graze animals on virtually all native grasslands suitable for grazing, the additional pasture area comes at the expense of forests and woody savannas.

Figure 2-5 | Grasses provide more than half of all livestock feed



Note: Soybean and other oil meals are included in "Food industry by-products" while whole soybeans are included in "Soybeans, starchy roots, and other edible crops." Data for 2010 represent mean values between two scenarios (1992–94 and 2030).
Source: Wirsenius et al. (2010).

Additional land-use challenges

Even closing these land gaps will not by itself solve the problem of land expansion into natural ecosystems for two main reasons. First, other nonagricultural land uses such as human settlements, plantation forestry, and mining are projected to expand. For example, Seto et al. (2012) estimate that urban areas will expand by 120 Mha between 2000 and 2030, based on current land-use and population trends.[57] Urban expansion often claims good agricultural land because many cities took root where agriculture was productive and land relatively flat.[58] Accommodating these nonagricultural land-use demands implies that an actual decline in agricultural area would be a valuable goal. Some of the scenarios in this report can free up land enough to accommodate this growth.

Second, agriculture continually shifts from one region to another, and even within regions, resulting in the encroachment of agriculture into natural ecosystems.[59] Addressing these shifts—conversion to agriculture in one place, reversion to a natural ecosystem in another place—is a part of the agricultural land-use challenge with respect to both biodiversity and GHG emissions, and we also address this challenge in this report.

Understanding the Greenhouse Gas Mitigation Gap

Agriculture contributes to GHG emissions in two principal ways: land-use change and the food production process itself (Figure 1-2).[60] The GHG mitigation gap is the difference between the expected level of emissions in 2050 and the level necessary to stabilize the climate at acceptable temperatures. Quantifying the gap requires, first, projecting those emissions in 2050 and, second, establishing an emissions target.

How high will agricultural emissions be in 2050?

Agricultural production emissions occur primarily in the form of methane and nitrous oxide—trace but powerful GHGs—generated by microorganisms in ruminant stomachs, soils, and manure slurries. Ruminant livestock—cows, buffalo, sheep, and goats—generate nearly half of all production-related emissions. Roughly 80 percent of these agricultural production emissions occur in emerging economies and the developing world, a percentage that is likely to be similar in 2050.[61]

As when analyzing the land-use gap, we develop a "no productivity gains" projection, which analyzes what emissions would be in 2050 if expected demand were met and if today's yields and production systems do not change. Using GlobAgri-WRR, we estimate that total emissions would rise from 12 Gt CO_2e per year in 2010 to roughly 33 Gt CO_2e per year, with about two-thirds of emissions coming from land-use change and one-third from the agricultural production process.

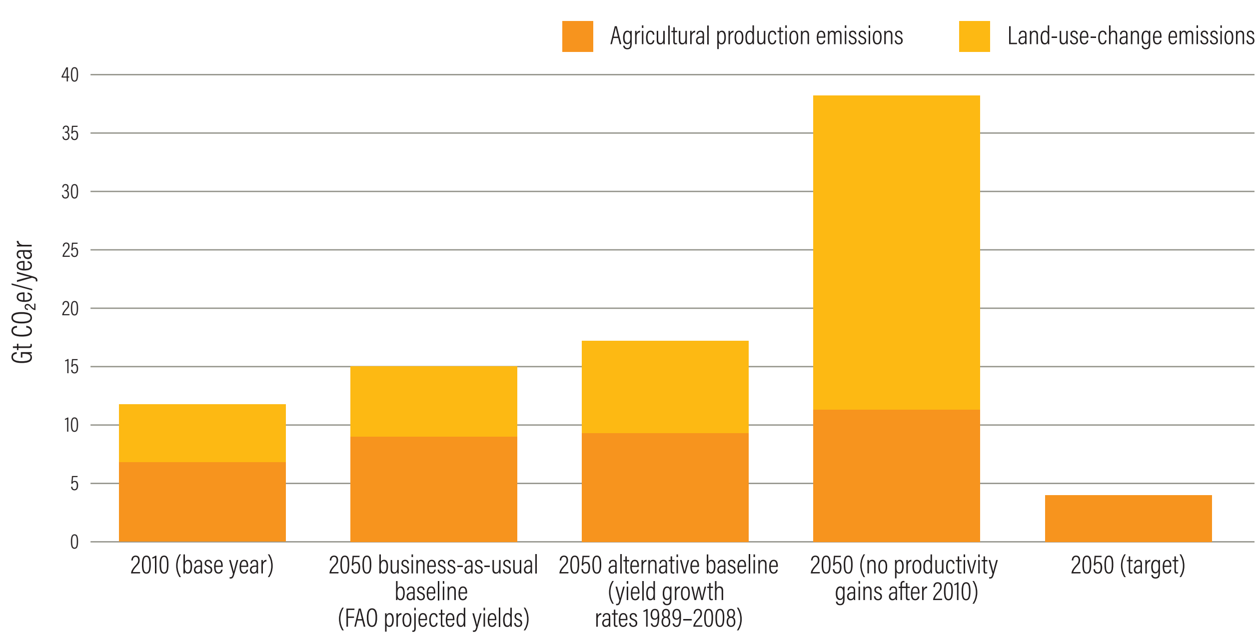
Fortunately, yields will probably continue to grow, and the use of chemicals, animals, and other inputs to the production process that lead to emissions will probably become more efficient as well. (We describe these assumptions in more detail in Course 5.)

Using GlobAgri-WRR, in our business-as-usual baseline, we project that CO_2e emissions from agricultural production will rise from 6.8 Gt per year in 2010 to 9.0 Gt per year in 2050. To estimate land-use-change emissions out to 2050, GlobAgri-WRR uses the global estimates for land-use expansion discussed in the previous section. These global projected changes represent the sum of estimated changes in each of nine major world regions. Including ongoing peat emissions between 2010 and 2050, we estimate total cumulative land-use emissions of 242 Gt CO_2e.[62]

These emissions will occur over 40 years. To present annual emissions in 2050, we divide these emissions by 40, which may or may not truly estimate the proportion of these total emissions that will occur in 2050 but is a way to convey the cumulative significance of these emissions. As a result, we estimate emissions from land-use change in 2050 at 6 Gt per year—1 Gt higher than recent levels.

Total agricultural emissions from land-use change and production under our business-as-usual baseline would thus rise from roughly 12 Gt per year in 2010 to 15 Gt per year by 2050 (Figure 2-6).

Figure 2-6 | Agricultural emissions are projected to grow by at least 28 percent between 2010 and 2050



Source: GlobAgri-WRR model.

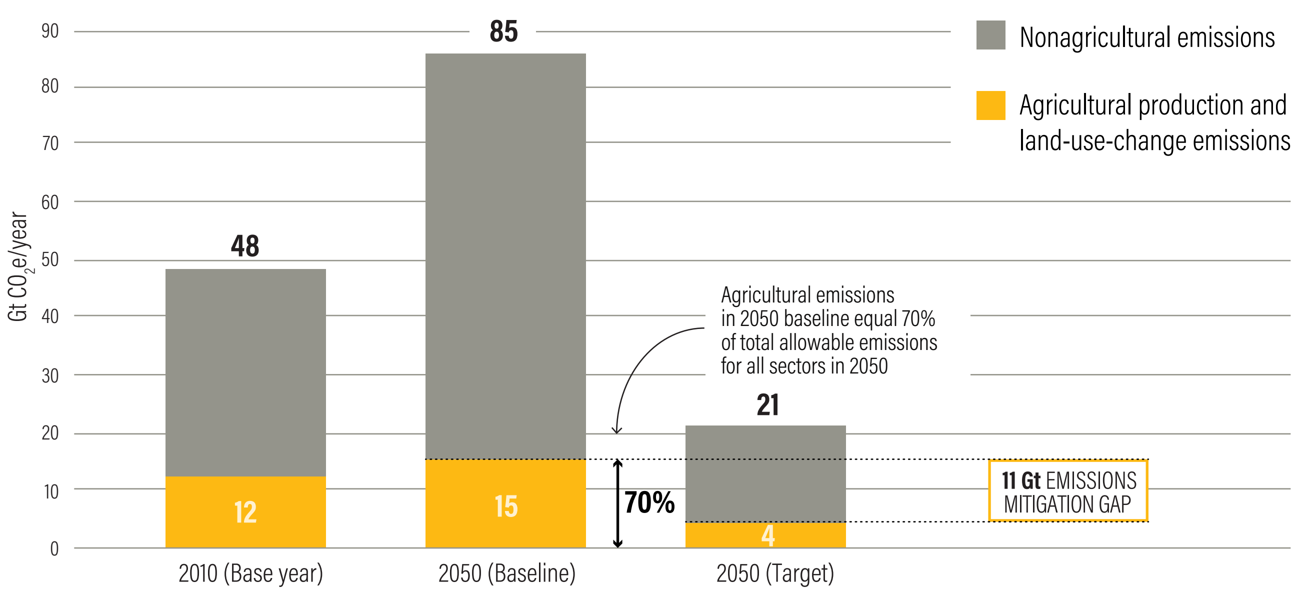
As with our land-use projections, we again develop a less optimistic alternative baseline using recent yield growth trends.[63] In this scenario, emissions from agricultural production would grow to 9.3 Gt CO_2e per year in 2050 and total emissions, including those from land-use change, would rise to 17.1 Gt CO_2e per year (Figure 2-6).[64]

Agricultural emissions and the Paris Agreement climate goals

How significant are agricultural GHG emissions? One way to view the answer is to focus on total emissions of all GHGs in 2050 relative to climate goals. In the Paris Agreement, countries agreed to set a target of stabilizing the average global temperature at no more than 2°C above preindustrial levels, and to explore a goal of 1.5°C. Although setting a 2050 target for all kinds of emissions to achieve these goals is complicated (for reasons we describe below), we believe the most plausible target is around 21 Gt CO_2e per year.[65] Based on this number, and using the annual production emissions and annualized emissions from land-use change in our business-as-usual baseline projection, we estimate that agriculture would generate about 70 percent of allowable emissions from all human sources, leaving little room for emissions from nonagricultural sectors (Figure 2-7). Under the alternative baseline, agriculture would generate more than 80 percent of allowable emissions.[66]

Another useful analysis is the contribution agriculture would make in our baseline toward allowable cumulative emissions of carbon dioxide alone. Because carbon dioxide persists in the atmosphere so long, some models now try to estimate the maximum cumulative emissions of carbon dioxide (from all sectors) that are consistent with a good chance of holding climate warming to the 2°C goal agreed in Paris. One of the first such studies estimated that maximum cumulative emissions of 670 Gt between 2010 and 2050 would give the world a 75 percent chance of meeting the target.[67] United Nations Environment uses average estimates of 1,000 Gt for a two-thirds chance of meeting the target. Another recent study estimates that cumulative emissions of 600 Gt between 2010 and 2050 would enable the world to hold temperature rise to somewhere between 1.5° and 2°C.[68]

Figure 2-7 | Agricultural GHG emissions are likely to be at least 70 percent of total allowable emissions from all sectors by 2050, creating an 11 gigaton mitigation gap



Sources: GlobAgri-WRR model, WRI analysis based on IEA (2012); EIA (2012); Houghton (2008); OECD (2012); and UNEP (2013).

Given these global maximum allowable emissions, our baseline estimate of cumulative agricultural and land-use-change CO_2 emissions of roughly 300 Gt (242 Gt from land-use change and peatlands, and 60 Gt from agricultural energy use) would use up 30–50 percent of the allowable CO_2 emissions from all human sources. Using the cumulative emissions approach, this scenario also would leave too little room for the bulk of GHG emissions from other human activities and prevent the world from reaching acceptable climate goals.

Agriculture's GHG mitigation target and climate goals

How high could agricultural GHG emissions be in 2050 if the world is to limit global warming either to 1.5 or 2°C? Choosing a target is not straightforward for many reasons, and these reasons apply not only to the agricultural and land-use-change target but also to the target for all emissions sources.

First, standard approaches to target-setting employed by researchers and international institutions involve the use of models to estimate the path of emissions levels each year over time that would meet a climate goal at the "least cost." Unfortunately, many of these future costs of mitigation are highly uncertain. The method also means that the mitigation goal assigned to agriculture will be informed by the estimated costs of agricultural mitigation as well as estimates of the costs of mitigation in other sectors. That gives the setting of climate targets a circular quality. Any assumed difficulty or expense with agricultural mitigation leads the models to impose higher mitigation requirements on other sectors, even if these requirements are expensive and uncertain. By assigning more mitigation requirements elsewhere, the models then suggest that the lower mitigation target for agricultural emissions is acceptable. We are reluctant to rely on such estimates when setting an agricultural target, in part because models may use simpler and now out-of-date estimates of agricultural mitigation,[69] in part because all estimates of future mitigation costs are highly uncertain, and in part because the more mitigation requirements are shifted to other sectors, the less realistic it is that those sectors can deliver.

Second, many modeling analyses now select paths for mitigation emissions that allow emissions to exceed the levels necessary to hold climate change to below 1.5 or 2°C and rely on "negative emissions" after 2050. Negative emissions remove carbon from the air. But the economic and technical potential for negative emissions approaches is highly uncertain.[70] The discussion of bioenergy later in this report explains why we believe one of the largest sources many models use for future negative emissions—bioenergy with carbon capture and storage (BECCS)—is based on incorrect premises. We are therefore reluctant to rely on modeling estimates that themselves rely heavily on negative emissions.

Third, other uncertainties in picking relatively simple 2050 targets include the uncertainties concerning how the climate responds to different emissions, the variable effects of the different GHGs over different time periods, and the uncertainty of post-2050 emissions.

Recognizing these challenges, to limit global warming below 2°C we select a target of zero net emissions from land-use change (and peatlands) between 2010 and 2050 and a target of 4 Gt CO_2e for emissions from agricultural production sources in 2050 (Figures 2-6 and 2-7). Our 4 Gt target is based on the concept of equal sharing. According to a projection by the Organisation for Economic Co-operation and Development (OECD), emissions from all human sources are on a course to reach 70 Gt of CO_2e per year by 2050.[71] Reaching 21 Gt in 2050 therefore requires a 75 percent reduction compared to projected 2050 levels. If the agriculture sector (including land-use change) also reduces its projected emissions under our principal business-as-usual scenario by 75 percent, agricultural emissions must decline to 4 Gt.[72]

Our target of zero net emissions from land-use change reflects both our own and others' analysis that it would be impossible to reach a 4 Gt target for total agricultural emissions without eliminating emissions from land-use change altogether. That is because it is even harder to reduce emissions from agricultural production than from land-use change. Reflecting this challenge, nearly all other researchers' scenarios for a stable climate with 2°C of warming assume that net emissions from land-use change have stopped by 2050, and many require net carbon sequestration on land.[73]

To limit warming to 1.5°C, typical scenarios contemplate similar levels of emissions from agricultural production but require extensive reforestation to offset other emissions.[74] In this report, we therefore also explore options for liberating agricultural land to provide such offsets.

This agricultural emissions target of 4 Gt per year in 2050 allows quantification of three possible GHG mitigation gaps. As shown in Figure 2-6, in our 2050 "no productivity gains after 2010" projection, the gap would be 34 Gt CO_2e. That gap represents the total reduction in emissions that must be achieved by improvements in food production or sustainable reductions in food consumption between 2010 and 2050. Compared with the 4 Gt target, our business-as-usual baseline results in a gap of 11 Gt, while our alternative (less optimistic) yield growth rate baseline results in a gap of 13 Gt. The 11 Gt gap is still large; it is the primary gap we use in this report and represents a measure of the *additional* efforts the world must make beyond the effort it has made in the past to improve agriculture if the world is to achieve climate goals.

Summary of the three gaps

The food, land, and GHG mitigation gaps will vary from region to region. In general, developing countries face the largest growth in food demand and the greatest challenges. Sub-Saharan Africa faces the biggest challenges of all (Box 2-4).

Globally, using our business-as-usual 2050 baseline, the three gaps make it possible to express the challenge of a sustainable food future in a quantitative form. Between 2010 and 2050, the world needs to close a food gap equal to more than half of present production, while avoiding projected land expansion even greater than that of the past 50 years, and while reducing agricultural GHG emissions by two-thirds.

BOX 2-4 | Sub-Saharan Africa: A hotspot for the challenge of a sustainable food future

The challenges outlined in this chapter are particularly acute in sub-Saharan Africa.

Food

Sub-Saharan Africa is already the world's hungriest region. FAO estimates that 23 percent of sub-Saharan Africa's people were undernourished in 2016.[a] The region contained 30 percent of the world's chronically hungry people that year, even while holding only 16 percent of the world's population.[b] The region is also the most dependent in the world on imports for its staple foods: in 2010, the region relied on imports for one-quarter of its cereals, two-thirds of its vegetable oil, and 14 percent of its meat and dairy.[c] Because the region is relatively poor, this reliance on imports makes the availability of and access to food unstable.

At the same time, sub-Saharan Africa currently has the world's highest fertility rates (discussed in Chapter 8), and the population is expected to grow from 880 million in 2010 to 2.2 billion in 2050. As poverty declines and incomes rise, people will rightly consume a better and more varied diet—including an increase in per capita demand for meat and dairy. As a result, a large portion of the global growth in food demand will occur in this region. Although sub-Saharan Africa consumed only 12 percent of the world's food calories annually in 2010, the region will account for 43 percent of global growth in demand for food calories between 2010 and 2050.[d] And although globally the demand for food calories is projected to grow by 55 percent between 2010 and 2050, food demand is projected to grow by 216 percent (i.e., more than triple) in sub-Saharan Africa during that period.[e]

Land

Many opportunities exist to boost food production in sub-Saharan Africa, but fully meeting needs on existing agricultural land will be difficult. Given projected growth in population and food demand, sub-Saharan Africa would need to more than triple its cereal yields by 2050 relative to 2010 to avoid expanding cereal cropland area.[f] Doing so would require an increase in

BOX 2-4 | Sub-Saharan Africa: A hotspot for the challenge of a sustainable food future (Cont'd)

production of 61 kilograms (kg) per hectare relative to the previous year—almost 50 percent higher than the global average annual cereal yield growth from 1962 to 2006.[g] FAO has predicted healthy growth in yield per hectare for the region from 2006 to 2050 at rates that would more than double yields for most important crops. Even with this growth, and while maintaining the same rate of imports, the region would likely have to expand cropland by roughly 100 Mha between 2010 and 2050.[h] Pastureland would expand by nearly 160 Mha.[i] This expansion would lead to extensive loss of forests and savannas, impacting people who currently rely on or live in those areas, releasing more than 2 Gt of CO_2e per year,[j] harming biodiversity, and degrading other ecosystem services.

Economic development

Approximately 62 percent of sub-Saharan Africa's population lives in rural areas, where economies are dominated by small-scale agriculture.[k] It is in these regions that poverty rates and hunger are highest.[l] Limited social welfare programs make subsistence agriculture an economic activity of last resort. Although healthy growth in other economic sectors is needed to provide more job opportunities, the welfare of hundreds of millions of people will be tied to small-scale agricultural production for the foreseeable future.

Water and soils

Ninety percent of the soils in sub-Saharan Africa are geologically old and nutrient-poor.[m] Nutrient depletion continues as farmers remove more nutrients from the soil than they add. For example, one study estimated during the period 2002–4, 85 percent of African farmland suffered a net annual loss of at least 30 kg of nutrients such as nitrogen, phosphorus, and potassium (NPK) per hectare.[n] In eastern and southern Africa, more than 95 percent of the food-producing sector is based on rainfed agriculture,[o] and over most of the continent, high rainfall variability poses practical challenges to farming. Rainfall can occur in distinct seasons, much in brief periods with high intensity and high rates of runoff, and farmers must contend with periodic droughts.[p]

These physical factors, along with much neglect of agriculture in postcolonial decades,[q] have contributed to low yields. For example, the region had cereal yields of 1.5 metric tons per hectare in 2011—roughly half the world average.[r] Until around 2006, the region had experienced no growth in yields of most staple crops for decades.

The soil and water challenges make it difficult for Africa to close its food gap and leverage agriculture for economic growth. Moreover, these challenges increase the difficulty of successful intensification of agriculture on existing farmland and grazing land, which puts pressure to clear more natural forests and savannas to gain new agricultural land.

Climate

Although different climate models project different changes in rainfall patterns, there is general agreement that climate change poses high risks to much of the continent, from both rising temperatures and increased rainfall variability. (We discuss these challenges more in Chapter 15 on adapting to climate change.) The growing season is often short, and a relatively small percentage of rainfall is actually used by growing crops. Climate change will only increase this challenge, as sub-Saharan Africa is expected to experience higher levels of water stress than today under most climate change scenarios.[s]

Notes:

a. FAO, IFAD, UNICEF, et al. (2017).
b. Authors' calculations from FAO, IFAD, UNICEF, et al. (2017) and UNDESA (2017).
c. The precise figures, measured by weight, were 24.5 percent of cereals, 65.7 percent of vegetable oils, and 13.7 percent of animal products. Authors' calculations based on FAO (2019a).
d. Authors' calculations from GlobAgri-WRR model, using the measure of food availability. These food calories consist of the food people actually eat, both crops eaten directly and animal products. Crop calories exclude animal products but include feed. Growth of food demand in sub-Saharan Africa is a larger percentage of the world's increase in food consumption because FAO projects that the region will consume only modest amounts of crops as animal feed.
e. GlobAgri-WRR model, using data from Alexandratos and Bruinsma (2012), with upward adjustments for more up-to-date population projections and elimination of hunger.
f. Authors' calculations based on average cereal yields of 1.2 metric tons per hectare in 2010 and yields of 3.8 metric tons needed in 2050 to avoid land-use change while meeting cereal demand. Demand calculations are based on the assumption that the proportion of imports and exports of food and feed does not change. These increases are independent of any other increases in cropland area that might occur because of investments focused on agricultural exports.
g. Authors' calculations from FAO (2019a).
h. GlobAgri-WRR model.
i. GlobAgri-WRR model.
j. GlobAgri-WRR model.
k. World Bank (2017d).
l. IFAD (2010).
m. Breman et al. (2007).
n. Henao and Baanante (2006), as cited in Noble (2012).
o. Rockström and Falkenmark (2000).
p. Rockström et al. (2003).
q. World Bank (2008).
r. Authors' calculations from FAO (2019a).
s. Gassert et al. (2015).

CHAPTER 3

ADDITIONAL SUSTAINABILITY CRITERIA

Although this report presents a menu of solutions that could help close the food, land, and GHG mitigation gaps, even closing these three gaps will not fully achieve a sustainable food future. Each menu item must also contribute to—or at least be compatible with—three other important criteria.

Promoting Economic Development and Alleviating Poverty

Agriculture's potential to reduce poverty is primarily related to making food affordable. The world's poor spend on average more than half of their incomes on food.[75] In South Asia and sub-Saharan Africa, food accounts for 40–70 percent of household spending. Even in rural areas, a majority of the poor are net purchasers of food.[76] Food prices therefore remain a critical variable—influencing not only how many people are in formal poverty but also the depths of their deprivation.[77] According to numerous studies, lower food prices account for much of the economic benefit from agricultural development to Asian and Latin American economies in general, and to the poor in particular. One study of the Green Revolution found that without improved crop yields, the proportion of malnourished children would have been 6 to 8 percent higher because of higher food prices, and overall calorie intake in the developing world have been roughly 14 percent lower.[78]

From 1962 through 2006, as poverty rates declined, food prices declined on average by 4 percent per year, which played a significant role in decreasing the number of the world's hungry.[79] This relatively consistent decline in food prices fostered a global complacency, which three successive global food crises interrupted in 2007–8, 2010–11, and 2012—especially in 2008, when global cereal prices doubled in just a few months.[80] During these periods, hardship led to major food riots.[81]

The future of global food prices is uncertain. A detailed comparison of 10 major long-term global economic model groups that forecast out to 2050 showed six projecting sustained food price increases of various magnitudes, one showing essentially no change in real terms, and three showing sustained price declines.[82] Regardless, studies typically find that productivity gains can greatly reduce food prices and the number of malnourished children.[83]

Overall, the most basic need is to meet growing demand for food for the simple reason that when food runs short, the world's wealthiest are affected marginally but continue to eat, while the poor become poorer and eat fewer and lower-quality nutrients. Extensive economic literature has found that stable or declining food prices also play a valuable role in the macroeconomics of developing countries both because they account for such a large share of the economy and consumer expenditures, and because they help household incomes go farther.[84]

A second role of agriculture is to support economic development through its direct contribution to national income. According to World Bank estimates, in 2016, value added by agriculture on the farm still accounted for 30 percent of gross domestic product (GDP) in the world's low-income countries, many of them in Africa, and 9 percent of GDP in the middle-income countries, mostly in Latin America and East Asia.[85] An important contribution to China's industrial-based economic boom over the past several decades was a boost in crop yields spurred by major institutional changes in rural governance and massive agricultural research investments in the 1970s and 1980s to adapt Green Revolution food production technologies to Chinese conditions.[86] Along with other drivers, the expansion of food production and domestic food sales permitted a large migration of people to the cities without a decline in overall food production, and higher agricultural profits that were subsequently invested by industry.[87]

A third role for agriculture is to help lift people out of poverty through employment. At least 70 percent of the world's poorest people live in rural areas, mostly in the tropics.[88] In sub-Saharan Africa (outside of South Africa), 47 percent of people lived on less than $1.25 a day in 2011.[89] Agriculture serves as a source of livelihood for well over 80 percent of these and other rural people. It provides at least part-time jobs for 1.3 billion smallholder farmers and landless laborers. In much of Africa, large parts of South Asia, and significant pockets elsewhere, smallholder farmers living at the economic margin comprise most of the population.

As economies develop and agricultural productivity increases, more of the poor prefer to look for job opportunities in cities, and the number of farm workers can decline. This migration has happened on a huge scale in China and can be observed in other Asian countries where rural populations have recently begun to decline. In the past two decades, this pattern has become apparent in Africa as well; the share of farm employment is declining across the continent, and in several countries—including Ghana, Tanzania, and Zambia—the share of medium-scale farms is on the rise.[90] Boosting the productivity and income opportunities of small farms is an important part of ensuring that this transition is humane.

Empowering Women Farmers

Around the world, women play a crucial role in household food security. Women represent an estimated 43 percent of the world's agricultural labor force, and half or more in many African and Asian countries.[91] However, on average, farms operated by women have lower yields than those operated by men, even when men and women come from the same household and cultivate the same crops. For example, the World Bank found that in parts of Burkina Faso women had an 18 percent lower crop yield than their male counterparts in the same household.[92]

Inequitable access to inputs and property explains much of this gap. Women typically have less access than men to fertilizer, to improved seeds, to technical assistance, and to market information. They have less ability to command labor, both from unremunerated family members and from other members of the community.[93] In some developing countries, women also may have lower levels of education, constraints on mobility, and high additional time commitments for child-rearing, gathering firewood and water, and cooking.[94]

Women farmers often have reduced property rights, which reinforces their limited access to inputs and credit because credit often requires collateral such as land. Women control very little land relative to their participation in agriculture. In Kenya, for example, women account for only 5 percent of the nation's registered landholders.[95]

Studies project that rectifying these imbalances can increase yields. For example, the World Bank has estimated that if women farmers were to have the same access as men to fertilizers and other inputs, maize yields would increase by 11–16 percent in Malawi, by 17 percent in Ghana,[96] and by 20 percent in Kenya.[97] Overall, ensuring women's equal access to productive resources could raise total agricultural output in developing countries by 2.5 to 4 percent.[98]

These gains in turn could have disproportionate benefits for food security because women are more likely than men to devote their income to food and children's needs.[99] IFPRI estimates that improvements in women's status explain as much as 55 percent of the reduction in hunger in the developing world from 1970 to 1995. Progress in women's education can explain 43 percent of gains in food security, 26 percent of gains in increased food availability, and 19 percent of gains in health advances.[100] In the same vein, FAO estimates that providing women with equal access to resources could reduce world hunger by 12–17 percent.[101]

Empowering women can both help boost production of crops and livestock and sustainably reduce demand, for example, by achieving replacement fertility rates. Empowering women is therefore not a single solution but rather a strategy that cuts across multiple menu items. We adopt a criterion that all menu items should either contribute to or at least not undermine this strategy.

Protecting Freshwater Resources

Although croplands that rely solely on rain account for 80 percent of cultivated land, the 20 percent of land that is irrigated probably accounts for 40 percent of global crop production, estimated very roughly.[102] In emerging and developing countries, irrigated agriculture plays an even more prominent role, accounting for nearly half of all crop production and nearly 60 percent of cereal production according to FAO.[103] Globally, irrigated crop yields are more than two-and-a-half times greater than those of rainfed agriculture.[104] A major driver of yield growth from 1962 and 2006 was an increase of 160 Mha in irrigated area[105] and an estimated doubling of water consumption by irrigation.[106]

This experience might suggest a strategy of expanding irrigation wherever feasible both to increase production and provide greater resilience for farmers. But the world's freshwater supplies are already greatly stressed, and agriculture is the principal reason. Globally, irrigation accounts for nearly 70 percent of total freshwater withdrawals[107] from rivers, lakes, and aquifers. Domestic and industrial users account for the remaining 30 percent. However, the agriculture sector accounts for more than 90 percent of water consumed.[108] This is because much of the water withdrawn for agriculture ends up in the atmosphere as a result of evaporation and plant transpiration.[109] By contrast, much of the water used by industry and households is returned to terrestrial water systems and may be reused.

Agriculture will increasingly compete with rising demands from these other water uses. Urban expansion has led to conflicts between urban and agricultural uses in the western United States. As populations expand and become more able to afford modern plumbing amenities, conflicts are likely to increase. In 2015, the World Economic Forum listed water disputes between both different users and different countries as the number one global risk over the coming decade.[110]

In many of the world's major agricultural areas, there is little additional water to provide. Roughly 60 percent of global irrigation comes from surface waters,[111] and this irrigation has already dewatered not only many small, local rivers but even some of the world's most massive rivers.[112] The other 40 percent of irrigation is supplied by groundwater, withdrawals of which have at least tripled over the past 50 years and continue to increase.[113] Aquifers are being depleted in key agricultural areas. According to one index of water availability calculated by WRI, more than half of the world's irrigated croplands are already in areas of high water stress.[114]

Increasing irrigation levels would also exacerbate serious environmental harms to aquatic life, wetland ecosystems, river deltas,[115] and even the global climate.[116] Fish die or move elsewhere when sections of rivers run dry, but even reduced water flows tend to raise water temperatures and deny access to much river habitat, reducing aquatic life.[117] Irrigation, whether from rivers or groundwater, often dries up wetlands.[118] The dams that create irrigation reservoirs also tend to block fish migrations, change water temperatures, and block sediment and fresh water from replenishing river deltas.[119] One recent study estimated that the world's reservoirs are responsible for between 1 and 2.4 percent of the global GHG emissions each year, mostly through the methane created by the decay of trees and other inundated vegetation.[120] Large irrigation demands, and dams in particular, cut off the regular overflow of rivers into floodplains, which typically provide critical habitat for fish to spawn and grow. Floodplains provide much of the food supply for the main stem of rivers and nourish trees, wetlands, and other vegetation critical to birds and other animal life.[121] Not surprisingly, irrigation projects, associated dam building, and water withdrawals for irrigation have shaped some of the world's most acute social and environmental conflicts.[122]

The global water challenge is complex and large scale, and an entire report could appropriately focus on it. Shrinking aquifers and overdrawn rivers present major challenges to agriculture at existing irrigation levels. Higher yields will increase pressure on freshwater resources as crops use and transpire more water. Left unchecked, pollution from agriculture and other sectors will further degrade water quality, increasing the competition for clean fresh water.[123] Moreover, climate change will place additional pressure on fresh water through changes in precipitation patterns and because hotter temperatures lead to more evaporation and transpiration.[124]

Accounting for these various limitations, FAO projects that irrigation will expand by only 20 Mha from 2006 through 2050—around 1 percent of global cropland.[125] By adopting FAO's yield projections, we implicitly accept this level of expansion. Yet given the scope and complexity of the water challenge, we exclude large-scale expansion of irrigation from our menu for a sustainable food future and identify wherever possible agricultural improvements that can conserve or make more efficient use of water.

CHAPTER 4

MENU FOR A SUSTAINABLE FOOD FUTURE

To explore how to close the three gaps while meeting our additional sustainability criteria, this report develops a "menu for a sustainable food future"—a menu of actions that can meet the challenge if implemented in time, at scale, and with sufficient public and private sector dedication.

We analyze the potential of 22 menu items to sustainably close the food, land, and GHG mitigation gaps by 2050 (Table 4-1). They are organized into five "courses":

1. Reduce growth in demand for food and other agricultural products
2. Increase food production without expanding agricultural land
3. Protect and restore natural ecosystems and limit agricultural land-shifting
4. Increase fish supply
5. Reduce GHG emissions from agricultural production

The report addresses each of the five courses in turn. Because many policies to advance the menu cut across the different courses, policy issues are addressed separately in "Cross-Cutting Policies for a Sustainable Food Future."

The menu items focus on an overall goal of achieving a sustainable level of food supply to meet food demands in 2050. Although expansive, the menu does not directly address all dimensions of food security, whose universal achievement also requires additional measures to reduce poverty and improve access to food (Box 4-1).

Table 4-1 | Menu for a sustainable food future: five courses

MENU ITEM	DESCRIPTION
DEMAND-SIDE SOLUTIONS	
Course 1: Reduce growth in demand for food and other agricultural products	
Reduce food loss and waste	Reduce the loss and waste of food intended for human consumption between the farm and the fork.
Shift to healthier and more sustainable diets	Change diets particularly by reducing ruminant meat consumption to reduce the three gaps in ways that contribute to better nutrition.
Avoid competition from bioenergy for food crops and land	Avoid the diversion of both edible crops and land into bioenergy production.
Achieve replacement-level fertility rates	Encourage voluntary reductions in fertility levels by educating girls, reducing child mortality, and providing access to reproductive health services.
SUPPLY-SIDE SOLUTIONS	
Course 2: Increase food production without expanding agricultural land	
Increase livestock and pasture productivity	Increase yields of meat and milk per hectare and per animal through improved feed quality, grazing management, and related practices.
Improve crop breeding to boost yields	Accelerate crop yield improvements through improved breeding.
Improve soil and water management	Boost yields on drylands through improved soil and water management practices such as agroforestry and water harvesting.
Plant existing cropland more frequently	Boost crop production by getting more than one crop harvest per year from existing croplands or by leaving cropland fallow less often where conditions are suitable.
Adapt to climate change	Employ all menu items and additional targeted interventions to avoid adverse effects of climate change on crop yields and farming viability.

Table 4-1 | Menu for a sustainable food future: five courses (continued)

MENU ITEM	DESCRIPTION
Course 3: Protect and restore natural ecosystems and limit agricultural land-shifting	
Link productivity gains with protection of natural ecosystems	Protect ecosystems by legally and programmatically linking productivity gains in agriculture to governance that avoids agricultural expansion.
Limit inevitable agricultural expansion to lands with low environmental opportunity costs	Where expansion seems inevitable—such as for local food production in Africa—limit expansion to lands with the lowest carbon and other environmental costs per ton of crop.
Reforest abandoned, unproductive, and liberated agricultural lands	Protect the world's remaining native landscapes; reforest abandoned, unproductive, and unimprovable agricultural lands as well as lands potentially "liberated" by highly successful reductions in food demand or increases in agricultural productivity.
Conserve and restore peatlands	Avoid any further conversion of peatlands to agriculture and restore little-used, drained peatlands by rewetting them.
Course 4: Increase fish supply	
Improve wild fisheries management	Stabilize the annual size of the wild fish catch over the long term by reducing overfishing.
Improve productivity and environmental performance of aquaculture	Increase aquaculture production through improvements in breeding, feeds, health care, disease control, and changes in production systems.
Course 5: Reduce GHG emissions from agricultural production	
Reduce enteric fermentation through new technologies	Develop and deploy feed additives to reduce methane releases from ruminant animals.
Reduce emissions through improved manure management	Use and advance different technologies to reduce emissions from the management of manure in concentrated animal production systems.
Reduce emissions from manure left on pasture	Develop and deploy nitrification inhibitors (spread on pastures and/or fed to animals) and/or breed biological nitrogen inhibition traits into pasture grasses.
Reduce emissions from fertilizers by increasing nitrogen use efficiency	Reduce overapplication of fertilizer and increase plant absorption of fertilizer through management changes and changes in fertilizer compounds, or breeding biological nitrification inhibition into crops.
Adopt emissions-reducing rice management and varieties	Reduce methane emissions from rice paddies via variety selection and improved water and straw management.
Increase agricultural energy efficiency and shift to nonfossil energy sources	Reduce energy-generated emissions by increasing efficiency measures and shifting energy sources to solar and wind.
Focus on realistic options to sequester carbon in agricultural soils	Concentrate efforts to sequester carbon in agricultural soils on practices that have the primary benefit of higher crop and/or pasture productivity and do not sacrifice carbon storage elsewhere.

BOX 4-1 | Food security and sustainability

According to FAO, "Food security exists when all people, at all times, have physical and economic access to sufficient, safe, and nutritious food to meet their dietary needs and food preferences for an active and healthy life."[a] The Committee on World Food Security identified four main "pillars of food security":[b]

- **Availability** is ensured if adequate amounts of food are produced and are at people's disposal.
- **Access** is ensured when all households and all individuals within those households have sufficient resources to obtain appropriate foods for a nutritious diet (through production, purchase, or donation).
- **Utilization** is ensured when the human body is able to ingest and metabolize food because of adequate health and social environment.
- **Stability** is ensured when the three other pillars are maintained over time.

Some experts have argued for a fifth pillar on environmental sustainability, which is ensured only if food production and consumption patterns do not deplete natural resources or the ability of the agricultural system to provide sufficient food for future generations.[c]

The sustainability dimension is a frequently overlooked but important pillar because food availability depends on the state of the environment and the natural resource base. The current global food production system—what is grown where, how, and when—has evolved within a climate that has been relatively stable over the past 8,000–10,000 years. Production of rainfed and irrigated crops depends on the supply of fresh water at appropriate levels at the appropriate time during the growing season. Natural ecosystems located in or around farmland underpin agricultural productivity by providing soil formation, erosion control, nutrient cycling, pollination, wild foods, and regulation of the timing and flow of water.[d]

In turn, access relates to availability because access depends on the cost of food both on average and in times of poor production. In regions with many poor people, food price increases can present acute issues of food security. In addition, if food production is not sustainable from an environmental perspective, then it will not be stable over time.

This report focuses on the interplay of food availability and sustainability. Both touch on the pillars of stability and access by influencing prices. Although assuring availability and sustainability is critical to food security, we do not address all issues related to income, distribution, nutrient balance, and disaster interventions.

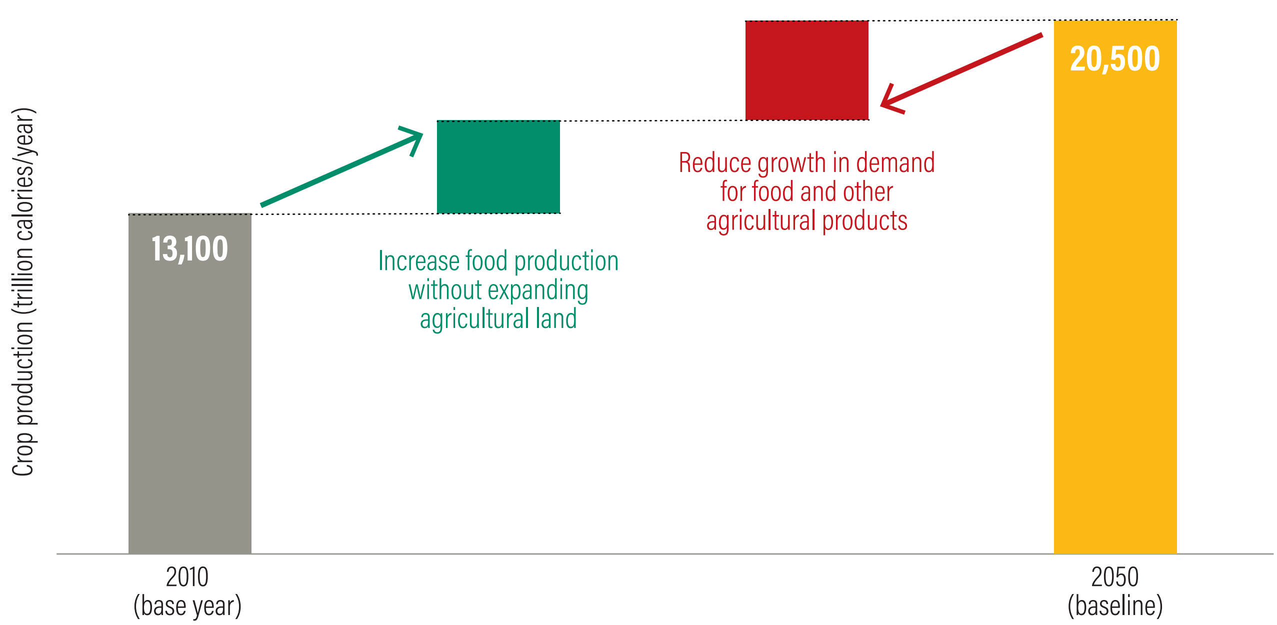
Notes:
a. FAO (2006a).
b. The following definitions are paraphrased from Gross et al. (2000).
c. Richardson (2010); Daily et al. (1998).
d. Millennium Ecosystem Assessment (2005).

In evaluating each menu item, our approach differs from an economic modeling approach, which is commonly employed to estimate mitigation costs, but which we believe often conveys a false sense of both precision and confidence. A broad range of changes in production and yields have effects on emissions, and researchers have too little real knowledge of the broad range of costs across vast agricultural areas even today to inspire much confidence in estimates of current mitigation costs, let alone to make confident projections about those costs in the future. Economic models also cannot focus on the potential of promising measures and potential innovations that are critical to a sustainable food future but that are still too uncertain to model. But we do not ignore economics. Instead, we use available information to evaluate menu items for their potential to provide economically desirable solutions.

We also wish to do more than simply compile a broad list of options. We therefore carefully review the available quantitative and qualitative information and identify the most promising and yet realistic paths forward. We then use the GlobAgri-WRR model to evaluate the potential of different measures or levels of achievement to close the overall food, land, and GHG mitigation gaps. As conceptually illustrated in Figures 4-1, 4-2, and 4-3, each course and its component menu items serve as a “step” toward closing the gaps.

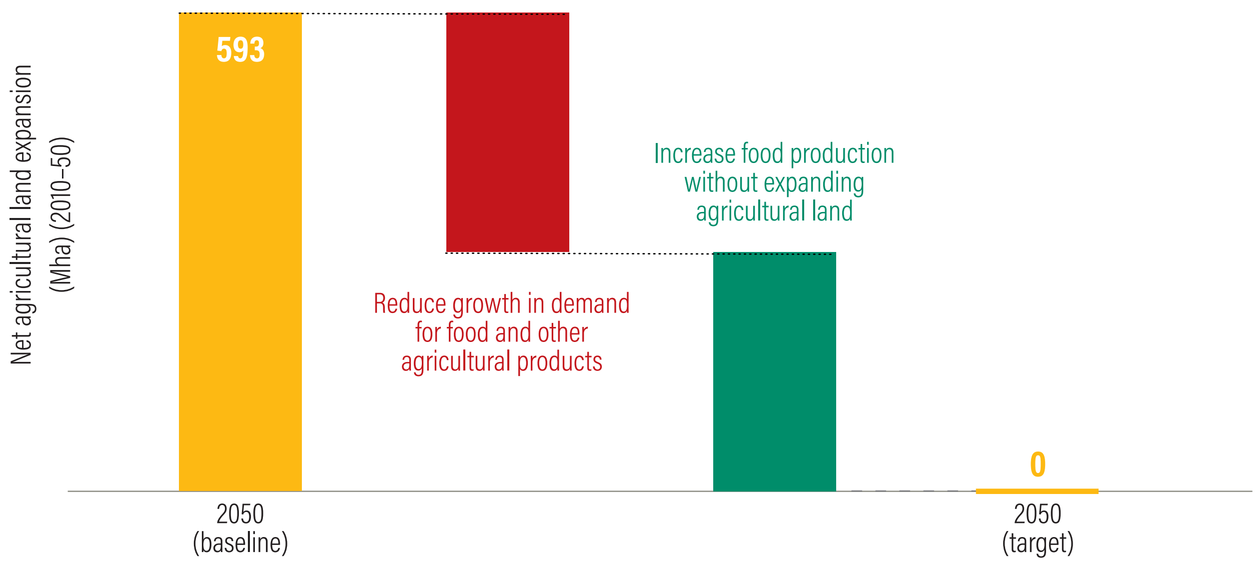
For each menu item, we also offer policy recommendations for moving forward. Policy recommendations can be broad or detailed. Our standard is one of “usefulness.” Where issues remain controversial, even broad recommendations can be useful, but we try to make detailed recommendations wherever feasible to identify immediate steps forward.

Figure 4-1 | Can a menu of solutions sustainably close the food gap?



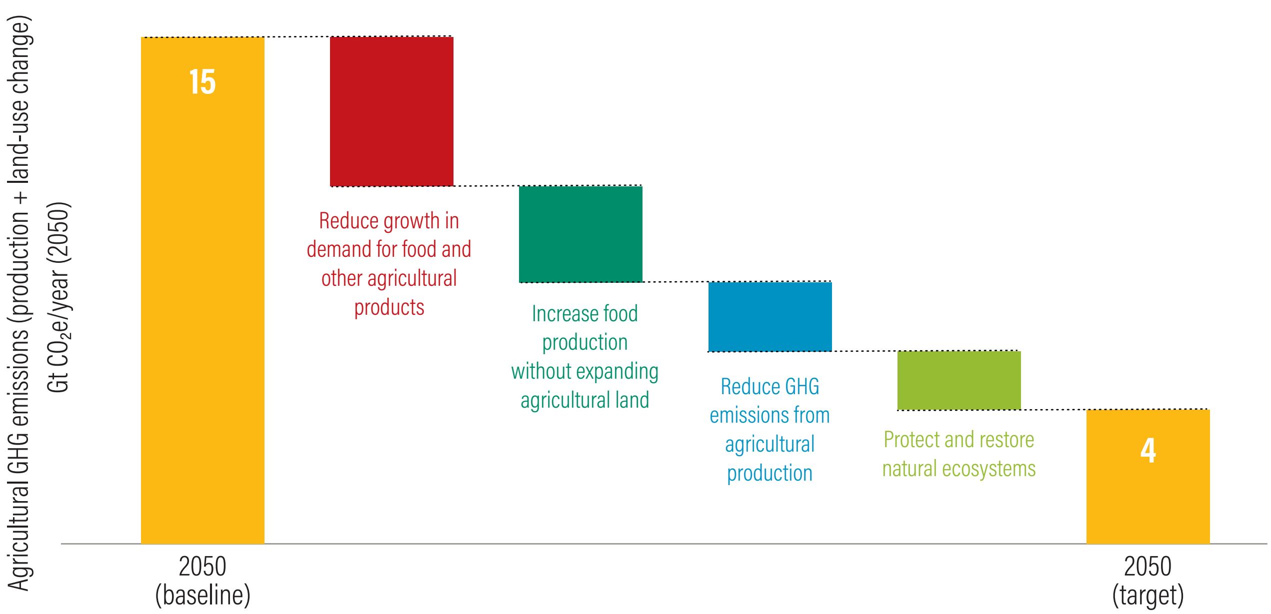
Note: Includes all crops intended for direct human consumption, animal feed, industrial uses, seeds, and biofuels. Bar sizes to close gap are illustrative only.
Source: GlobAgri-WRR model.

Figure 4-2 | Can a menu of solutions close the agricultural land gap?



Note: Bar sizes to close gap are illustrative only.
Source: GlobAgri-WRR model.

Figure 4-3 | Can a menu of solutions close the agricultural GHG mitigation gap?



Note: Bar sizes to close gap are illustrative only.
Source: GlobAgri-WRR model.

Combining Menu Items for a Sustainable Food Future

Our analysis of individual menu items in Courses 1–5 estimates how much each item could help the world close the three gaps and meet targets to increase food production, minimize expansion of agricultural land area, and reduce GHG emissions. In the penultimate section of this report, "The Complete Menu: Creating a Sustainable Food Future," we use the GlobAgri-WRR model to aggregate menu items into three plausible (or at least possible) combined scenarios. Each combined scenario represents a different level of ambition in terms of the political will, technological developments, and financial resources that will need to be applied to achieve a sustainable food future.

The "Coordinated Effort" scenario represents the lowest level of ambition—but it still involves a dramatic increase in global effort. Success depends more on strong, coordinated, global commitment to actions that are already well understood, rather than significant advances in technology. The "Highly Ambitious" scenario, as its name suggests, represents a greater level of effort. It incorporates all the efforts of the Coordinated Effort scenario but pushes further in terms of implementing improved technologies, even where they involve higher costs or appear somewhat impractical today. The "Breakthrough Technologies" scenario combines the efforts of the previous two scenarios but builds in levels of achievement that could be realized only with innovations that dramatically improve the performance and/or costs of technologies. The scenario includes only technologies where there are genuine grounds for optimism in that the science is demonstrating progress.

We refer to these combined scenarios throughout the report in our discussions of the potential of various menu items.

ENDNOTES

1. UNDESA (2017). The figure of 9.8 billion people in 2050 reflects the "medium fertility variant" or medium population growth scenario (as opposed to the low-growth and high-growth scenarios published by the United Nations Department of Economic and Social Affairs).
2. "Middle class" is defined by the Organisation for Economic Co-operation and Development (OECD) as having per capita income of $3,650 to $36,500 per year or $10 to $100 per day in purchasing power parity terms. "Middle-class" data from Kharas (2010).
3. Foresight (2011a).
4. FAO, IFAD, UNICEF, et al. (2018).
5. FAO, WFP, and IFAD (2012).
6. Authors' calculations from GlobAgri-WRR model and Alexandratos and Bruinsma (2012).
7. IFAD (2010). In 2010, about 1 billion of the 1.4 billion people living on less than $1.25 per day lived in rural areas. A more recent analysis by Castañeda et al. (2016) estimated that in 2013, about 80% of people living on less than $1.90 per day in developing countries lived in rural areas.
8. World Bank (2008).
9. World Bank (2018). The World Bank number is based on agriculture, forestry, and fishing value added.
10. World Bank (2012a).
11. SOFA Team and Doss (2011).
12. FAO (2011a).
13. Millennium Ecosystem Assessment (2005).
14. Figures exclude Antarctica. FAO (2011b).
15. Foley et al. (2011).
16. Millennium Ecosystem Assessment (2005). In this report, we treat the negative impacts on ecosystems to imply a negative impact on biodiversity as well.
17. This estimate is based on the GlobAgri-WRR model. Previous analyses in this series used a figure of 13% for agricultural production using an analysis based on UNEP (2012); FAO (2012a); EIA (2012); IEA (2012); and Houghton (2008) with adjustments. This figure excludes downstream emissions from the food system in processing, retailing, and cooking, which are overwhelmingly from energy use, and which must be addressed primarily by a broader transformation of the energy sector.
18. The variability is high, and there are even differences from meta-analyses, but a summary of recent evidence confirming that this estimate is still the most reasonable is included in the supplement to Searchinger et al. (2018a).
19. Houghton (2008); Malhi et al. (2002).
20. This figure is based on an estimate of 5 Gt of CO_2e emissions per year from land-use change in recent years. It attempts to count carbon losses from the conversion of other lands to agriculture, or conversion of grasslands to cropland, the carbon gains from reversion of agricultural land to forest or other uses, and the ongoing losses of carbon due to degradation of peat. Because it is impossible to estimate land-use-change emissions with data from a single year, we do not choose to pinpoint a specific year for these emissions but instead treat them as a typical rate from recent years. In reality, it is not possible to generate a precise estimate of these numbers because it is not possible to track each hectare of land globally and its carbon changes from year to year. There is a large difference between gross and net losses, and assumptions must be made about rates of carbon gain and loss from land-use change. In addition, much of these data are based on national reporting of net changes in forest area, which therefore assume carbon losses only on the net difference in each country where it occurs and carbon gains from net gains in forest where that occurs. This calculation cannot capture the real net losses because the losses in areas losing forest are unlikely to be different (and are often higher) than the gains from regenerating forests.

    In earlier reports in this series, we estimated emissions from land-use change at 5.5 Gt CO_2e based on an average from other estimates found in UNEP (2012), FAO (2012a), and Houghton (2008). These estimates included losses from 2000 to 2005, in which FAO's Forest Resources Assessment (FRA) estimated heavy declines in forest. Several more recent papers have reduced estimates of deforestation and therefore emissions. Smith et al. (2014) estimates 3.2 Gt CO_2e/yr in 2001–10 including deforestation (3.8 Gt CO_2e/yr), forest degradation and forest management (-1.8 Gt CO_2e/yr), biomass fires including peatland fires (0.3 Gt CO_2e/yr), and drained peatlands (0.9 Gt CO_2e/yr). Another paper estimates 3.3 Gt of CO_2 equivalent from land-use change in 2011 but does not include drained peatland (Le Quéré et al. 2012). Federici et al. (2015), which based its estimates on FAO's 2015 FRA, estimated emissions from net deforestation at 2.904 Gt CO_2e/year from 2011 to 2015 but also suggested that this figure was likely 30% too low due to failure to count carbon in some forest pools, which would increase the figure to 3.78 Gt/year. FAO also estimated peatland emissions separately of 0.9 Gt CO_2eq/year to the IPCC, leading to a recent FAO estimate of 4.7 Gt/year (Federici et al. [2015]). Our peatland emissions estimate of 1.1 Gt CO_2e/year includes fire and is further explained in Chapter 20. Federici et al. (2015) also reported a large increase in "forest degradation," which is due principally to logging and other nonagricultural activities, and which we do not discuss here.

21. Using the FRA, Federici et al. (2015) estimated gross land conversion to be more than 1 Gt of CO_2 higher than the net conversion, but this definition of gross represented only the "net" conversion in countries that had net deforestation. In other words, it excluded countries that had net gains in forest, but if a country lost 1 million hectares of forest while 500,000 hectares reforested, this method counts only the 500,000 hectares lost in that country as a "gross" loss. As we discuss elsewhere in this report, there are large shifts in locations of agricultural land within countries, which suggests much higher carbon losses on a gross basis. Seymour and Busch (2016) reviewed a series of studies estimating gross pan-tropical land use-change emissions during the 2000s and found a median estimate of 5 Gt CO_2e/year with a high estimate of 10 Gt CO_2e/year.

22. Foley et al. (2005).

23. Selman and Greenhalgh (2009).

24. Porter et al. (2014). See discussion in Chapter 13 on adaptation.

25. The Green Revolution was a concerted, multidecade effort to modernize farming in the developing world. High-yield varieties of rice, wheat, and maize were developed and widely distributed, and the use of agricultural inputs (e.g., irrigation water, fertilizers) sharply increased. Across Asia, for instance, average rice yields nearly doubled, and wheat yields nearly tripled (Conway 2016).

26. Alexandratos and Bruinsma (2012); WWAP (2012).

27. Delgado et al. (1999).

28. Alexandratos and Bruinsma (2012), Table 4.8. FAO data estimate an increase in arable land in use of 220 million hectares from 1962 to 2006. According to FAO (2019a), pasture area has increased by 270 million hectares since 1962.

29. FAO, IFAD, UNICEF, et al. (2018).

30. Alexandratos and Bruinsma (2012).

31. We adjusted diets to assure food availability of 3,000 kcal per person per day in sub-Saharan Africa and South Asia by proportionately scaling up all food items in the FAO 2050 projections until this level of calories would be available. Food availability defines food available to consumers but excludes postconsumer waste. The total quantity of calories available must be adequate to feed all individuals after accounting first for this food waste and second for the unequal distribution of food, which means that many individuals will consume less than the regional average. We based the 3,000 kcal/person/day on a recognition that once regions obtain this level of food availability, they have low levels of food insecurity.

32. UNDESA (2017).

33. Biofuels contributed 2.5% of world transportation energy in 2010. EIA (2013). For this comparison with FAO projections, we used data provided by FAO for the crops used for biofuels in 2050 and back-calculated the quantity of ethanol and biodiesel.

34. There is no one perfect measure of the production increase challenge. This figure does include the rise in crops fed to livestock measured in calories, rather than the calories in the livestock products themselves. Doing so recognizes that animal products only return a small percentage of the calories in crops fed to them. However, this calculation does not reflect the additional calories from grasses that livestock also consume to provide people with milk and meat. The number reported in the text has the advantage of fully estimating the total increase in crop production, including that for feed and biofuels. But it leaves out the increase in pasture and other feeds that must be generated to produce the additional animal products.

    Careful readers of this series of reports will also notice that we earlier expressed the crop gap as 6,500 trillion kcal between 2006 and 2050 (Searchinger, Hanson, Ranganathan, et al. 2013) rather than 7,400 trillion kcal between 2010 and 2050. The reason for the larger gap in the current report is that GlobAgri-WRR counts calories in a ton of many crops differently and higher than those used for primary crops in Alexandratos and Bruinsma (2012), which did not include many crop calories that go into certain separate products. Those products include the bran in cereals and surprisingly the protein cakes from oilseeds. One advantage of GlobAgri-WRR is its careful mapping of all eventual food and feed outputs to primary crops. However, this adjustment affects estimates both in 2010 and 2050. On a percentage basis, the earlier gap estimates are close to those estimated by GlobAgri-WRR after adjustment for further updates to population growth and the change in the base year from 2006 to 2010, so that our gap now covers 40 years rather than 44.

35. Authors' calculations from GlobAgri-WRR model and Alexandratos and Bruinsma (2012).

36. See, e.g., Holt-Gimenez (2012); Bittman (2013); and Berners-Lee et al. (2018).

37. FAO, IFAD, UNICEF, et al. (2018); Ng, Fleming, et al. (2014). The World Health Organization (WHO) defines "overweight" as having a body mass index (BMI) greater than or equal to 25 and "obese" as having a BMI greater than or equal to 30. BMI is an index of weight-for-height that is commonly used to classify overweight and obesity in adults. It is defined as a person's weight in kilograms divided by the square of his height in meters (kg/m^2) (WHO 2012).

38. See Chapter 6 for discussion of the relative resource use requirements for different foods.

39. In this report, we use the term "per capita [calorie or protein] availability" to mean the quantity of food reaching the consumer, as defined in the FAO Food Balance Sheets (FAO 2019a). We use the term "per capita consumption" to mean the quantity of food actually consumed, when accounting for food waste at the consumption stage of the value chain. "Consumption" quantities (which exclude all food loss and waste) are therefore lower than "availability" quantities. Data on "per capita consumption" are from the GlobAgri-WRR model, using source data from FAO (2019a) on "per capita availability" and FAO (2011c) on food loss and waste.

    In 2010, global average daily calorie consumption from both plant- and animal-based foods was 2,487 kcal/person. Multiplying this figure by the 2010 global population of 6,958,126,000 yields a total daily global calorie availability of 17,304,859,362,000 kcal. Spreading this amount of calories evenly among the projected 2050 global population of 9,771,589,000 people results in a daily calorie consumption of 1,771 kcal/person. For daily calorie availability, which was 2,871 kcal/person in 2010, the same calculation yields 2,044 kcal/person available in 2050. As a point of comparison, FAO's suggested average daily energy requirement (ADER)—the recommended amount of caloric consumption for a healthy person weighted globally by age and gender—for the world in 2010–12 was 2,353 kcal/person/day (FAO 2014a).

40. Figure 2-1 implies a global average of 13.3% of "available" food (measured in calories) wasted at the consumption stage of the food supply chain. It is smaller than the global average of 24% of all food lost or wasted across the food supply chain that is quoted in Chapter 5 (authors' calculations from FAO 2011c).

41. The evidence for this out-competition comes from measurements of "elasticities" of demand for food, which are much higher for people in poorer countries than in wealthier countries (Regmi and Meade [2013]).

42. Kolbert (2014).

43. Sala et al. (2000).

44. Shackelford et al. (2014).

45. Chaplin-Kramer et al. (2015).

46. These assumptions are reflected in Alexandratos and Bruinsma (2012).

47. "Rate" refers to linear not compound growth rates; that is, an additional number of kilograms per hectare per year, because that is the historical pattern of yield growth as discussed elsewhere in this report. This projection is not obvious, however, because FAO projects that yields of cereals, which receive most attention, will grow at only 57% of their historical rates, and soybeans at 88%. But FAO projects that yields of most other major crops will grow much faster than their historical rates, including pulses (dry beans and lentils) (397%), potatoes (200%), cassava (209%), and sugarcane (192%). Using the method described below, the higher and lower growth rates of different crops roughly balance out future projections from the past.

    There is no perfect way to calculate an average growth rate of different crops. For example, calculating the total growth of all crops by weight would be misleading because it would greatly overvalue growth rates for high-yielding crops and undervalue the importance of growth rates for lower-yielding crops. "Effective yields" also depend not merely on how much yields grow but also on how much increase there is in "cropping intensity," the ratio of crops harvested each year to the quantity of cropland. To determine an overall growth rate relative to the past, we instead do a calculation that compares future crop area using FAO projected yields and future crop area if yields of each crop grew at their prior (linear) rates. This method not only averages out the effects of different crops but weights each crop by both its yield and its level of demand in 2050.

    We do these calculations in two ways. If we use one global growth rate for each crop from 1961 to 2010 to project the trend line, 20% less cropland would be required in 2050 according to FAO, which means by this method that FAO is projecting 20% lower growth in yields than historical trends. But if we use historical, regional growth rates for each crop to project trend lines, roughly 20% more cropland would be required, which means that FAO projected yields in 2050 are 20% greater than historical trends would suggest. In both cases, we use FAO projected increases in cropping intensity. As there is no obvious reason to use one growth rate rather than another, we think it is appropriate to treat FAO projected growth in yields as roughly matching historical rates.

    In the Interim Findings, we did the same kind of analysis using FAO's projection of total crop production in 2050 from Alexandratos and Bruinsma (2012), rather than our modeled estimates of crop production using FAO projected yields, and we came to the same conclusion.

48. We use the same method to calculate an average rate of yield growth across multiple crops as described in note 47.

49. Alexandratos and Bruinsma (2012). Globally, cropping intensity is below 100% (i.e., there is more cultivated area than harvested area). Cropping intensity can exceed 100% in areas where more than one crop cycle occurs on a given cultivated area, as in India.

50. Ray et al. (2013).

51. Ray et al. (2013) used local data to estimate rates of yield growth for five major crop categories. For the remainder, we calculated and used regional, linear rates of yield growth for each other major crop category from 1989 to 2008.

52. Estimates vary and appear to be based on the number of livestock that researchers assume must be present before they call an area a pasture. FAO data place cropland at 1,530 Mha in 2011, and permanent meadows and pastures at 3,374 Mha in 2011 (Alexandratos and Bruinsma 2012, 107). But estimates for permanent meadows and pastures can be as high as 4.7 billion hectares (Erb et al. 2007).

53. FAO (2019a).

54. By one estimate, cattle ranching accounted for 75% of the 74 Mha of deforestation in the Brazilian Amazon during the first decade of the 21st century (Barreto and Silva 2010). Aide et al. (2012) shows the pattern continuing across Latin America. See also Murgueitio et al. (2011).

55. GlobAgri-WRR model.

56. For beef and meat from sheep and goats, we project 20% increases between 2010 and 2050 in the efficiency of converting feed to food (i.e., the same quantity of feed produces 20% more meat), and 15% increases in efficiency for milk. We developed this projection first by using two different sets of estimates of the relationship between output per animal and feed per kilogram of milk or meat in contemporary livestock systems globally (data underlying Herrero et al. 2013; and Wirsenius et al. 2010). We also used FAOSTAT estimates of milk and meat production globally and numbers of livestock to establish a trend line of changes in output per animal. Putting the two together, we could translate the trend line of output per animal into a trend line of output per kilogram of feed. Although the two data sets yield different estimates from each other of milk and meat per kilogram of feed, they actually resulted in similar projections of changes in this ratio over time and therefore between 2010 and 2050. We also project a 23% increase in the quantity of forage consumed per hectare (measured in dry weight), which could result either from better production or better grazing methods.

    Finally, using GlobAgri-WRR, we project changes in the quantity of feeds other than grass-based forages. This change is implemented by the model to achieve the gains in feed efficiency (milk and meat output per kilogram of feed) using different production systems and possible, plausible improved production systems over time in each major livestock-producing country or region. We established a series of decision rules to guide which systems would be adopted.

    Ultimately, GlobAgri-WRR calculated increases in output per hectare, which reflect the global increases in feed efficiency, the increases in forage consumption per hectare of forage area (pasture), and the shift in the percentage of feeds other than forage.

57. Seto et al. (2012).

58. Seto et al. (2012).

59. See discussion in Chapter 16 on shifting agricultural lands.

60. GlobAgri-WRR's estimates of agricultural production emissions in 2050 employ a variety of calculations and assumptions based on our best estimates of trend factors wherever possible, which we describe more fully in Course 5. Some studies include emissions from regular human burning of savannas and grasslands, but we do not because these systems burn naturally on occasion and we consider any increase in emissions due to human efforts too uncertain. GlobAgri-WRR does, however, consider a smaller set of emissions from the burning of crop residues.

61. Authors' calculations from GlobAgri-WRR model (counting emissions outside North America, the European Union, and other OECD countries as "developing and emerging." Smith et al. (2007) and Popp et al. (2010) came to a similar conclusion but put the percentage of current emissions from developing and emerging economies at closer to 70%, rising above 80% by 2050.

62. GlobAgri-WRR model.

63. Recent crop yields are given in Ray et al. (2013). In our less optimistic baseline scenario, the growth in beef output per hectare between 2010 and 2050 falls from 64% (in our 2050 baseline) to 51%, and the growth in milk output per hectare falls from 59% (in our 2050 baseline) to 52%.

64. GlobAgri-WRR model.

65. The 2°C scenario roughly corresponds with the scenario RCP 2.6, which is the lowest climate change scenario analyzed by global modeling teams for the 2014 Intergovernmental Panel on Climate Change (IPCC) assessment. That ambitious scenario, which actually relies on negative emissions in the later part of the century, also assumes that emissions of carbon dioxide, nitrous oxide, and methane fall to roughly 21 Gt of CO_2 equivalent by 2050, which includes reductions of methane by roughly 50%. Authors' calculations come from data presented in van Vuuren (2011), Figure 6. UNEP (2013) puts the figure for stabilization at 22 Gt. Newer modeling has roughly the same levels as summarized in Sanderson et al. (2016) and UNEP (2017). In this modeling, the emissions target is that required to have a greater than two-thirds chance of holding temperatures to the 2° goal, reflecting the uncertainties of climate sensitivity to higher GHGs. There are scenarios presented in both papers, particularly UNEP (2017), that allow higher emissions in 2050, but they rely even more on negative emissions later in the century. As we consider any large negative emissions to be questionable at best, we focus only on the scenarios allowing emissions of 21–22 Gt CO_2e in 2050. This use of a single emissions target ignores many possible patterns of emissions that would each have the same emissions in 2050 based on 100-year global warming potential but which involve different levels of emissions between 2010 and 2050 that might involve different balances of gases (i.e., different shares of carbon dioxide, nitrous oxide, and methane). Under different variations of such scenarios, the emissions allowable in 2050 would vary greatly. This target for total emissions in 2050, then, merely provides a useful benchmark.

66. GlobAgri-WRR model.

67. For example, Meinshausen et al. (2009), estimated that cumulative emissions of carbon dioxide would need to be limited to 1,000 Gt between 2000 and 2050 to provide a 75% chance of holding warming to 2°C. As carbon dioxide emissions were roughly 330 Gt from 2000 to 2010, that leaves 670 Gt. For a 50% chance of holding climate to 2°C, this paper calculated the 2000–2050 CO_2 budget of 1,440, which leaves 1,310 from 2010 to 2050.

68. UNEP (2017); Figueres et al. (2017).

69. For example, in Wollenburg et al. (2016), the authors select agricultural mitigation targets for methane and nitrous oxide that are based on three models, each of which the paper indicates relies for its agricultural mitigation on agricultural mitigation analyses performed for the U.S. Environmental Protection Agency sometime between 2006 and 2008. Our report uses more recent data, explores a wider range of mitigation options than those EPA reports, and we believe does so at a far more sophisticated level.

70. Smith et al. (2016).

71. OECD (2011).

72. Going from a 2050 baseline of 85 Gt of total global emissions (15 Gt from agriculture and land-use change, and 70 Gt from other sources) to a target of 21 Gt implies an emissions reduction of 75%. Twenty-five percent of 15 Gt (from agriculture and land-use change) is 3.8 Gt, which we rounded to 4 Gt.

73. Rogelj et al. (2018).

74. Although some modeling analyses call for much steeper overall reductions in emissions by 2050, to around 8 Gt CO_2e per year, it appears that strategies to meet that goal have not relied on lower agricultural emissions of nitrous oxide and methane (Rogelj et al. 2018; Sanderson et al. 2016). Instead, they typically rely on faster mitigation of emissions from the energy sector and often large negative emissions after 2050.

75. Von Braun et al. (2009).

76. See Hazell (2009) for a perspective on the Green Revolution. Aksoy and Hoekman (2010) provide copious evidence from around the developing world of the same phenomenon. An in-depth empirical investigation that supports this view for four African countries is found in Christiaensen and Demery (2007).

77. World Bank (2012b).

78. Evenson and Gollin (2003a).

79. FAO (2011d). The decline in inflation-adjusted prices over the period averaged more than 4% per annum.

80. World Bank (2012b).

81. Bush (2009).

82. Von Lampe et al. (2014). The range of average annual changes forecast between 2005 and 2050 was -0.4% to +0.7% per year.

83. For example, Nelson et al. (2010) estimates that productivity gains of 40% greater than baseline estimates would reduce the annual number of future malnourished children by 19 million people and hold down otherwise expected food price increases dramatically.

84. A comprehensive survey of the literature and discussion of the issues is in Timmer (2002).

85. World Bank (2018). This does not include backward- and forward-linked activities such as input supply or food processing and retailing.

86. Huang et al. (2007). For more detail, see the historical material in Sonntag et al. (2005).

87. Also see Christiaensen (2012).

88. World Bank (2017a).

89. World Bank (2017b); World Bank (2008).

90. Jayne et al. (2016a).

91. SOFA Team and Doss (2011).

92. World Bank (2011).

93. UN (2012).

94. World Bank, FAO, and IFAD (2009).

95. World Bank (2011a).

96. World Bank (2011a).

97. World Bank, FAO, and IFAD (2009).

98. UN (2012).

99. World Bank, FAO, and IFAD (2009).

100. IFPRI (2000).

101. FAO (2011a).

102. FAO (2011b).

103. Alexandratos and Bruinsma (2012).

104. WWAP (2012).

105. Alexandratos and Bruinsma (2012); WWAP (2012).

106. Shiklomanov (2000).

107. "Water withdrawal" refers to the total amount of water abstracted from freshwater sources for human use. See Gassert et al. (2013) and WWAP (2012).

108. Hoekstra and Mekonnen (2012).

109. "Water consumption" is the portion of all water withdrawn that is consumed through evaporation or incorporation into a product, such that it is no longer available for reuse (Gassert et al. 2013).

110. WEF (2015).

111. Siebert and Doll (2010).

112. For a good pictorial presentation, see National Geographic (2017).

113. WWAP (2012). Two-thirds of groundwater withdrawals are for agriculture (Margat and van der Gun 2013).

114. "Water stress" is the ratio of total water withdrawals to available renewable supply in an area. In high-risk areas, 40% or more of the available supply is withdrawn every year. In extremely high-risk areas, that number goes up to 80% or higher. A higher percentage means more water users competing for limited supplies (WRI Aqueduct 2013).

115. Scanlon et al. (2007).

116. Deemer et al. (2016).

117. Malherbe et al. (2016).

118. Lemly (1994).

119. Ziv et al. (2012).

120. Deemer et al. (2016).

121. Frenken and Faurès (1997); Junk et al. (1989); Baldock et al. (2000).

122. Reisner (1993) provides a great history of irrigation in the United States and the conflicts resulting from it.

123. Mekonnen and Hoekstra (2011). Mekonnen and Hoekstra (2011) have also developed a measure of gray water consumption, defined as the volume of fresh water that is required to assimilate the load of pollutants based on existing ambient water quality standards. However, the estimates of agricultural water consumption in this report refer to only green and blue water.

124. IPCC (2014); Comprehensive Assessment of Water Management in Agriculture (2007).

125. Alexandratos and Bruinsma (2012).

REFERENCES

To find the References list, see page 500, or download here: www.SustainableFoodFuture.org.

PHOTO CREDITS

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