WORLD RESOURCES INSTITUTE

WORLD RESOURCES REPORT

CREATING A SUSTAINABLE FOOD FUTURE

A Menu of Solutions to Feed Nearly 10 Billion People by 2050

FINAL REPORT, JULY 2019

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CREATING A SUSTAINABLE FOOD FUTURE: FINAL REPORT

This report is the result of a multiyear partnership between World Resources Institute, the World Bank Group, the United Nations Environment Programme, the United Nations Development Programme, the Centre de coopération internationale en recherche agronomique pour le développement, and the Institut national de la recherche agronomique. The synthesis report was published in December 2018. Previously published installments analyzing many of the issues covered in this report in greater detail are available at www.SustainableFoodFuture.org.

The report focuses on technical opportunities and policies for cost-effective scenarios to meet food, land-use, and greenhouse gas emissions goals in 2050 in ways that can also help to alleviate poverty and do not exacerbate water challenges. It is primarily global in focus. As with any report, it cannot address all issues related to the global food system, such as many ethical, cultural, and socioeconomic factors or remedies for tackling acute food shortages in the short term. Future research may pursue quantitative estimates of agricultural freshwater use.

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NOTES

All unreferenced numbers are results from the GlobAgri-WRR model.

All dollars are U.S. dollars unless otherwise indicated.

All tons are metric tons unless otherwise indicated.

All general references to greenhouse gas emissions are in carbon dioxide equivalents using a 100-year global warming potential unless otherwise indicated.

"Kcal" = kilocalorie, also referred to as simply "calorie."

PHOTO CREDITS

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Tim Searchinger, Richard Waite, and Tim Beringer (Humboldt University at Berlin) contributed to development of the GlobAgri-WRR model, as did a number of researchers from the Centre de coopération internationale en recherche agronomique pour le développement, and the Institut national de la recherche agronomique, including Agneta Forslund, Hervé Guyomard, Chantal Le Mouël, Stéphane Manceron, and Elodie Marajo-Petitzon.

Major GlobAgri-WRR model subcomponents include a livestock model with lead developers Mario Herrero (Commonwealth Scientific and Industrial Research Organisation) and Petr Havlík (IIASA), with additional contributions from Stefan Wirsenius (Chalmers University of Technology); a land-use model with lead developer Fabien Ramos (European Commission Joint Research Centre); a rice model with lead developer Xiaoyuan Yan (Chinese Institute for Soil Science); a nitrogen emissions model with lead developer Xin Zhang (Princeton University); and an aquaculture model with lead developers Mike Phillips (WorldFish) and Rattanawan Mungkung (Kasetsart University).

A number of individuals were co-authors on working papers that serve as the foundation for this report and for many of the menu items profiled in Courses 1–5. They include:

- *The Great Balancing Act (Installment 1):* Tim Searchinger (WRI and Princeton University), Craig Hanson (WRI), Janet Ranganathan (WRI), Brian Lipinski (WRI), Richard Waite (WRI), Robert Winterbottom (WRI), Ayesha Dinshaw (WRI), and Ralph Heimlich (Agricultural Conservation Economics).

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- *Wetting and Drying: Reducing Greenhouse Gas Emissions and Saving Water from Rice Production (Installment 8):* Tapan K. Adhya (KIIT University, India), Bruce Linquist (University of California at Davis), Tim Searchinger (WRI and Princeton), Reiner Wassmann (International Rice Research Institute, Philippines), and Xiaoyuan Yan (Institute for Soil Science, Chinese Academy of Sciences).

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- *Shifting Diets (Installment 11):* Janet Ranganathan (WRI), Daniel Vennard (Mars Corporation), Tim Searchinger (WRI and Princeton), Richard Waite (WRI), Patrice Dumas (CIRAD), and Brian Lipinski (WRI).

TABLE OF CONTENTS

FOREWORD

The world urgently needs to change the way it produces and consumes food. In the coming decades, the global agricultural system must find ways to meet pressing but sometimes competing needs. Farmers must provide enough food for a population that is expected to reach nearly 10 billion people by 2050. Employing around 2 billion people today, agriculture must continue to be an engine of inclusive economic and social development that contributes to poverty reduction, even as many small farmers transition into other forms of employment. At the same time, agriculture must lighten its environmental footprint. The impacts of agriculture are large and growing, to the point where they are already undermining food production through land degradation, water scarcity, and adverse impacts of climate change.

As the global population grows and incomes rise across the developing world, overall food demand is on course to increase by more than 50 percent by mid-century, and demand for animal-based foods by nearly 70 percent. Yet even today, hundreds of millions of people remain undernourished as local agricultural systems fail to provide enough nutritious food, and economic factors prevent equitable distribution of available food.

This World Resources Report is the product of a multiyear collaboration between World Resources Institute, the World Bank Group, the United Nations Environment Programme, the United Nations Development Programme, the Centre de coopération internationale en recherche agronomique pour le développement, and the Institut national de la recherche agronomique. *Creating a Sustainable Food Future* defines and quantifies three specific challenges facing the global food system:

- **Food supply.** If consumption trends continue as projected, the world will need to increase food production by more than 50 percent to feed nearly 10 billion people adequately in 2050.

- **Land use.** To protect natural ecosystems critical to biodiversity and climate change mitigation, the additional food must be produced with no net expansion in the area of agricultural land. Without action, cropland and pastureland are projected to increase by nearly 600 million hectares by 2050.

- **Greenhouse gas emissions.** Agriculture has not been a major focus of emissions mitigation, other than as a potential source of carbon sequestration in soils. Yet farming is a significant and growing source of emissions. To limit agriculture to its "fair share" of total allowable emissions in a world where global temperatures have risen by 2 degrees Celsius, the sector must address the demand for 50 percent more food while reducing emissions by two-thirds from 2010 levels. And to stay under a 1.5-degrees Celsius rise in temperature, these emissions will need to be further reduced by reforesting at least 585 million hectares of agricultural land freed up by productivity gains and reductions in demand.

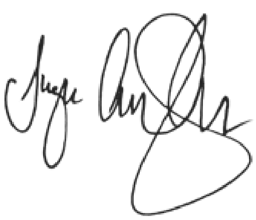
Meeting these challenges will be an immense task, but this report proposes a 22-item "menu of solutions" that, together, could deliver a sustainable food future. The solutions target both supply- and demand-side measures: We must produce more food, but we must also slow the rate of growth in demand—especially demand for resource-intensive foods such as beef.

A new model, developed specifically for this report, allows us to quantify the potential contribution of each "menu item" to the goals of raising production, limiting demand, and/or reducing GHG emissions. The report analyzes specific obstacles that must be overcome and identifies the most promising solutions that are currently available or show promise in the near term. It also identifies the policies, practices, and incentives necessary to implement the solutions at the necessary scale.

A common thread in many of the solutions is the urgent need to "produce, protect, and prosper." The world must act decisively to intensify production on agricultural land. The world must also act decisively to protect natural ecosystems that store carbon, support biodiversity, and provide the many ecosystem services on which humanity depends. Food production and ecosystem protection must be linked at every level—policy, finance, and farm practice—to avoid destructive competition for precious land and water. And this combination must—and can—result in greater prosperity to lift people out of poverty and sustain political will.

We do not argue for full implementation of all 22 menu items in every country, as some solutions will not be relevant or feasible everywhere. Interested governments, businesses, and stakeholders across food supply chains will need to decide which menu items are relevant for them.

The report demonstrates that big changes are possible and that a sustainable food future is achievable. The menu proposed in this report can create a world with sufficient, nutritious food for everyone. It also offers the chance to generate the broader social, environmental, and economic cobenefits that are the foundation of sustainable development. But such a future will only be achieved if governments, the private sector, and civil society act upon the entire menu quickly and with conviction.



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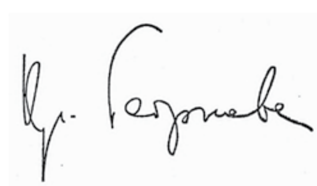

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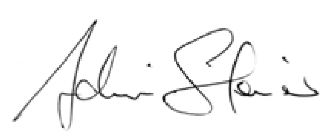

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EXECUTIVE SUMMARY

As the global population grows from 7 billion in 2010 to a projected 9.8 billion in 2050, and incomes grow across the developing world, overall food demand is projected to increase by more than 50 percent. Demand for more resource-intensive foods like meat and dairy products is projected to rise even faster, by nearly 70 percent. Yet even today, more than 800 million people are hungry or malnourished. Increasing food production in ways that respect human well-being and the environment presents enormous challenges. Agriculture already uses almost half of the world's vegetated land, and agriculture and related land-use change generate one-quarter of annual greenhouse gas (GHG) emissions.

This World Resources Report proposes a menu of options that could allow the world to achieve a sustainable food future by meeting growing demands for food, avoiding deforestation, and reforesting or restoring abandoned and unproductive land—and in ways that help stabilize the climate, promote economic development, and reduce poverty.

Achieving these goals requires closing three great "gaps" by 2050:

- **The food gap**—the difference between the amount of food produced in 2010 and the amount necessary to meet likely demand in 2050. We estimate this gap to be 56 percent more crop calories than were produced in 2010.
- **The land gap**—the difference between global agricultural land area in 2010 and the area that will be required in 2050—even if crop and pasture yields continue to grow at rates achieved in the past. We estimate this gap to be 593 million hectares, an area nearly twice the size of India.
- **The GHG mitigation gap**—the difference between the level of annual GHG emissions from agriculture and land-use change in 2050, which we estimate to be 15 gigatons (Gt), and a target of 4 Gt that represents agriculture's proportional contribution to holding global warming below 2°C above pre-industrial temperatures. Holding warming below a 1.5°C increase would require meeting this 4 Gt target *plus* freeing up hundreds of millions of hectares for reforestation.

This report explores a 22-item "menu for a sustainable food future," which is divided into five "courses" that together could close these gaps: (1) reduce growth in demand for food and agricultural products; (2) increase food production without expanding agricultural land; (3) protect and restore natural ecosystems; (4) increase fish supply (through improved wild fisheries management and aquaculture); and (5) reduce GHG emissions from agricultural production.

On the one hand, the challenge of simultaneously closing these three gaps is harder than often recognized. Some prior analyses overestimate potential crop yield growth, underestimate or even ignore the challenge of pastureland expansion, and "double count" land by assuming that land is available for reforestation or bioenergy without accounting for the world's growing need to produce more food, protect biodiversity, and sequester more carbon. Significant progress in all 22 menu items is necessary to close the three gaps, requiring action by many millions of farmers, businesses, consumers, and all governments.

On the other hand, the scope of potential solutions is often underestimated. Prior analyses have generally not focused on the promising opportunities for technological innovation and have often underestimated the large social or economic cobenefits. Our menu is detailed but several themes stand out:

- **Raise productivity.** Increased efficiency of natural resource use is the single most important step toward meeting both food production and environmental goals. This means increasing crop yields at higher than historical (linear) rates, and dramatically increasing output of milk and meat per hectare of pasture, per animal—particularly cattle—and per kilogram of fertilizer. If today's levels of production efficiency were to remain constant through 2050, then feeding the planet would entail clearing most of the world's remaining forests, wiping out thousands more species, and releasing enough GHG emissions to exceed the 1.5°C and 2°C warming targets enshrined in the Paris Agreement—even if emissions from all other human activities were entirely eliminated.

- **Manage demand.** Closing the food gap will be far more difficult if we cannot slow the rate of growth in demand. Slowing demand growth requires reducing food loss and waste, shifting the diets of high meat consumers toward plant-based foods, avoiding any further expansion of biofuel production, and improving women's access to education and healthcare in Africa to accelerate voluntary reductions in fertility levels.

- **Link agricultural intensification with natural ecosystems protection.** Agricultural land area is not only expanding; the location of agricultural land is also shifting from one region to another (e.g., from temperate areas to the tropics). The resulting land-use changes increase GHG emissions and loss of biodiversity. To ensure that food production is increased through yield growth (intensification) not through expansion, and that productivity gains do not encourage more shifting, governments must explicitly link efforts to boost crop and pasture yields with legal measures to protect forests, savannas, and peatlands from conversion to agriculture.

- **Moderate ruminant meat consumption.** Ruminant livestock (cattle, sheep, and goats) use two-thirds of global agricultural land and contribute roughly half of agriculture's production-related emissions. Demand for ruminant meat is projected to grow by 88 percent between 2010 and 2050. Yet, even in the United States, ruminant meats (mostly beef) provide only 3 percent of calories and 12 percent of protein. Closing the land and GHG mitigation gaps requires that, by 2050, the 20 percent of the world's population who would otherwise be high ruminant-meat consumers reduce their average consumption by 40 percent relative to their consumption in 2010.

- **Target reforestation and peatland restoration.** Rewetting lightly farmed, drained peatlands that occupy only around 0.5 percent of global agricultural lands provides a necessary and cost-effective step toward climate change mitigation, as does reforesting some marginal and hard-to-improve grazing land. Reforestation at a scale necessary to hold temperature rise below 1.5 degrees Celsius (i.e., hundreds of millions of hectares) is potentially achievable but only if the world succeeds in reducing projected growth in demand for resource-intensive agricultural products and boosting crop and livestock yields.

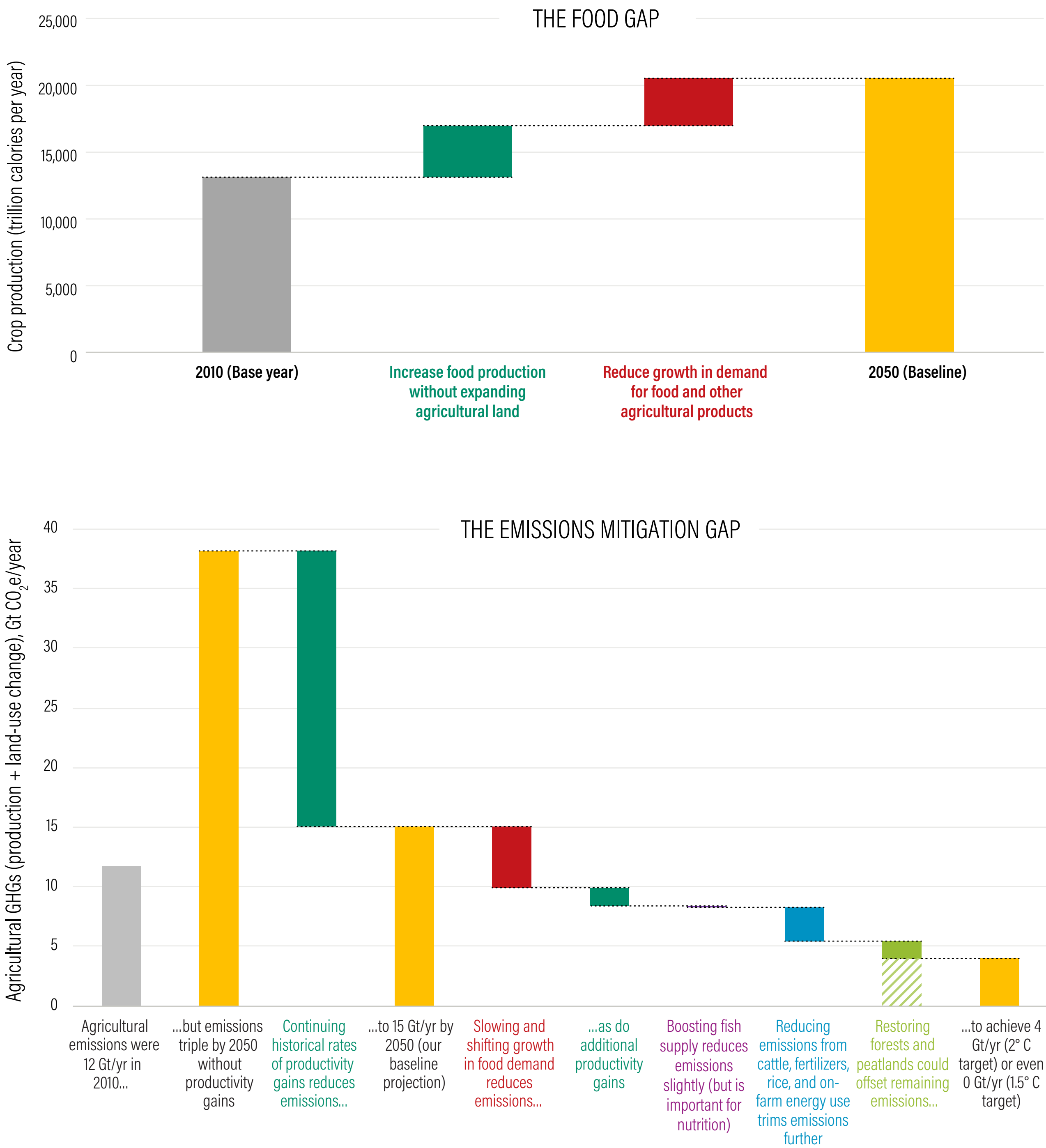
- **Require production-related climate mitigation.** Management measures exist to significantly reduce GHG emissions from agricultural production sources, particularly enteric fermentation by ruminants, and from manure, nitrogen fertilizers, and energy use. These measures require a variety of incentives and regulations, deployed at scale. Implementation will require far more detailed analysis and tracking of agricultural production systems within countries.

- **Spur technological innovation.** Fully closing our gaps requires many innovations. Fortunately, researchers have demonstrated good potential in every necessary area. Opportunities include crop traits or additives that reduce methane emissions from rice and cattle, improved fertilizer forms and crop properties that reduce nitrogen runoff, solar-based processes for making fertilizers, organic sprays that preserve fresh food for longer periods, and plant-based beef substitutes. A revolution in molecular biology opens up new opportunities for crop breeding. Progress at the necessary scale requires large increases in R&D funding, and flexible regulations that encourage private industry to develop and market new technologies.

Using a new model called GlobAgri-WRR, we estimate how three scenarios we call Coordinated Effort, Highly Ambitious, and Breakthrough Technologies can narrow and ultimately fully close our three gaps. As one example, Figure ES-1 illustrates how our five courses of action could feed the world and help hold down global temperature rise.

We believe that a sustainable food future is achievable although the challenges are formidable. The world must act swiftly to define goals and scale up the multiple efforts that will be necessary to achieve them.

Figure ES-1 | **Ambitious efforts across all menu items will be necessary to feed 10 billion people and help keep global temperature rise well below 2 degrees Celsius**



Note: These charts show the most ambitious "Breakthrough Technologies" scenario. "Restore forests and peatlands" item includes full reforestation of at least 80 million hectares of liberated agricultural land, in order to reach the 4 Gt CO_2e/year target by 2050 for limiting global temperature rise to 2°C. As an even more ambitious option, in order to limit warming to 1.5°C, full reforestation of at least 585 million hectares of liberated agricultural land could offset global agricultural production emissions for many years.
Source: GlobAgri-WRR model.

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.

TABLE OF CONTENTS

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]

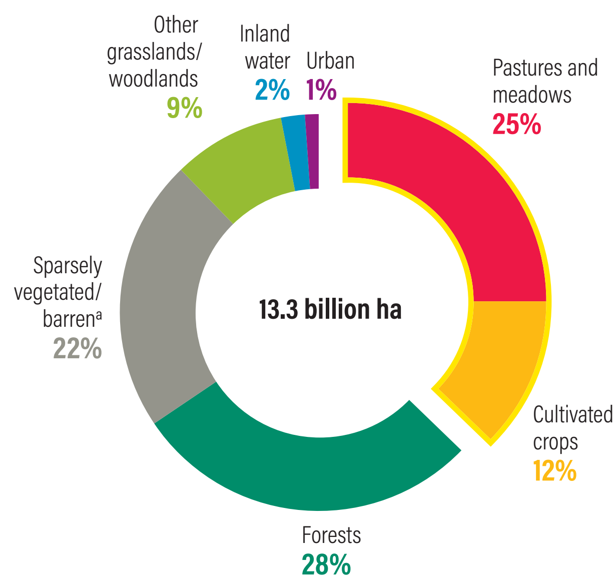
Second, the world needs agriculture to contribute to inclusive economic and social development to help reduce poverty. More than 70 percent of the world's poor live in rural areas, where most depend on agriculture for their principal livelihood.[7] Growth originating in the agricultural sector can often 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

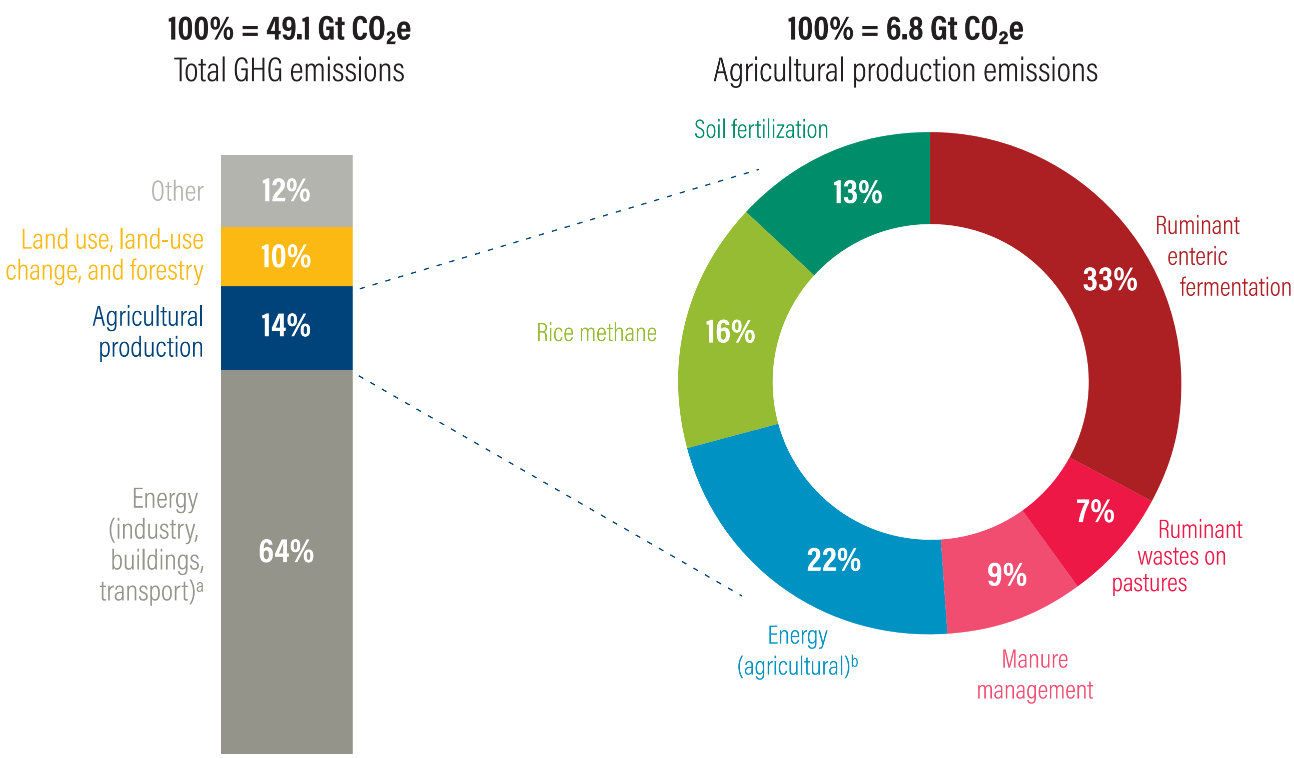
Agriculture and associated land-use change such as deforestation accounted for nearly one-quarter of global greenhouse gas (GHG) emissions in 2010 (Figure 1-2). Of these, agricultural production contributed more than one-half.[17]

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.

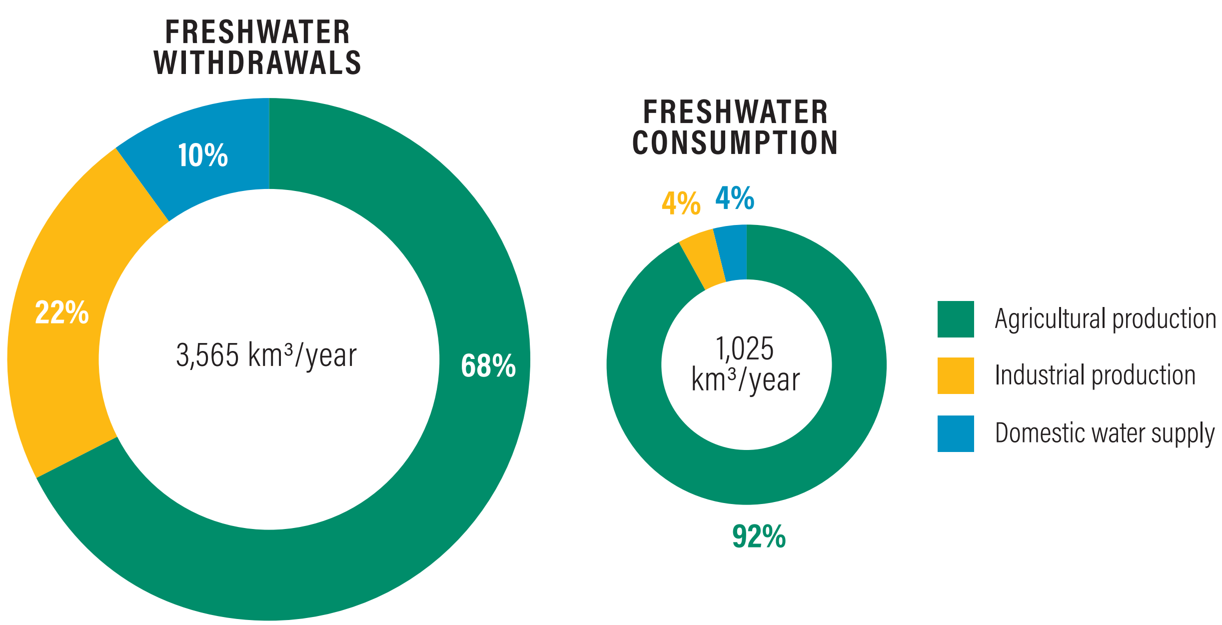
Addressing Food Supply, Development and Poverty Reduction, and Environmental Protection

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]

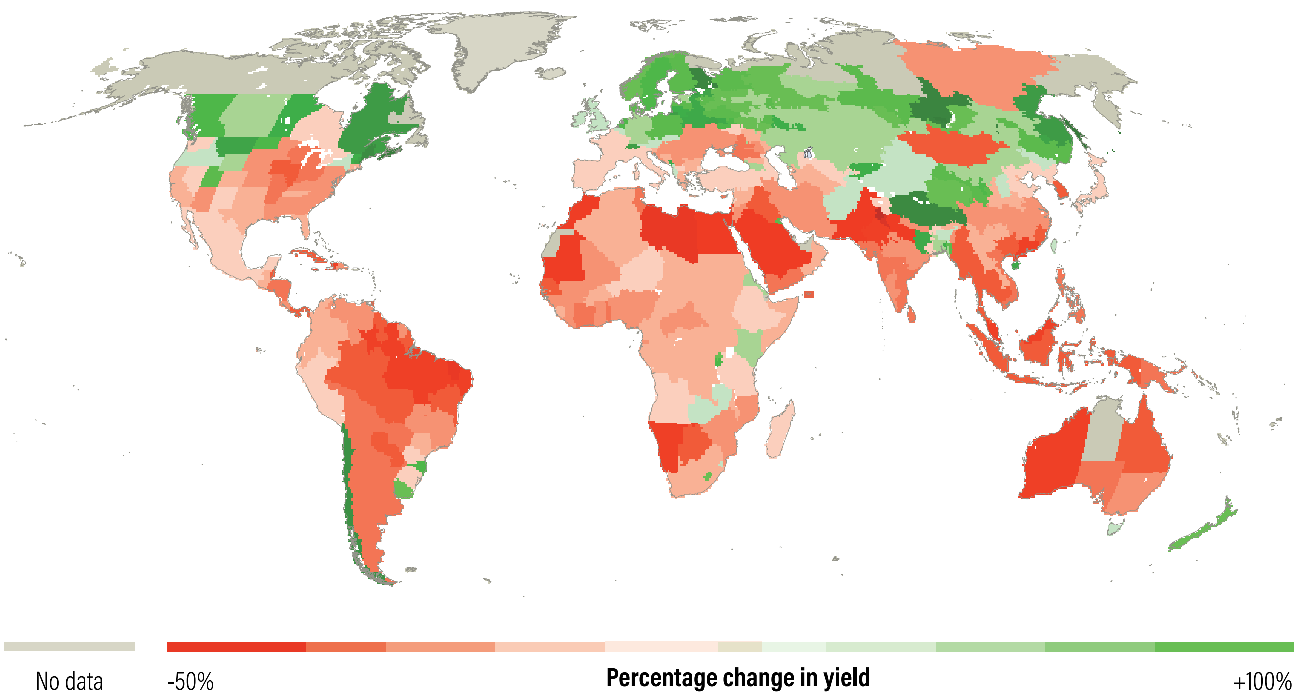
To balance by midcentury the three great needs—meeting food demand, supporting development, and protecting the earth's natural resources—the world's food system must exceed previous achievements in increasing food production while reducing poverty, avoiding land conversion, and mitigating agriculture-related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

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



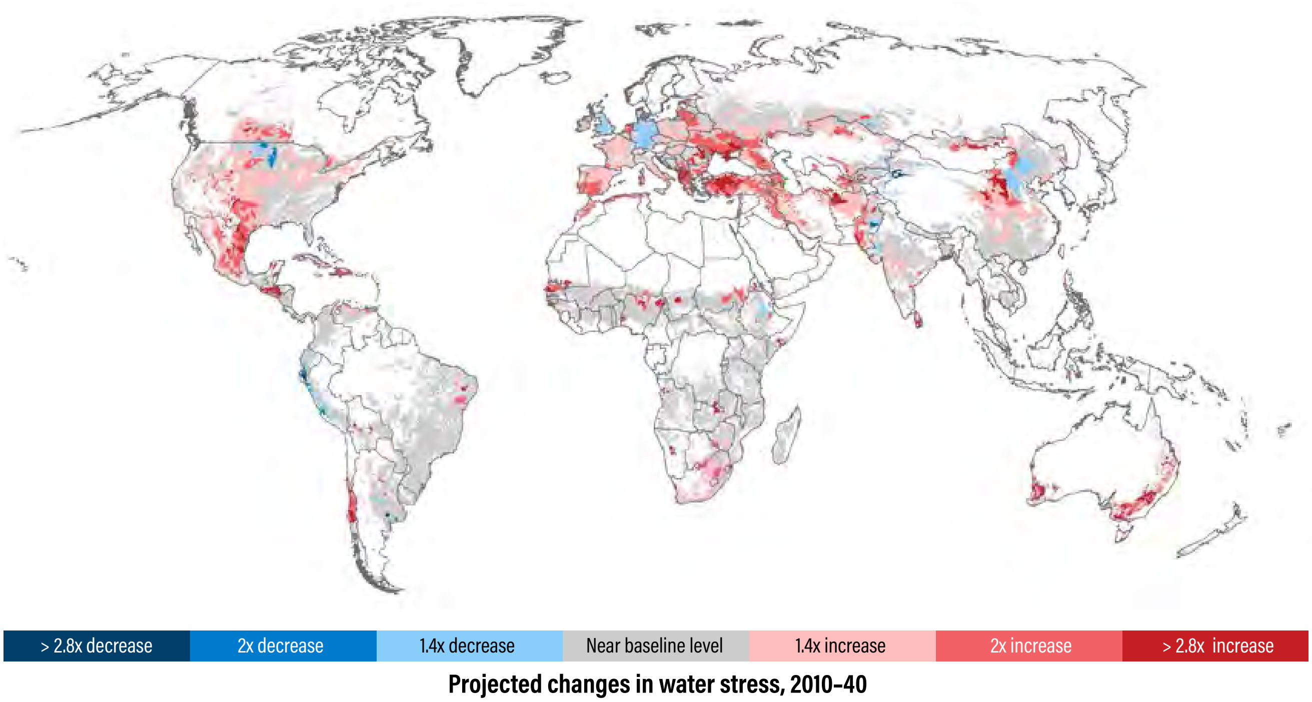
Note: Figures measure only "blue water" demand and do not consider rainfed agriculture ("green water"). Consumption figures are averaged for the years 1996–2005; withdrawal figures are for the year 2000.
Sources: Hoekstra and Mekonnen (2012) (consumption); OECD (2012) output from IMAGE model (withdrawals).

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



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



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?

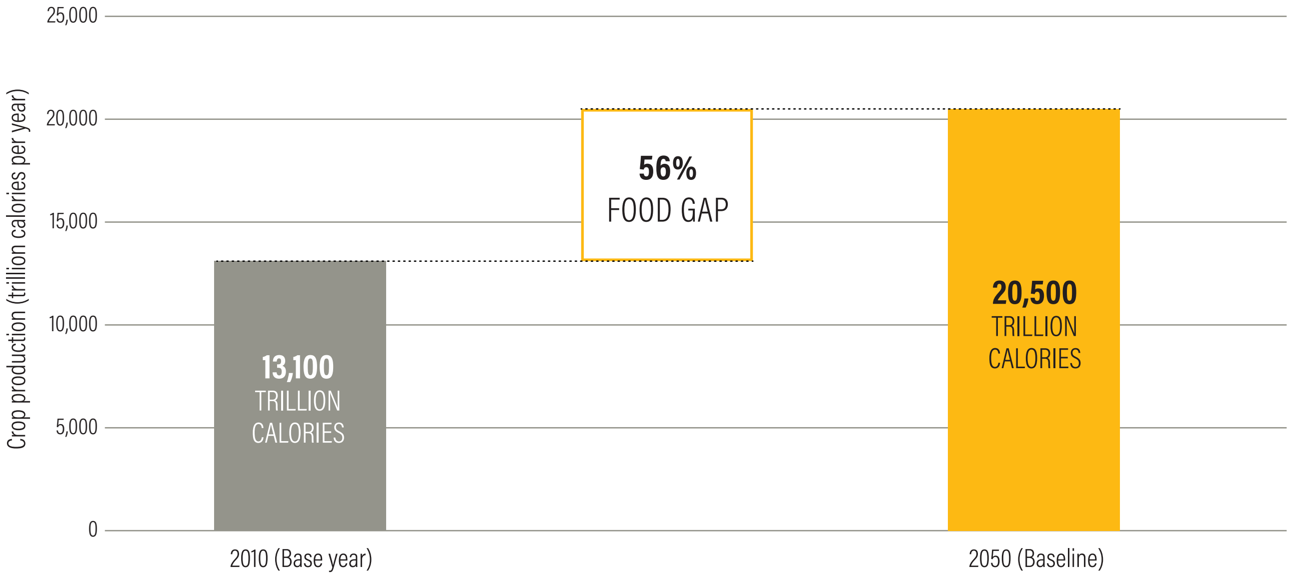
To project food demands in 2050, we start with a 2012 FAO projection of the diets that the average person in each country will consume in that year.[30] FAO based its projections on economic growth and income trends and culture in different countries. We adjust these projections per person moderately, 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).

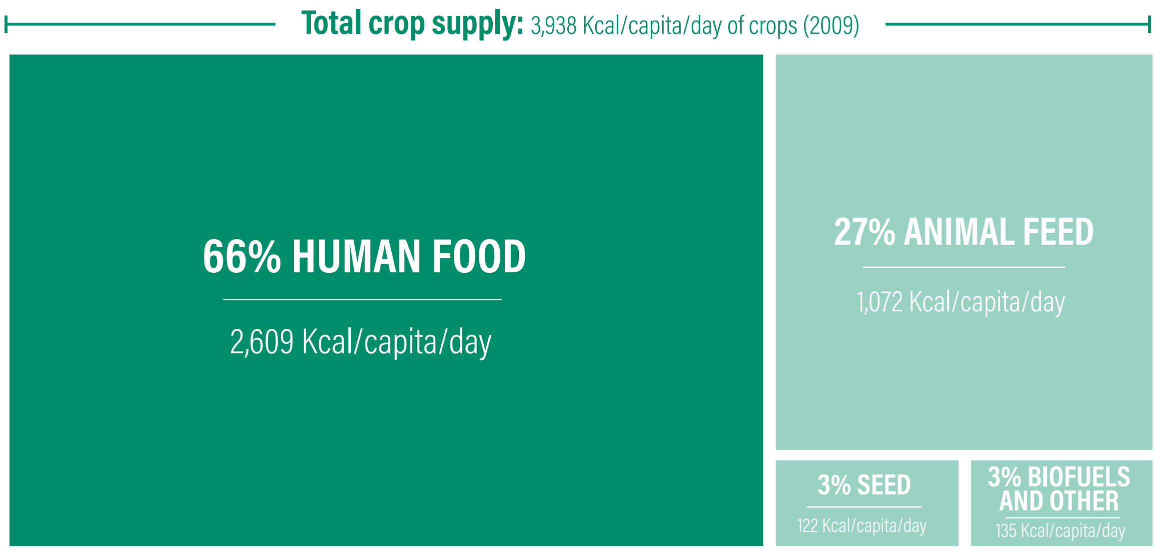
Is there really a "food gap"?

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]

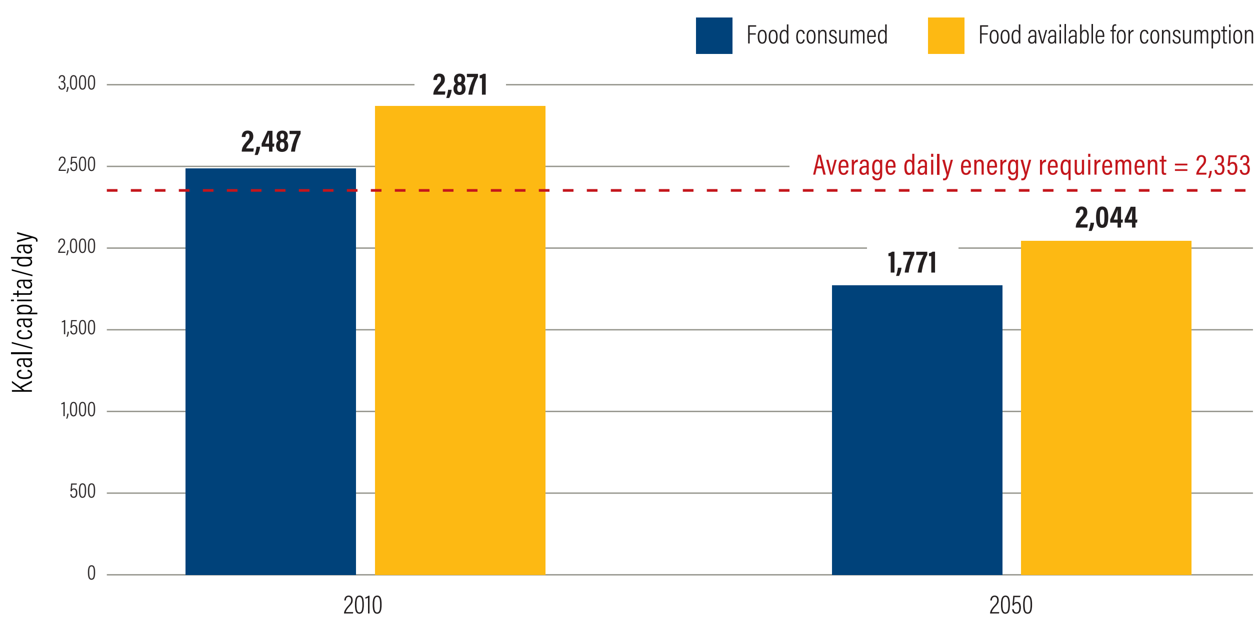
Realistically, we should focus on actual food consumption patterns, including meat and milk, and account for food losses and waste. Doing so yields a very different result. The amount of food consumed in 2010 (nearly 2,500 kcal per person per day), spread over the projected population in 2050, would 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.

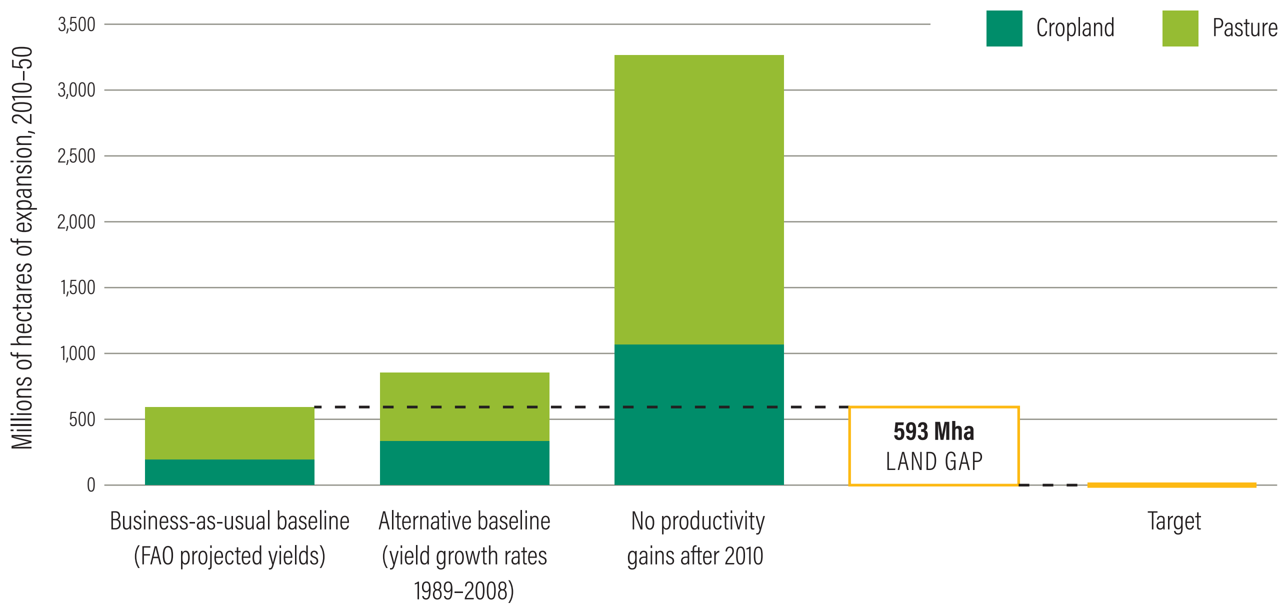
Using these FAO estimates of growth in yield and cropping intensity, GlobAgri-WRR projects a net increase in global cropland between 2010 and 2050 of 171 Mha. Using an analysis of aquaculture systems described more in Course 4, we also project an additional 20 Mha of aquaculture ponds, bringing the total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



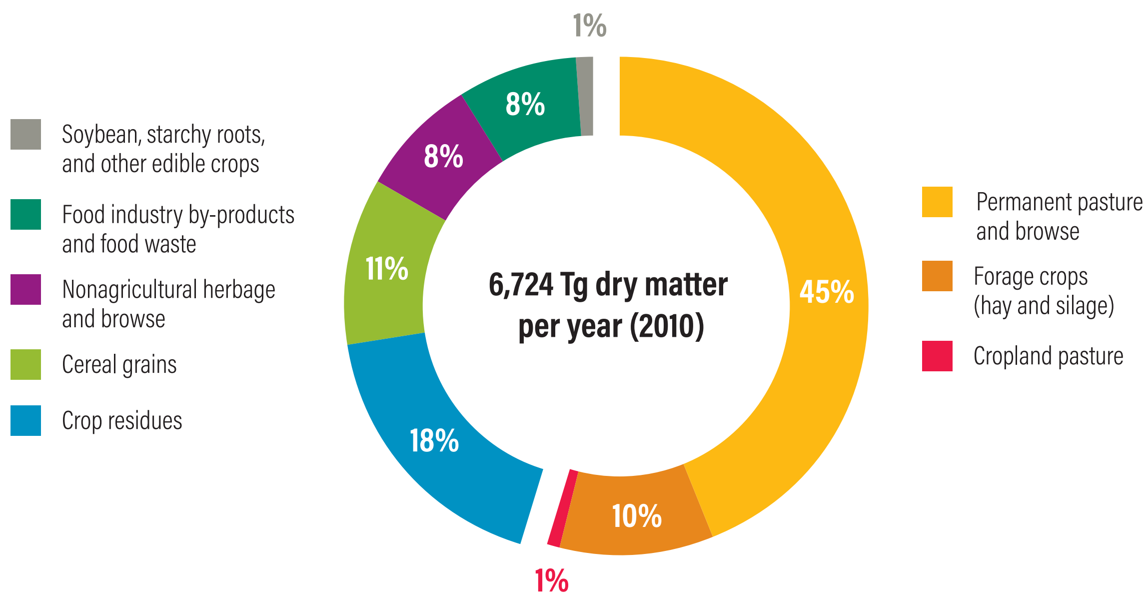
Note: "Cropland" increase includes a 20 Mha increase in aquaculture ponds under the two projected baselines and a 24 Mha increase in the "no productivity gains after 2010" projection.
Source: GlobAgri-WRR model.

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.

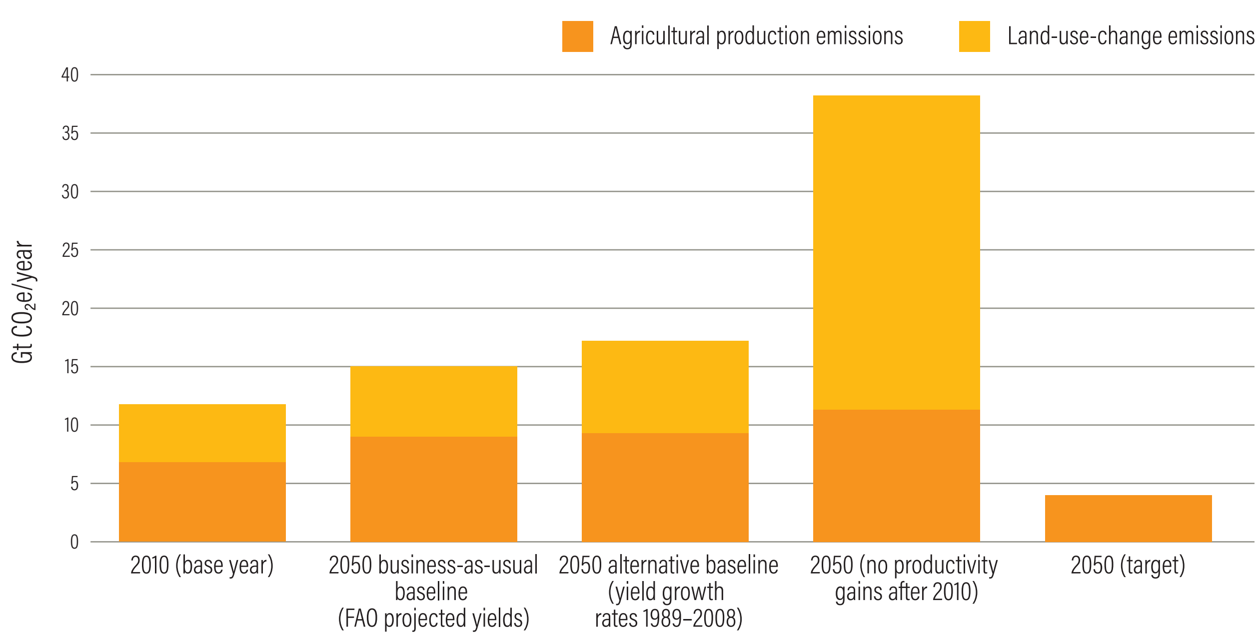
Fortunately, yields will probably continue to grow, and the use of chemicals, animals, and other inputs to the production process that lead to emissions will probably become more efficient as well. (We describe these assumptions in more detail in Course 5.)

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.

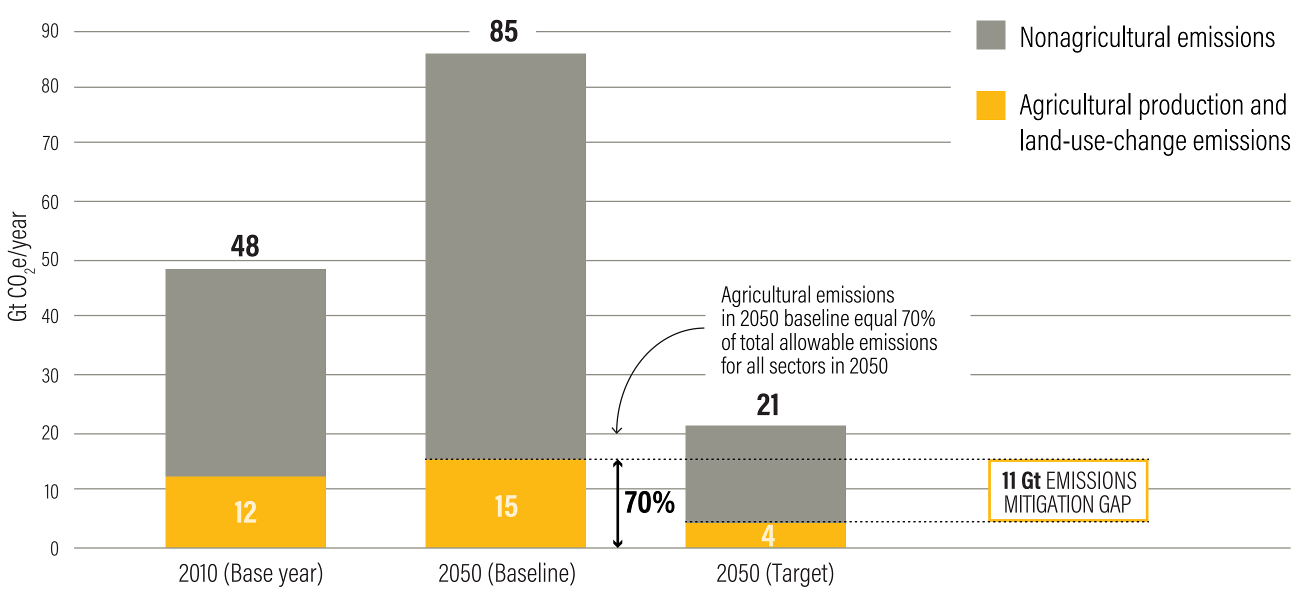
As with our land-use projections, we again develop a less optimistic alternative baseline using recent yield growth trends.[63] In this scenario, emissions from agricultural production would grow to 9.3 Gt CO_2e per year in 2050 and total emissions, including those from land-use change, would rise to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

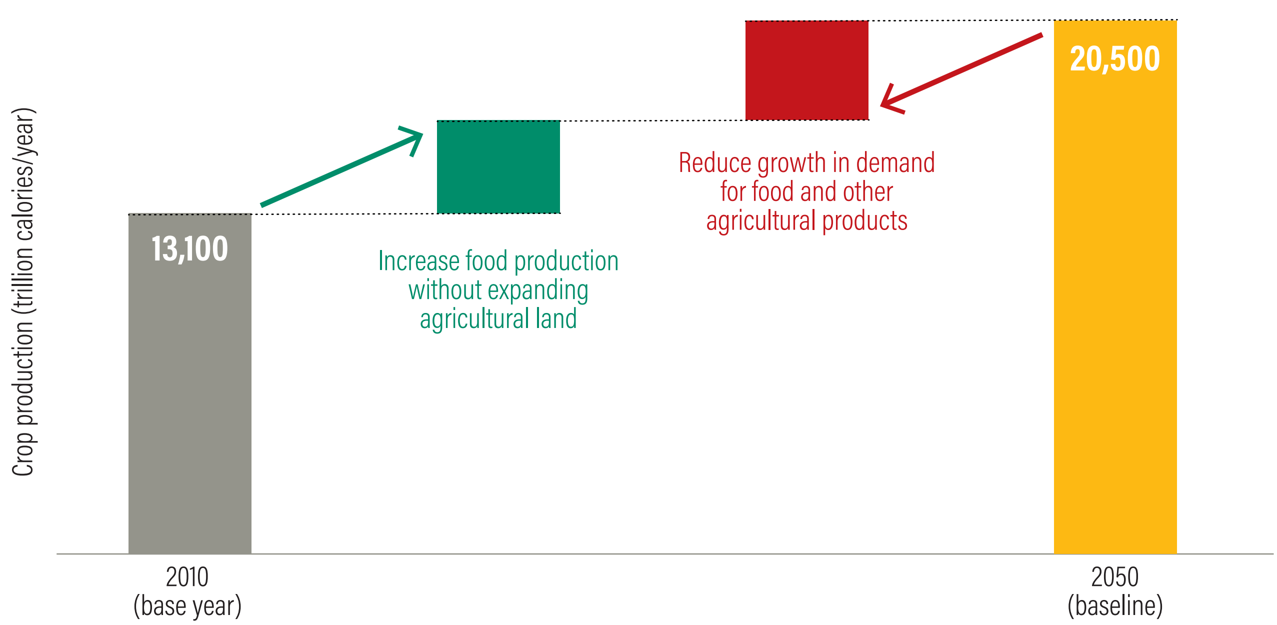
Notes:
a. FAO (2006a).
b. The following definitions are paraphrased from Gross et al. (2000).
c. Richardson (2010); Daily et al. (1998).
d. Millennium Ecosystem Assessment (2005).

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.

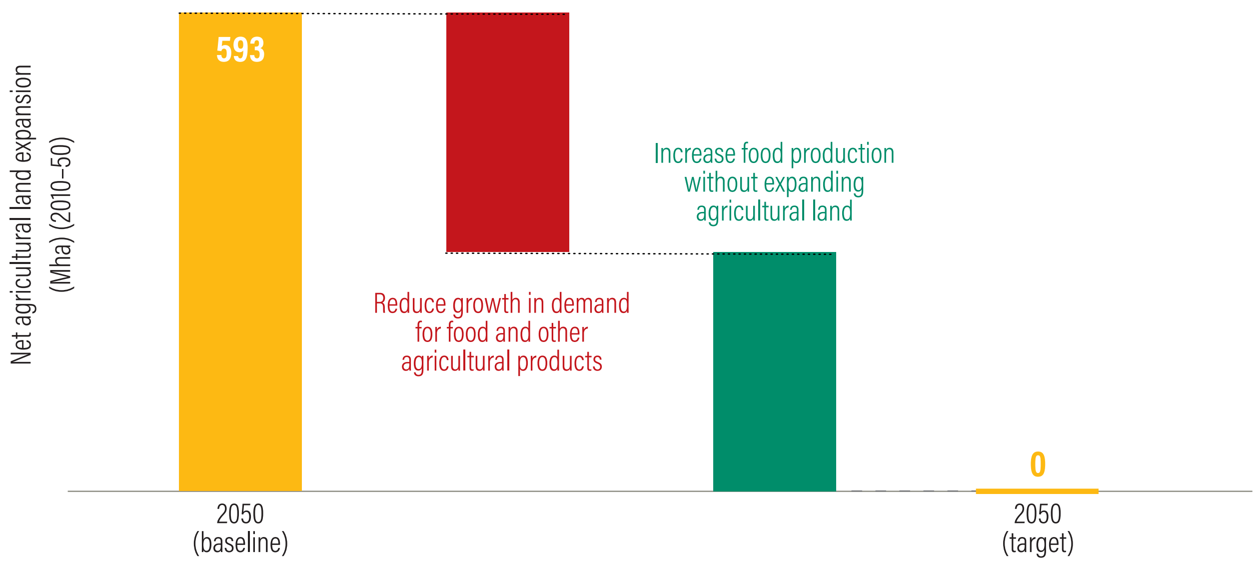
For each menu item, we also offer policy recommendations for moving forward. Policy recommendations can be broad or detailed. Our standard is one of "usefulness." Where issues remain controversial, even broad recommendations can be useful, but we try to make detailed recommendations wherever feasible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

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



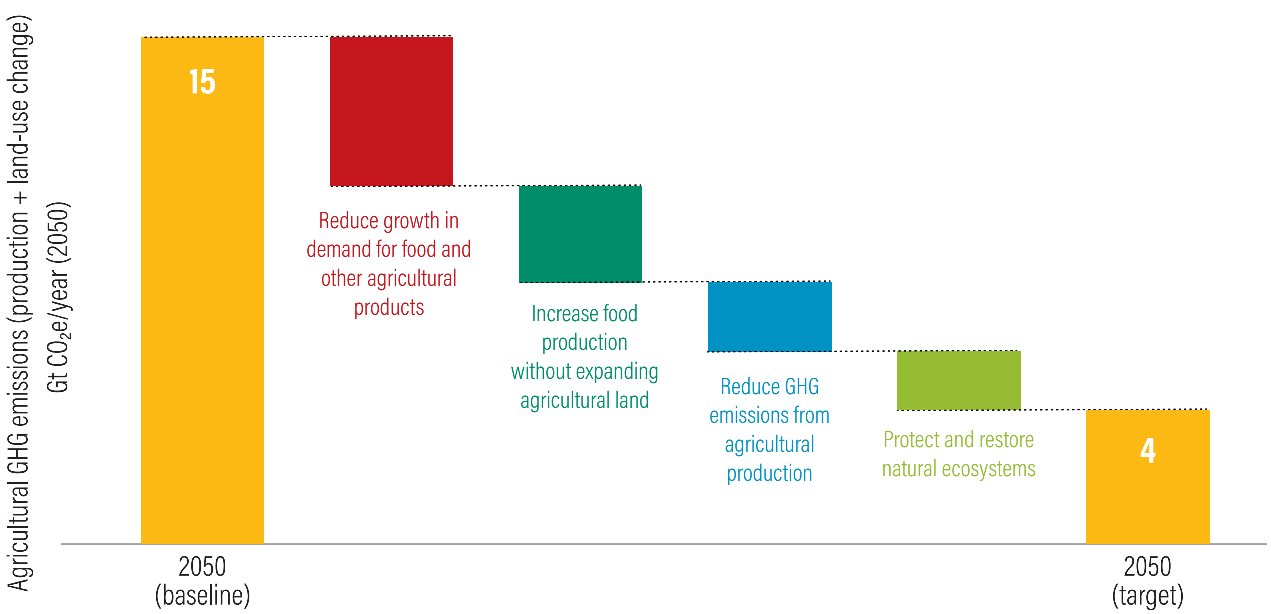
Note: Includes all crops intended for direct human consumption, animal feed, industrial uses, seeds, and biofuels. Bar sizes to close gap are illustrative only.
Source: GlobAgri-WRR model.

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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COURSE 1

Reduce Growth in Demand for Food and Other Agricultural Products

The size of the food challenge—and the associated environmental and economic challenges—depends on the scale of the increase in demand for crops and animal-based foods by midcentury. The food, land, and GHG mitigation gaps are derived from reasonable estimates of business-as-usual growth in demand for food crops and livestock. Yet such levels of growth are not inevitable. Course 1 menu items explore ways to reduce this projected growth in socially and economically beneficial ways.

TABLE OF CONTENTS

CHAPTER 5

MENU ITEM: REDUCE FOOD LOSS AND WASTE

A significant share of the food produced for consumption is never consumed by people. Reducing present rates of food loss and waste could, in principle, reduce the three gaps significantly. We believe such a reduction is possible in practice, given the economic costs of food loss and waste, some recent success stories, and the emergence of promising new technologies.

The Challenge

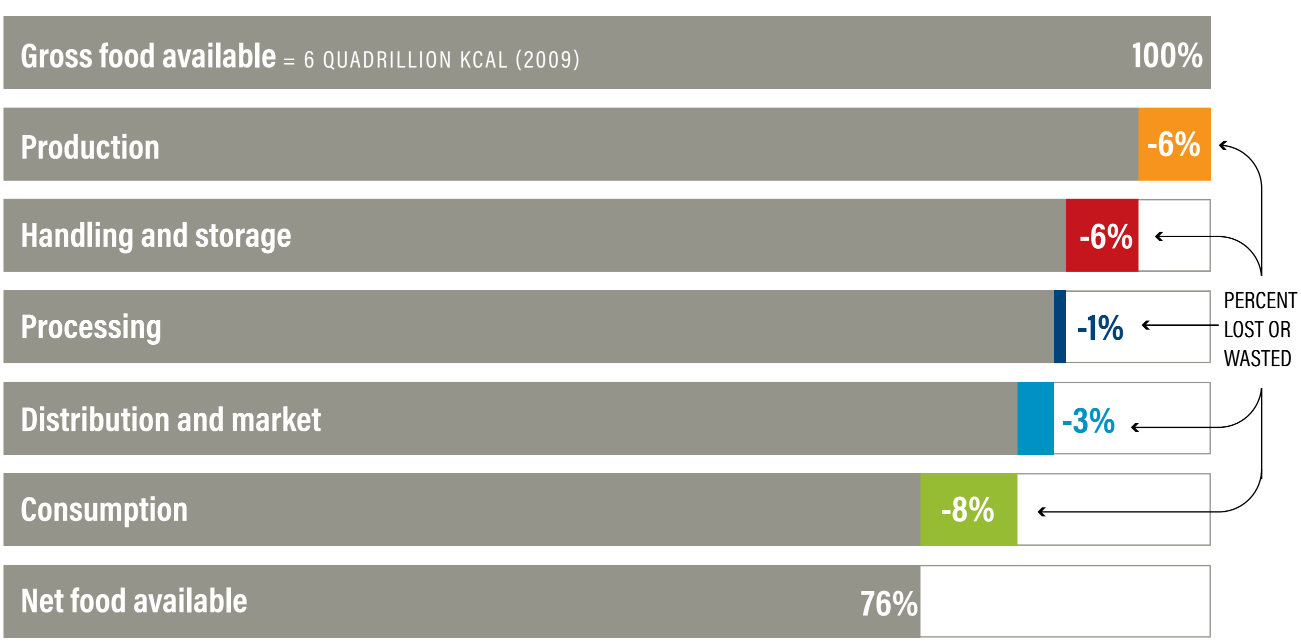
Efforts to reduce food loss and waste (FLW) must overcome the challenge posed by the fact that losses occur mostly in relatively small percentages at different stages as different handlers move food from farm to fork. To reduce these losses requires broadly shared commitments to strong quantitative goals, careful measurement, and persistent action. This menu item explores the challenges and opportunities.

According to the best available estimates by FAO, approximately one-third of all food produced in the world in 2009, measured by weight, was lost or wasted.[1] Food loss and waste refers to food intended to be eaten by people that leaves the food supply chain somewhere between being ready for harvest and being consumed, and thus is not consumed by people (Box 5-1). Converted into calories, this amount is equivalent to 24 percent of the world's food supply lost somewhere between farm and fork (Figure 5-1).[2]

Globally, this inefficiency in the food system results in losses of almost $1 trillion per year.[3] In sub-Saharan Africa, postharvest grain losses total up to $4 billion per year.[4] In the United States, the average family of four wastes roughly $1,500 worth of food annually,[5] while in the United Kingdom, the average household with children discards approximately £700 of edible food each year.[6]

In some regions such as sub-Saharan Africa and South Asia, food losses are concentrated during harvesting and storage and therefore reduce farmers' income and, at times, even their ability to feed their families. In other places—including Europe and North America—food wasted near the fork can affect local people who are food-insecure when the food is not donated or redistributed.

Figure 5-1 | Approximately 24 percent of all food produced (by caloric content) is lost or wasted from farm to fork



Source: WRI analysis based on FAO (2011c).

FLW also wastes natural resources. It consumes about one-quarter of all water used by agriculture each year.[7] It requires an area of agricultural land greater than the size of China.[8] And it generates about 8 percent of global greenhouse gas (GHG) emissions annually.[9] If food loss and waste were a country, it would be the third-largest GHG emitter on the planet (Figure 5-2).

FLW can occur at each stage of the food supply chain:

- During production or harvest in the form of grain left behind by poor harvesting equipment, discarded fish, and fruit not harvested or discarded because they fail to meet quality standards or are uneconomical to harvest.
- During handling and storage in the form of food degraded by pests, fungus, and disease.
- During processing and packaging in the form of spilled milk, damaged fish, and fruit unsuitable for processing. Processed foods may be lost or wasted because of poor order forecasting and inefficient factory processes.
- During distribution and marketing in the form of edible food discarded because it is noncompliant with aesthetic quality standards or is not sold before "best before" and "use-by" dates.
- During consumption in the form of food purchased by consumers, restaurants, and caterers but not eaten.[10]

BOX 5-1 | Defining food loss and waste

In this report, "food loss and waste" refers to food intended to be eaten by people that leaves the food supply chain somewhere between being ready for harvest or slaughter and being consumed. Some definitions also include the associated inedible parts of food.

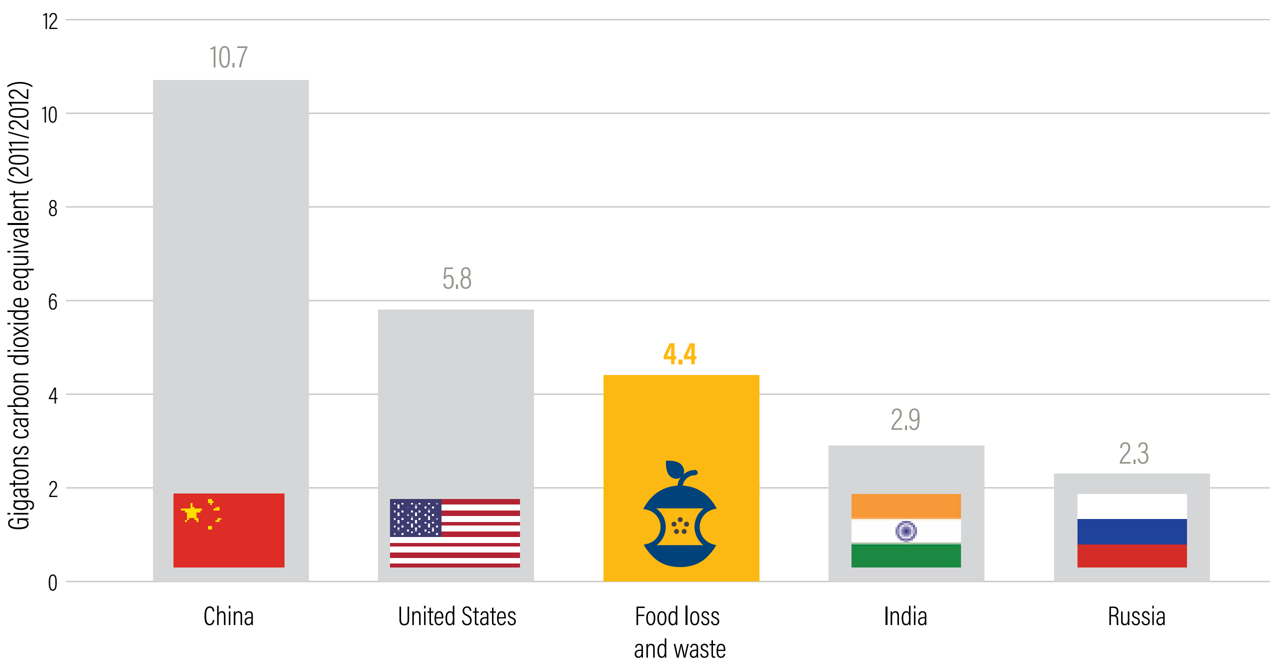
"Food" refers to any substance—whether processed, semiprocessed, or raw—that is intended for human consumption or, more specifically, ingestion. "Inedible parts" refers to components associated with a food that, in a particular food supply chain, are not intended to be consumed by people; inedible parts include bones, rinds, and pits. What is considered inedible depends strongly on the cultural context. In this report and its calculations, we include only food and exclude the associated inedible parts, following FAO (2019a).

The distinction between food loss and food waste is not always sharply defined but, where used, is primarily based on the underlying reasons for material leaving the food supply chain. "Food loss" typically refers to what occurs between the farm and the retail store, and is typically considered to be unintended and caused by poor functioning of the food production and supply system or by poor institutional and legal frameworks. Examples include food that rots in storage because of inadequate technology or refrigeration, or food that cannot make it to market because of poor infrastructure and goes unconsumed. "Food waste" typically refers to what occurs from the retail store through to the point of intended consumption. It occurs due to intended behaviors—choice, poor stock management, or neglect. Examples include food that has spoiled, expired, or been left uneaten after preparation.

Given this definition, food loss and waste calculations do not include surplus food that is redirected to food banks and subsequently eaten by people; food grown intentionally for feed, seed, or industrial use; or overconsumption beyond recommended caloric needs.

Sources: Food Loss and Waste Protocol (2016); Global Initiative on Food Loss and Waste Reduction (2016).

Figure 5-2 | If food loss and waste were a country, it would be the third-largest greenhouse gas emitter in the world



Note: Figures reflect all six anthropogenic GHG emissions, including those from land use, land-use change, and forestry (LULUCF). Country data are for 2012, while the food loss and waste data are for 2011 (the most recent data available). To avoid double counting, the food loss and waste emissions figure should not be added to the country figures.
Sources: CAIT (2017); FAO (2015a).

The distribution of food loss and waste along stages of the food supply chain varies significantly between developed and developing regions. More than half of the food loss and waste in North America, Oceania (which includes Australia and New Zealand), and Europe occurs at the consumption stage. In contrast, the two stages closest to the farm—production and storage—account for more than two-thirds of food loss and waste in South and Southeast Asia and in sub-Saharan Africa (Figure 5-3). As more countries develop, we can therefore anticipate that food losses and waste will shift from the farm toward consumers.

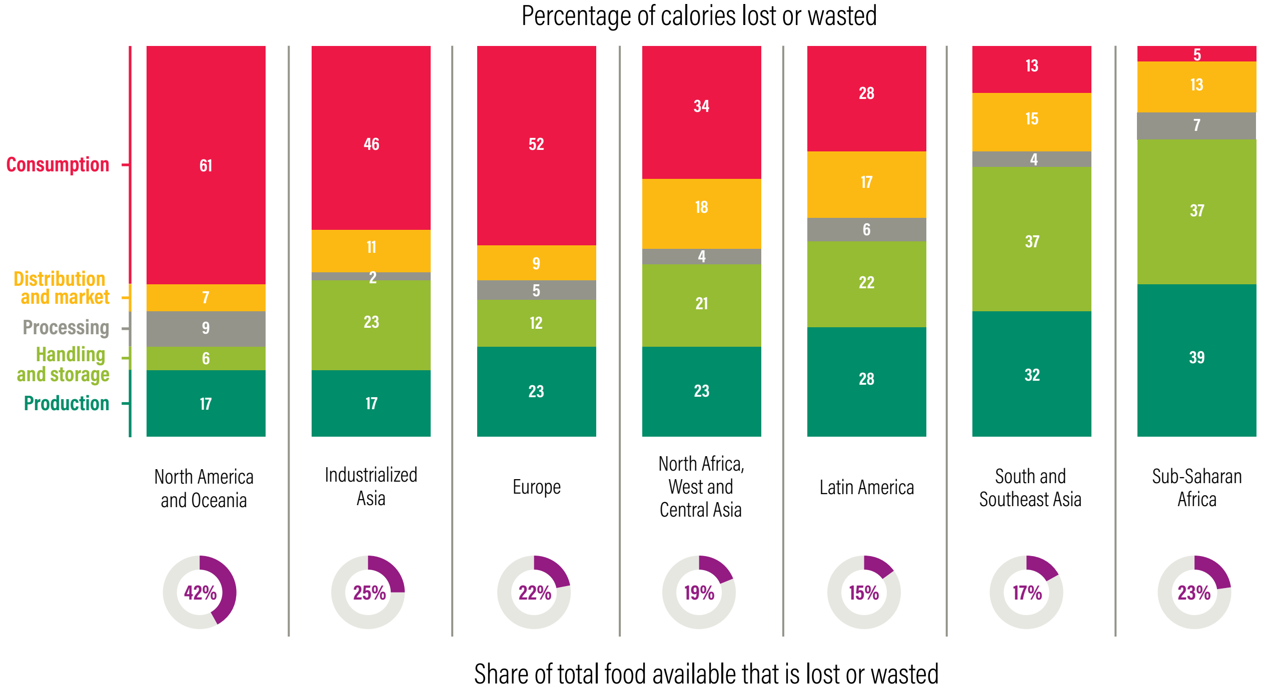
The total share of available food that becomes lost or wasted ranges from 15 percent to 25 percent across most regions. As Figure 5-3 indicates, the outlier is North America and Oceania, where loss and waste is approximately 42 percent of all available food.

On a per capita basis, North America and Oceania[11] stand out, with about 1,500 kcal per person per day lost or wasted from farm to fork, while Europe and industrialized Asia hover around 750 kcal per person per day and all other regions lose or waste under 600 kcal per person per day.[12]

Regionally, about 56 percent of total food loss and waste occurs in the developed world—North America, Oceania, Europe, and the industrialized Asian nations of China, Japan, and South Korea. The developing world accounts for 44 percent (Figure 5-4).

The choice of whether to measure food loss and waste in terms of calories or weight alters the relative contribution of different food categories. While cereals comprise the most FLW relative to other food categories on a caloric basis, fruits and vegetables are the largest source by weight (Figure 5-5). This difference results primarily from the high-water content of fruits and vegetables. Yet because fruits and vegetables have high nutritional values

Figure 5-3 | Where food loss and waste occurs along the food supply chain varies among regions

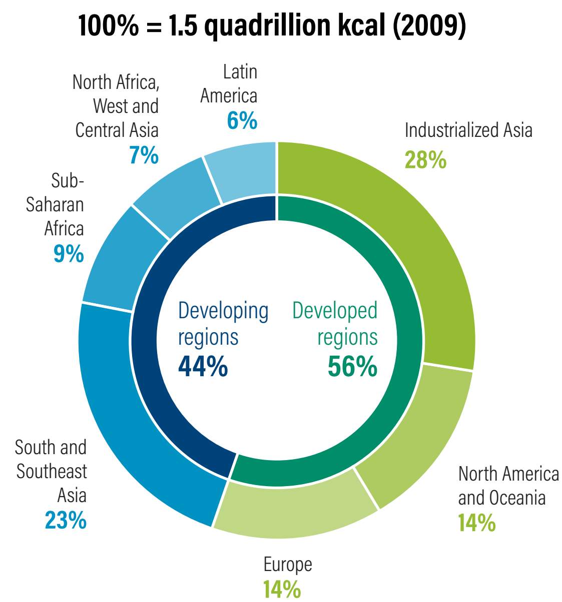


Note: Numbers may not sum to 100 due to rounding. Data are for the year 2009.
Source: WRI analysis based on FAO (2011c).

relative to their calories and require more natural resources to produce than cereals, the significance of their waste is greater than just their calories.[13]

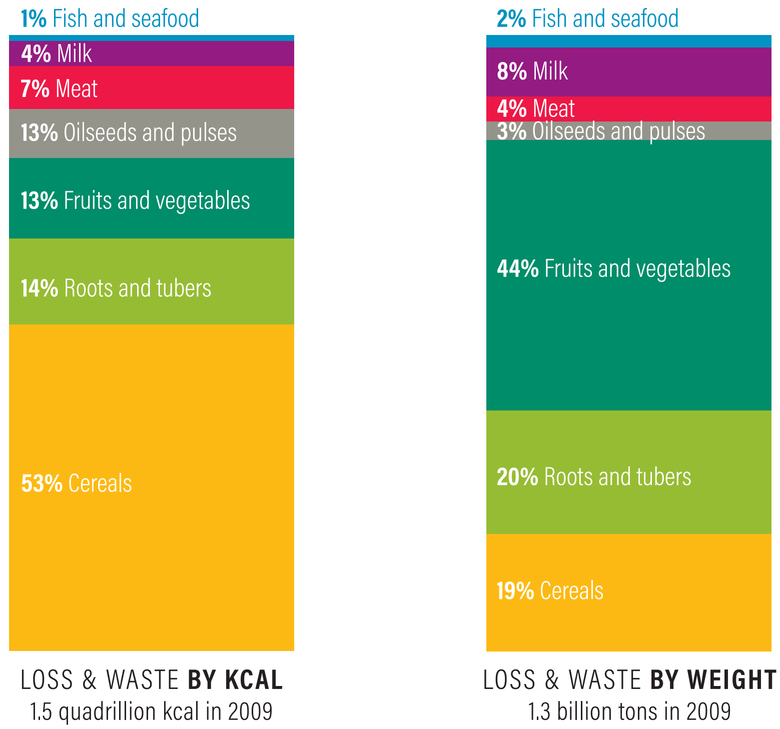
A significant challenge in reducing FLW results from the fact that most of the total FLW is caused in small quantities by different handlers. If one person or a single process in the food supply chain had a 25 percent rate of FLW, progress would be relatively easy. But for most individual farmers, companies, or consumers, the rates are less, which means each may have limited incentive to improve. Figure 5-6 illustrates the multiple causes of loss and waste estimated by a Nigerian study of gari, a traditional product made from cassava.[14] Total gari losses are more than 50 percent. Causes of losses vary from some of the tubers being too small or too woody to meet consumer preferences, to losses during storage. The largest cause of loss of edible gari occurs during the peeling stage. On the one hand, this example shows a hotspot of waste, which therefore should have large potential for improvement. On the other hand, even this hotspot causes less than half of the FLW.

Figure 5-4 | About 56 percent of food loss and waste occurs in developed regions and 44 percent in developing regions



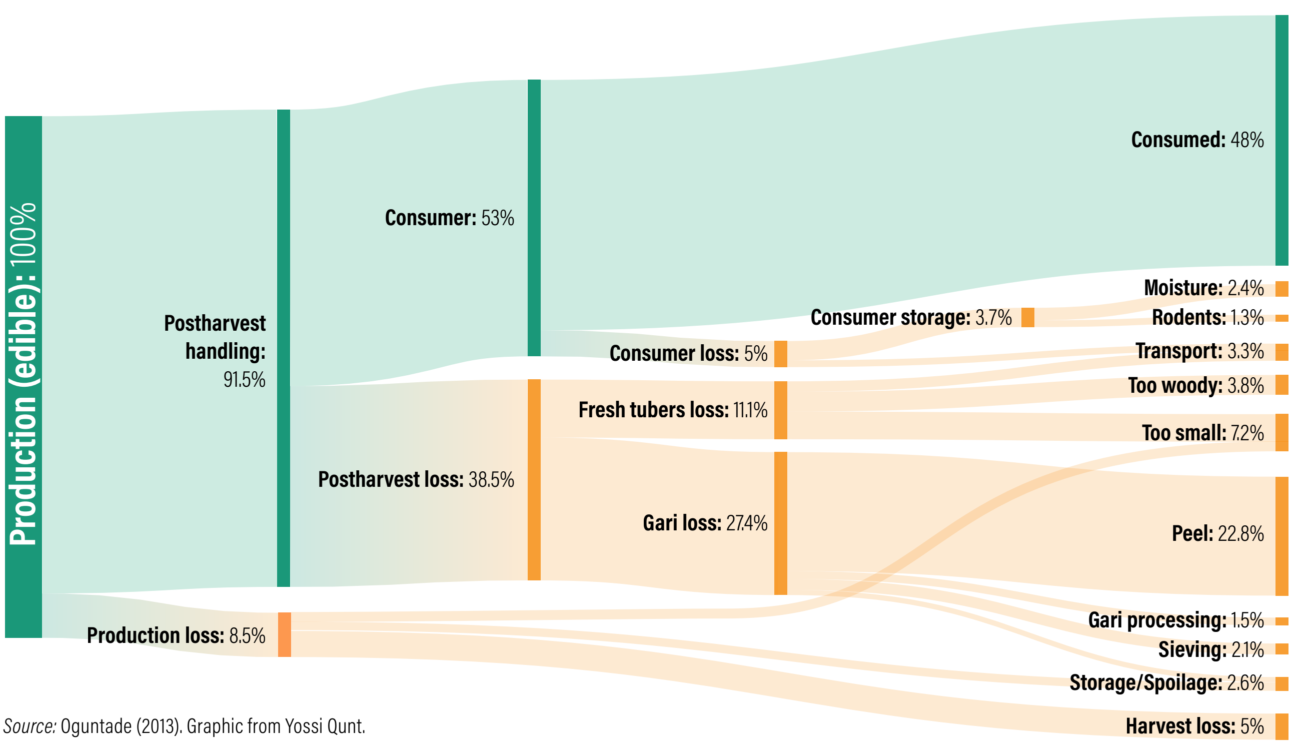
Source: WRI analysis based on FAO (2011c).

Figure 5-5 | Cereals comprise half of food loss and waste in terms of caloric content, while fruits and vegetables comprise just under half in terms of weight



Source: WRI analysis based on FAO (2011c).

Figure 5-6 | Food loss and waste occurs along the food supply chain: Example of gari (cassava) in Nigeria



Source: Oguntade (2013). Graphic from Yossi Qunt.

The Opportunity

From a purely technical perspective, potential reductions in FLW must be large because developed countries have managed to achieve relatively low loss rates at the harvest and storage stages of the food supply chain, while developing countries waste relatively little food during the consumption stage. But present levels of FLW represent the decisions of literally billions of farmers, processors, retailers, and consumers, and every one of them makes at least some effort not to lose or waste food or they would sell or consume nothing at all.

What is the evidence that public and private initiatives could reduce FLW? Although limited, evidence comes in three forms: experience with recent efforts, estimates of economic savings, and a variety of technical and management opportunities.

Recent experience

The United Kingdom launched a nationwide initiative to reduce food waste in 2007 and has probably put more effort into reducing food waste than any other country (Box 5-2). By 2012, the United Kingdom achieved a 21 percent reduction in household food waste relative to 2007 levels, and a 14 percent reduction in total FLW.

Economic savings

The potential for economic savings, documented by several studies, also indicates the potential for change, and again the United Kingdom provides some of the most compelling evidence. For example, the United Kingdom's nationwide initiative saved households approximately £6.5 billion.[15] One study found that each £1 invested generated savings of £250 (although costs did not include any additional time or convenience costs to consumers).[16] In one specific urban effort in 2012–13, six West London boroughs implemented an initiative to reduce household food waste primarily through communications. The initiative resulted in a 15 percent reduction, with a benefit-cost ratio of 8 to 1 when considering the financial savings to the borough councils alone and 92 to 1 when factoring in the financial benefits to households.[17]

BOX 5-2 | How the United Kingdom reduced household FLW by 21 percent

Between 2007 and 2012, the United Kingdom achieved a 21 percent reduction in household FLW (equivalent to an estimated 14 percent total reduction in food loss and waste for the country), mostly through a variety of labeling and public relations efforts. For example, supermarket chains started printing tips for improving food storage and for lengthening shelf-life for fruits and vegetables directly onto the plastic produce bags in which customers place their purchases. Some chains shifted away from "Buy-One-Get-One-Free" promotions for perishable goods toward using price promotions on such goods instead. The government revised its guidance on food date labels, suggesting that retailers remove "sell by" dates—which many consumers mistakenly interpret as meaning that food was unfit to eat after that date—and instead display "use by" dates which more clearly communicate when food is no longer fit for consumption. In addition, many food manufacturers, food retailers, and local government authorities participated in the "Love Food Hate Waste" campaign that raised public awareness about food loss and waste and provided practical waste reduction tips through in-store displays, pamphlets, and the media.

Source: Lipinski et al. (2013).

To gain a wider perspective, along with the organization Waste and Resources Action Programme (WRAP), we surveyed efforts to reduce food loss and waste at nearly 1,200 business sites across 17 countries and more than 700 companies. They represented a range of sectors, including food manufacturing, food retail (e.g., grocery stores), hospitality (e.g., hotels, leisure), and food service (e.g., canteens, restaurants). We found that the median benefit-cost ratio was 14 to 1 across all types of companies, while hotels, food manufacturers, and food retailers tended to have ratios between 5 to 1 and 10 to 1.[18]

Technical and management approaches to reducing FLW

The last piece of evidence comes from the variety of practical, technical, and management approaches to reduce FLW. Figure 5-7 lists some of these approaches that show the most promise for near-term gains.[19] We highlight examples of opportunities at each major step in the chain.

Production stage

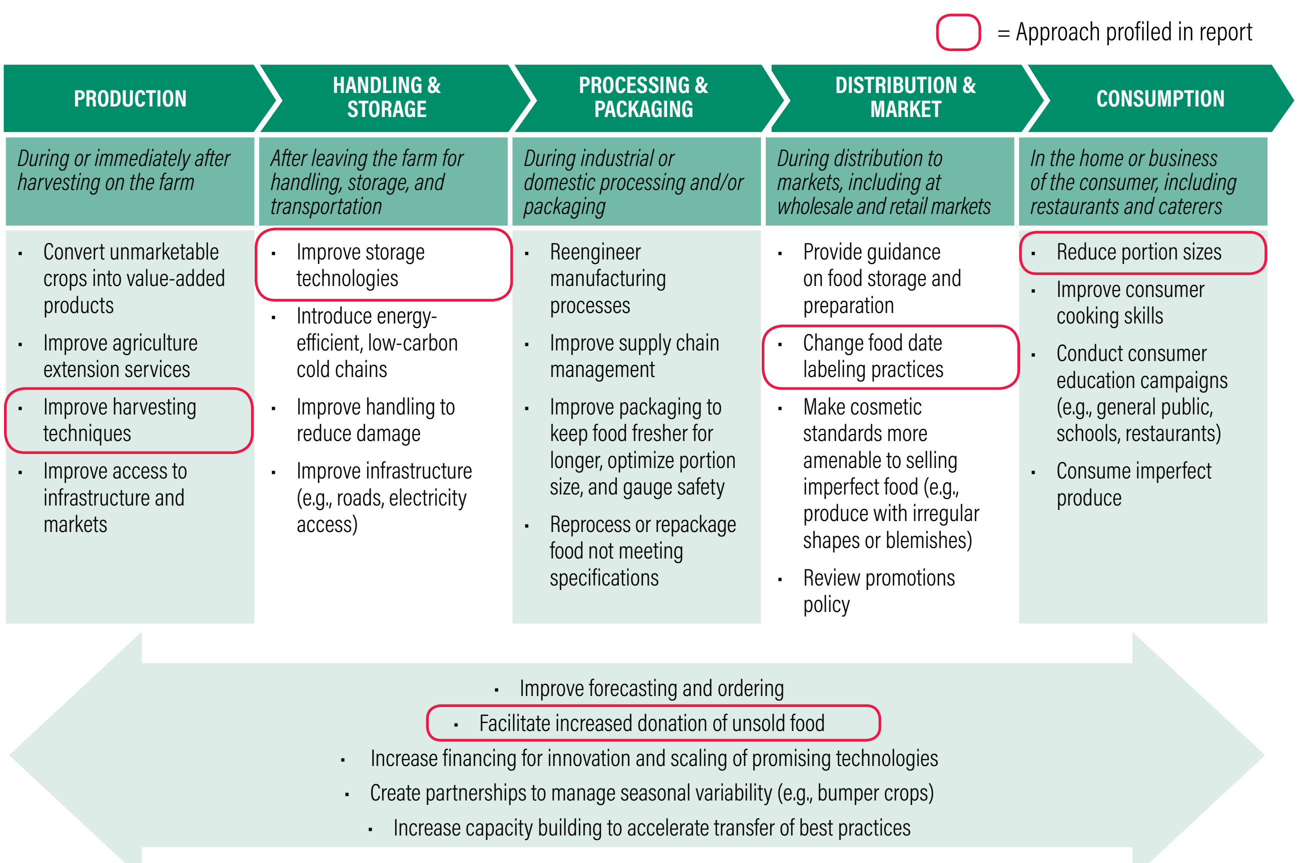
FLW in the production stage often occurs because of poor harvesting equipment, because of uneven ripening, or because bad weather prevents crops from being harvested in time. In Senegal in the early 1990s, hand threshing processes led to losses of 35 percent of harvested rice. Researchers worked with farmers to modify a mechanized threshing tool for local conditions that proved able to harvest six tons of rice per day and capture 99 percent of grains. Despite a cost of $5,000, the benefits were sufficiently high that the technology is today used in half of rice production in Senegal.[20] Similar harvesting technology improvements are needed across a wide array of crops.

Handling and storage stage

In developing countries, limited refrigeration and food processing lead to large storage losses, yet innovative, cheap alternative storage systems provide powerful technical options to reduce handling and storage losses.

Evaporative coolers. Evaporative cooling is a relatively low-cost method of preserving fruits, vegetables, roots, and tubers, especially in regions where electric refrigeration is either prohibitively expensive or unavailable.[21] Evaporative coolers are based on the principle that when air passes over a wet surface, water evaporates and withdraws heat from the surface, creating a cooling effect upon that surface. One vessel, holding the food being stored, is placed inside another vessel filled with water. As the water evaporates, the inner vessel stays cool and water is refilled as needed.[22]

Figure 5-7 | A wide range of approaches could reduce food loss and waste (not exhaustive)



Source: Hanson and Mitchell (2017).

Table 5-1 | Increases in shelf life via zero-energy cool chamber

CROP	SHELF LIFE (IN DAYS)		ADDED SHELF LIFE (PERCENT)
	ROOM TEMPERATURE	ZERO-ENERGY COOL CHAMBER	
Banana	14	20	43%
Carrot	5	12	140%
Cauliflower	7	12	71%
Guava	10	15	50%
Lime	11	25	127%
Mango	6	9	50%
Mint	1	3	200%
Peas	5	10	100%
Potato	46	97	111%

Source: Adapted from Roy (n.d.).

Evaporative coolers are constructed from locally available materials and do not require elaborate training. Extension agencies could help spread awareness of their potential to preserve food (Table 5-1), and agencies could also create demonstration sites showing how to construct a zero-energy cool chamber.[23]

PICS bags. To reduce pest damage, researchers at Purdue University have developed a simple reusable plastic storage bag, the Purdue Improved Cowpea Storage (PICS) bag. PICS uses three bags nested within each other, with the innermost bag holding the crop being stored. After filling, each bag is tied tightly to form an airtight seal.[24] Although designed originally for cowpeas, the bags may be useful for other crops as well.[25]

The main obstacle to more widespread use is the limited availability of PICS bags in many countries, due to the low density of agricultural input retailers.[26] In some parts of Niger, for example, the average distance to a PICS retailer is nearly 13 kilometers.[27] Low levels of awareness about PICS bags can also be a constraint.[28] High import tariffs on raw materials for manufacturing the bags add to the cost, as do high transportation costs for vendors who sell the bags. These kinds of constraints can be overcome through education by extension services, increased support by donors, and reduction of tariffs on key material imports.

Processing and packaging stage

Causes of FLW during this stage include discarding of damaged food, losses by inefficient factory machinery, and food never processed because of poor order forecasting. Potential improvements include changes in production processes, and improvements in forecasting and responses to changes in orders.[29]

This stage is also where opportunities exist to improve the long-term resistance of products to spoilage. Traditional approaches include canning, pickling, and drying, but opportunities exist for some "next-generation" approaches.

The Apeel Science company, for example, has illustrated the potential for innovation by developing sprays of thin lipids to coat fruits and vegetables from organic sources. The sprays have extended shelf life by 30 days or more. The lipid, extracted from plant material such as banana leaves and peels, is designed separately for each fruit or vegetable. It helps hold in water, which prevents fruits and vegetable from shriveling. It also controls the exchange of gases between the interior of the fruit or vegetable and the atmosphere, particularly oxygen and ethylene, to slow decay. Finally, it blocks the ability of bacteria on the surface of foods to sense that they are near a food source, and thus the bacteria multiply much slower.[30] Because this method works without refrigeration, it offers great potential benefits in developing countries with limited refrigeration.

Distribution and marketing stage

The United Kingdom group WRAP studied loss and waste that occurs in the retail sector in the United Kingdom and found that although loss and waste levels were fairly low, one-seventh could be avoided through improved packaging and handling, stock ordering, and inventory control.[31] It also found that another two-sevenths could be donated to charities for distribution and consumption.

The leading obstacles to food donations are related to transportation and legal or economic factors. Farmers and stores with surplus food might not be physically close enough to food banks or food rescue groups to deliver unused food economically. Prospective food donors might be concerned about legal repercussions should the food somehow be unsafe and the recipients of the food suffer health consequences.[32]

Although the transportation obstacles can be difficult to address, establishing additional food banks could lessen travel distances and make redistribution easier for many farmers and retailers. An adequately funded nonprofit organization could run scheduled retrieval services, driving to farms and retail stores, picking up donated goods, and delivering to food banks. Internet apps are now being rolled out that inform food banks when unsold food is available at retail stores in near-real time.[33]

To address the legal obstacle, governments can pass “Good Samaritan” laws that limit the liability of donors in case redistributed food unexpectedly turns out to be somehow harmful to the consumer.[34] These laws generally do not protect against gross negligence or intentional misconduct but instead assure food donors that they will not be penalized for redistributions made in good faith.[35] In addition to granting legal protection to donors, these laws may also be seen as an endorsement of food redistribution, bringing it to the attention of those who might not have considered the practice.[36]

To help address the economic obstacles, governments could introduce tax incentives for food donations. In the United States, the states of California, Arizona, Oregon, and Colorado have passed state laws providing tax credits for food redistribution to state food banks.[37]

Consumption stage

One obvious reason for food waste by consumers in restaurants and other food service providers is excessive portion sizes.[38] Restaurants use larger portion sizes as selling points to suggest to consumers that they are receiving good value for their money.[39] However, this trend toward larger sizes causes more food waste when customers are unable to finish a meal, and also contributes to obesity and overconsumption of food. On average, U.S. diners do not finish 17 percent of the food they buy at restaurants and leave 55 percent of these leftovers behind.[40]

Reducing portion sizes is one straightforward approach to reducing this food waste. Another option is offering smaller portion sizes at a lower price while still offering larger portion sizes at a higher price. This approach would allow customers with smaller appetites to order a smaller meal and presumably leave less of it behind, while also lowering preparation costs for the restaurant.[41]

In a buffet or cafeteria-style food service environment, however, the customer generally determines the portion size of food purchased—but food service operators can eliminate cafeteria-style trays and make customers carry the food they purchase on plates, which prevents “hoarding.” One study of dining halls in 25 U.S. universities found that eliminating trays reduced food waste by 25–30 percent.[42]

Some of the FLW in homes occurs because of confusion about spoilage dates. Dates provided on the packaging of food and drinks are intended to provide consumers with information regarding the freshness and safety of foods. However, these seemingly simple dates can confuse consumers about how long food may be safely stored. One study, for instance, found that one-fifth of food thrown away by households in the United Kingdom is disposed of because the food is perceived to be “out of date” due to labeling, when in fact some of the food is still suitable for human consumption.[43]

Part of the confusion surrounding product dating results from multiple dates that might appear on the packages. For example, three commonly seen terms in the United States are “use by,” “sell by,” and “best before,” none of which are required by the federal government.[44] “Sell by” informs the store how long to display the food product. “Best by” recommends the date before which a product should be consumed in order to experience peak flavor and quality. Only “use by” concerns product safety, indicating the last date recommended for safely consuming the food product. However, consumers often view each of these dates as being a measure of food safety.[45]

Manufacturers of food products could also move to a “closed date” system, which would replace a “sell by” date with a code that can be scanned or read by the manufacturer and retailer, but not by the consumer. To reduce confusion, retailers can post in-store displays, provide leaflets and online guidance, or print messages on grocery bags that define the various food date labels and explain the differences between them. A sign of progress is that in 2017 the Consumer Goods Forum organized a “call to action” to streamline food date labels by 2020 in accordance with these recommendations.

Model Results

Because coordinated efforts to reduce FLW are relatively new, we cannot know how much reduction of what kind of food loss or waste, and in which regions, is truly economical or practicable. We therefore chose to model in GlobAgri-WRR only “across the board” estimates of reduction in rates of FLW for each food in each region by 2050 compared to present FLW rates. For our three levels of ambition (Coordinated Effort, Highly Ambitious, and Breakthrough Technologies), we model FLW reductions of 10, 25, and 50 percent to estimate how much each would close the food, land, and GHG mitigation gaps. The 50 percent reduction reflects the FLW reduction target in the UN Sustainable Development Goals (SDGs), but we believe this level of reduction will require major new technologies, such as the Apeel coatings that dramatically change how easy it is to use and keep food without spoilage.

Not surprisingly, each of the scenarios would significantly contribute to meeting our food, land, and GHG targets (Table 5-2). To illustrate, a 25 percent reduction in FLW would make more food available and reduce the size of the food gap from a 56 percent shortfall in crop calories to 50 percent. It would close the land gap by 27 percent (163 million hectares [Mha]) and the GHG mitigation gap by 15 percent.

Recommended Strategies

To reduce food loss and waste, we recommend that public and private sector decision-makers follow a three-step approach: target, measure, and act.

1. Target

Targets set ambition, and ambition motivates action. In September 2015, a historic window of opportunity opened to elevate the issue of food loss and waste reduction on the global agenda as the UN General Assembly formally adopted a set of 17 SDGs—global goals to end poverty, protect the planet, and ensure prosperity. These goals include SDG Target 12.3, which calls for cutting in half per capita global food waste at the retail and consumer levels and reducing food losses along production and supply chains (including postharvest losses) by 2030. Implicitly, governments have accepted this goal. But because it is only one of 169 targets, it may not be garnering sufficient attention. To create the needed focus, governments and companies should adopt explicit food loss and waste reduction targets aligned with SDG Target 12.3.

How much progress has been achieved to date? The United States, the European Union, Australia, Japan, Norway, and the African Union[46] have now adopted specific FLW reduction targets consistent with Target 12.3. Courtauld 2025, a voluntary commitment on the part of more than 100 businesses and government agencies in the United Kingdom, has set a target for FLW reduction that will put the country on a trajectory to deliver Target 12.3.[47] Several groups of companies have also set reduction targets, including the Consumer Goods Forum (CGF), the Global Agri-business Alliance, and 2030 Champions (a U.S. business partnership).[48]

Table 5-2 | Global effects of 2050 food loss and waste reduction scenarios on the food gap, agricultural land use, and greenhouse gas emissions

SCENARIO	FOOD GAP, 2010–50 (%)	CHANGE IN AGRICULTURAL AREA, 2010–50 (MHA)			ANNUAL GHG EMISSIONS, 2050 ($GT CO_2E$)			GHG MITIGATION GAP ($GT CO_2E$)
		Pastureland	Crop-land	Total	Agricultural production	Land-use change	Total	
2050 BASELINE	**56**	**401**	**192**	**593**	**9.0**	**6.0**	**15.1**	**11.1**
10% reduction in rate of food loss and waste *(Coordinated Effort)*	54	367 (-34)	159 (-33)	526 (-67)	8.9	5.5	14.4	10.4 (-0.7)
25% reduction in rate of food loss and waste *(Highly Ambitious)*	50	318 (-84)	112 (-79)	430 (-163)	8.7	4.7	13.4	9.4 (-1.6)
50% reduction in rate of food loss and waste *(Breakthrough Technologies)*	44	240 (-162)	39 (-152)	279 (-314)	8.3	3.6	11.9	7.9 (-3.1)

Notes: "Cropland" includes cropland plus aquaculture ponds. Numbers not summed correctly are due to rounding. Numbers shown in parentheses are changes relative to 2050 baseline.
Source: GlobAgri-WRR model.

Going forward, notable gaps in explicit adoption of a food loss and waste reduction target need to be closed, including the following:

- Targets by developing and middle-income countries outside of Africa
- Targets set as part of implementing a country's nationally determined contribution (NDC) to the Paris Agreement on Climate Change (only Rwanda's NDC currently includes a quantified food loss and waste reduction target as part of its strategy)[49]
- Targets at the subnational level, including cities

2. Measure

The adage that "what gets measured gets managed" has particular significance for FLW because data are still relatively weak. For instance, existing globally consistent estimates are at the near-continental scale and rely on extrapolations from a limited set of target studies. Moreover, different analyses even of one commodity within one country can produce a wide range of estimates. To prioritize reduction strategies and track progress, decision-makers need not just better overall estimates but also estimates of where and why FLW occurs in the food chain.

How much progress has been achieved to date? Some governments and companies have started quantifying their food loss and waste and are publishing the results. Country and region leaders include the United Kingdom, the United States, and the European Union. City leaders include Denver, Jeddah, London, Nashville, and New York. Although many companies measure and report on overall material waste levels, only a handful specifically measure food loss and waste and report on it separately. Among those that do, Tesco—one of the world's largest food retailers—has conducted an annual food loss and waste inventory for its operations since 2013 and publicly reported the results.[50]

Going forward, more governments at the national and subnational levels and companies need to start quantifying and reporting on their food loss and waste. The release of the Food Loss & Waste Protocol's[51] *Food Loss and Waste Accounting and Reporting Standard* in 2016 can help with this quantification. The *FLW Standard* provides global requirements and guidance for quantifying and reporting on the weight of food and/or associated inedible parts removed from the food supply chain.[52] The *FLW Standard* empowers countries and companies to create base-year food loss and waste inventories and quantify progress over time toward meeting Target 12.3 or any other goals they may have. Measurement does not need to be a complex and resource-intensive exercise. Quantification and periodic monitoring can be integrated with other resource monitoring programs that governments and companies have in place.

3. Act

How much progress has been achieved to date? Efforts to address food loss and waste are not new, and activity in many places has been ongoing for some time. But since the launch of the SDGs in 2015, many governments and businesses have started to tackle high rates of FLW. For instance, some food retailers now are selling imperfectly shaped but perfectly nutritious produce that in previous years would have been discarded at the farm because it did not meet cosmetic standards. Internet-based apps are now being used by food retailers and restaurants to quickly transport unsold—yet still safe—food to charities, feeding those in need and avoiding food waste. Coalitions involving food service companies such as Sodexo are now working collaboratively to reduce food waste in schools and elsewhere.[53] Innovations in crop storage continue to gain popularity in Africa.[54]

What is needed going forward? Given the scale of the food loss and waste challenge, there is a need for more action by more entities across more regions. Exactly what should be done varies between entities and by stage in the food supply chain; no simple, single recommendation can adequately capture the actions needed. In many developing regions, a majority of food loss occurs between the point of harvest and when the food reaches the market. Thus pursuing actions during the production, storage, and processing stages of the food supply chain are important. In developed regions, as well as in rapidly growing urban areas just about everywhere, a significant share of food waste occurs closer to the fork. Thus pursuing actions during the market and consumption stages is vital.

Figure 5-7 lists some of the approaches that the authors, literature, and interviews suggest could be particularly practical and cost-effective, could be implemented relatively quickly, and could achieve near-term gains once put into place at the appropriate stage in the food supply chain.[55] Some involve large-scale infrastructure development. For instance, building roads and introducing electric-powered refrigeration in low-income countries would contribute to reducing food losses from spoilage during the handling and storage stage by enabling fresh food to get to market more quickly.[56] Others involve targeted technology, policy, and consumer behavior interventions.

For more detail about this menu item, see "Reducing Food Loss and Waste," a working paper supporting this World Resources Report available at www.SustainableFoodFuture.org.

CHAPTER 6

MENU ITEM: SHIFT TO HEALTHIER AND MORE SUSTAINABLE DIETS

The food gap assumes that by 2050 several billion people will increase their consumption of calories, protein, and animal-based foods—including not only meat but also dairy, fish, and eggs. This menu item involves shifting the diets of people who consume high amounts of calories, protein, and animal-based foods.

Although we explore a range of scenarios, we identify reductions in consumption of ruminant meat (beef, sheep, and goat) as the most promising strategy for reducing land requirements and GHG emissions—while also achieving health benefits. Other researchers have also found that shifting diets can mitigate climate change, but by counting the full consequences of diets for land use, we find that diets in general—and consumption of ruminant meat in particular—are even more significant for GHG mitigation than commonly understood.

The Challenge

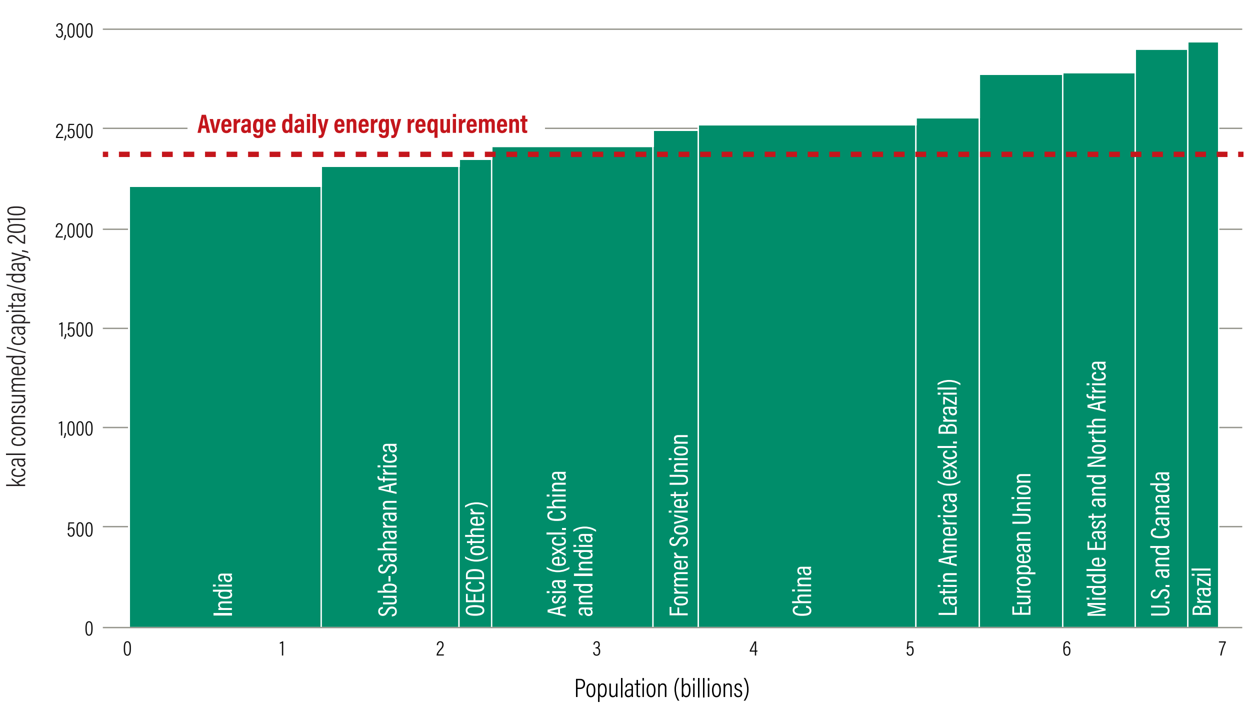
The global convergence toward Western-style diets will make it harder for the world to achieve several of the UN Sustainable Development Goals, including those related to hunger (SDG 2), good health and well-being (SDG 3), water management (SDG 6), climate change (SDG 13), and terrestrial ecosystems (SDG 15).

The great dietary convergence

Around the world, diets are converging toward the Western style—high in refined carbohydrates, added sugars, fats, and animal-based foods. As part of this shift, per capita consumption of beans and other pulses,[57] other vegetables, coarse grains, and dietary fiber is declining.[58] Rising incomes provide the main stimulus for this shift because they allow people to eat more resource-intensive foods, particularly meat and dairy.[59] Urbanization provides easy and convenient access to these foods and encourages consumption of foods prepared outside the home, including "convenience" or fast food.[60] Both advertising and improvements in the processing and transportation of meat and other resource-intensive foods encourage more consumption.[61]

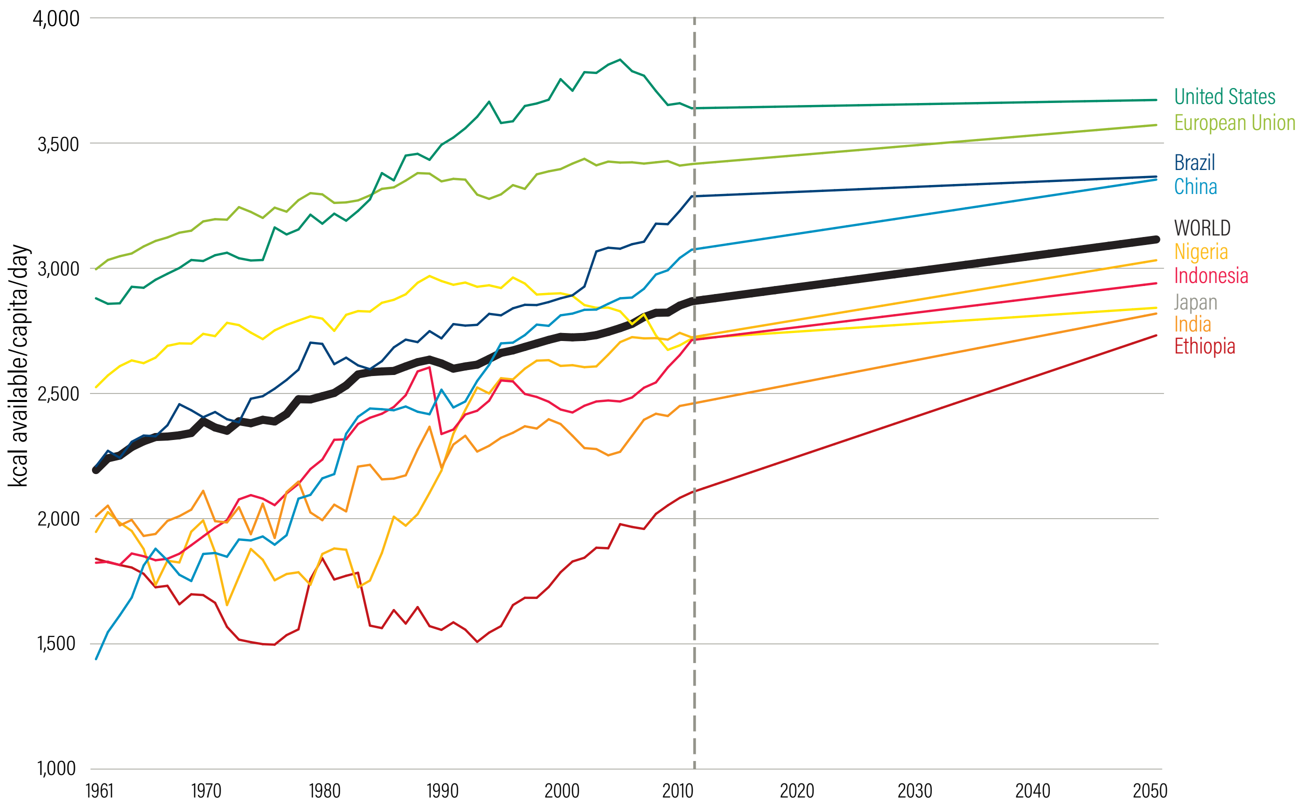
Even as chronic hunger remains widespread in poor countries, the average consumption of calories is already above daily energy requirements in most world regions (Figure 6-1).[62] These excesses are likely to grow (Figure 6-2).

Figure 6-1 | Average per capita calorie consumption exceeds average daily energy requirements in most world regions



Note: Width of bars is proportional to each region's population. Average daily energy requirement of 2,353 kcal/capita/day is given in FAO (2014a). Individuals' energy requirements vary depending on age, sex, height, weight, pregnancy/lactation, and level of physical activity.
Source: GlobAgri-WRR model with source data from FAO (2019a) and FAO (2011c).

Figure 6-2 | Per capita calorie availability is on the rise



Source: FAO (2019a) for historical data 1961–2011; Alexandratos and Bruinsma (2012) for 2050 projection, linear interpolation from 2012 to 2050.

Most people also consume more protein than they need, and protein consumption is still growing. The average daily protein requirement for adults is around 50 grams per day, which incorporates a margin of safety to reflect individual differences.[63] Although some people are deficient in protein, global average protein consumption per capita in 2010 was approximately 71 grams per day. In the world's wealthier regions, protein consumption was even higher (Figure 6-3).[64] By 2050, we estimate that global average per capita protein consumption will rise to nearly 80 grams per day (Figure 6-4).[65]

This overconsumption of protein results from growth in demand for animal-based foods. Between 1961 and 2009, the global average availability of animal-based protein per person grew by 59 percent, while that of plant-based protein grew by only 14 percent.[66] By 2010, as Figure 6-3 shows, more than half the protein in the world's wealthiest regions was animal-based. Arguments that this animal-based protein is necessary for health, or "efficient" because of "essential amino acids," are incorrect (Box 6-1).

The continuing shifts to animal-based diets plus the rise in population are likely to drive a large growth in demand for animal-based foods (Table 6-1). Between 2010 and 2050, we project additional global growth in demand for animal-based foods to be 68 percent.[67] We project even more growth in demand for ruminant meat (beef, sheep, and goat) at 88 percent.

BOX 6-1 | Debunking protein and meat myths

Protein is an essential macronutrient for building, maintaining, and repairing the human body's tissues. Nine of the 20 amino acids that are used to make protein cannot be produced by the human body and must be obtained from food. However, several myths overstate the dietary importance of protein, especially from animal-based sources.

Myth: Animal-based foods are necessary or efficient because they supply some essential amino acids.

People cannot make nine "essential amino acids" (EAAs) and must therefore acquire them from foods. Animal-based foods provide all of these essential amino acids while individual plant-based foods—with the exception of soy, quinoa, and a few others—lack some EAAs. However, for any person receiving adequate calories, it is not difficult to acquire the required EAAs just by consuming a small amount of animal-based foods, or just by combining different plant-based foods. Rice and beans or peanut butter and bread are examples of such combinations.

One recent article claimed that vegan diets were inefficient based on a calculation that if a person ate only a single food, that person would have to eat so much of any plant-based food (e.g., rice) that a meat-based diet would produce fewer GHGs.[a] However, people do not eat only one food. All the alternative diets we analyze in this report with less or no meat supply EAAs many times the necessary minimum amounts.

And while meat also contains high levels of other essential micronutrients, including iron, A and B vitamins, and zinc, even a diverse diet based entirely on plants can provide an adequate supply of micronutrients.[b] The exception is vitamin B12, which only occurs naturally in animal-based foods, but which people can obtain through supplements.[c]

Myth: More protein is better.

More protein is not necessarily better, unless an individual is malnourished or undernourished. Although the word "protein" comes from the Greek *proteios*, meaning "of prime importance," protein is no more important than the other nutrients required for good health, and many people do not need as much protein as they believe. For instance, the average U.S. adult consumed 66 percent more protein per day in 2012 than the average estimated daily requirement, but 21 percent of adults still considered themselves deficient in protein in a 2014 survey.[d] The World Health Organization suggests that only 10–15 percent of the daily calorie requirement needs to come from protein.[e] A balanced plant-based diet can easily meet this need. Meanwhile, overconsumption of protein is linked to some health problems, including kidney stones and the deterioration of kidney function in patients with renal disease.[f]

Myth: Plant-based foods need to be combined in single meals to meet protein nutritional needs.

In fact, separate consumption of amino acids during different meals still ensures nutritional benefits[g] because the body breaks down proteins into separate amino acids, which it stores for later use.[h]

Notes:
a. Tessari et al. (2016).
b. Craig and Mangels (2009).
c. Antony (2012).
d. USDA (2014), French (2015).
e. WHO (2003).
f. WHO, FAO, and UNU (2007).
g. Young and Pellett (1994).
h. *Tufts University Health & Nutrition Letter* (2012).

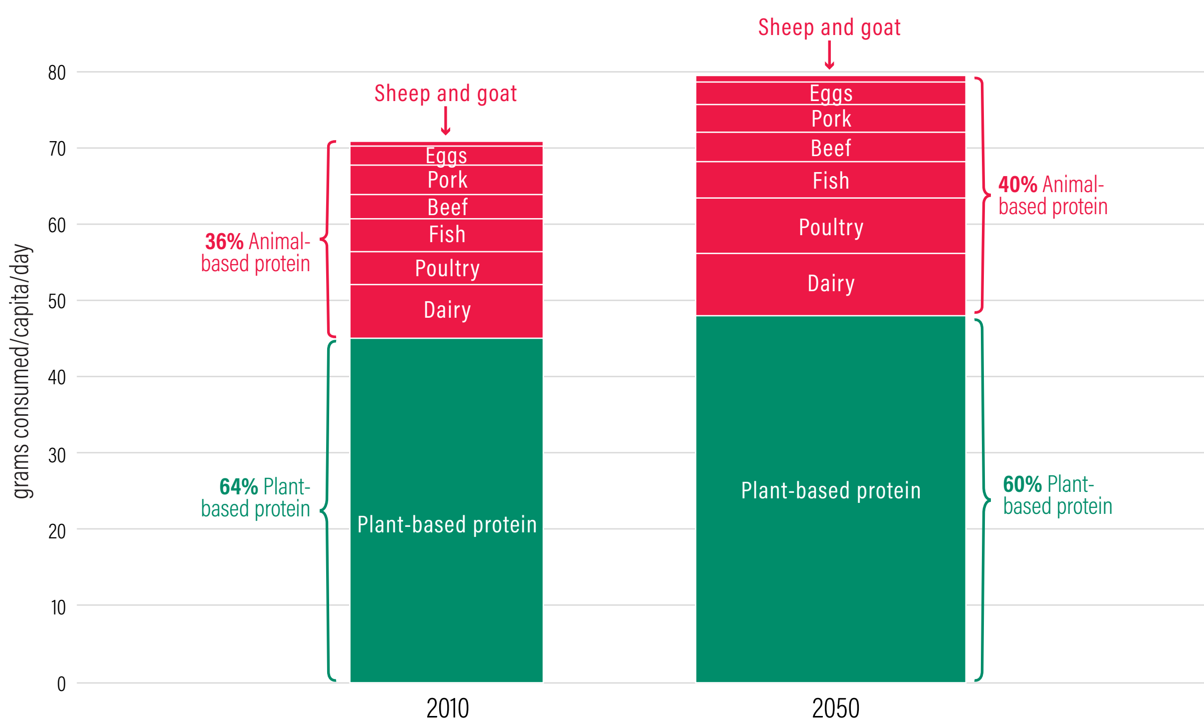
Even these figures, based on FAO projections of 2050 diets, may be conservative. A majority of global agricultural models, and other analyses that link animal-based food consumption to income, project substantially greater increases in animal-based food consumption.[68] Today U.S. per capita consumption of all animal-based foods is 750 kcal.[69] Although FAO projects that more than 3.6 billion of the world's people will equal or approach this consumption (more than 600 calories per person per day) (Table 6-1), its projections also imply that 6.1 billion people in poorer regions (India, Asia outside of China and India, Middle East and North Africa, and sub-Saharan Africa) will still eat few animal-based foods in 2050 (Table 6-1). In sub-Saharan Africa more than 2 billion people will consume on average just 200 kcal per person per day. If these 6.1 billion people were to consume, on average, even 450 kcal of animal-based foods per day by 2050, the growth in demand for animal-based foods would rise from the 68 percent in our 2050 baseline to 92 percent.[70]

FAO's projection of a continued inequitable distribution of animal-based food consumption has important implications when developing options for a sustainable food future. It means that large *global* reductions in meat and dairy consumption by all would be highly inequitable. Instead, policy should focus on substantial reductions in high-consuming regions. It also means that some reductions in animal-based food consumption by the world's wealthier populations will be important just to open

Figure 6-3 | Average protein consumption greatly exceeds average estimated daily requirements in the world's wealthier regions

Note: Width of bars is proportional to each region's population. Average daily protein requirement of 50 g per day is based on an average adult body weight of 62 kg (Walpole et al. 2012) and recommended protein intake of 0.8 g per kg body weight/day (Paul 1989). Individuals' energy requirements vary depending on age, sex, height, weight, pregnancy/lactation, and level of physical activity.
Source: GlobAgri-WRR model with source data from FAO (2019a) and FAO (2011c).

Figure 6-4 | Both global protein consumption and the share from animal-based foods are likely to grow by 2050



Note: Width of bars is proportional to world population.
Source: GlobAgri-WRR model with source data from FAO (2019a) and FAO (2011c).

Table 6-1 | Projected regional changes in consumption of animal-based foods

REGION	POPULATION (MILLIONS)		TOTAL ANIMAL-BASED FOODS				RUMINANT MEAT (BEEF, SHEEP, GOAT)			
	2010	2050	kcal/ capita/ day (2010)	kcal/ capita/ day (2050)	% change per capita (2010–50)	% of global consumption (2050)	kcal/ capita/ day (2010)	kcal/ capita/ day (2050)	% change per capita (2010–50)	% of global consumption (2050)
European Union	528	528	772	858	11	10	68	71	4	7
U.S. and Canada	344	433	774	794	3	7	92	82	-10	6
Brazil	197	233	629	748	19	4	140	153	9	6
China	1,390	1,396	551	716	30	21	33	62	87	15
Former Soviet Union	288	298	575	704	22	4	93	119	28	6
OECD (other)	205	198	489	615	26	3	55	77	41	3
Latin America (excl. Brazil)	400	547	462	605	31	7	87	110	27	11
Asia (excl. China and India)	1,035	1,476	263	418	59	13	23	37	62	9
India	1,231	1,659	195	419	114	15	9	24	181	7
Middle East and North Africa	460	751	308	402	30	6	50	70	40	9
Sub-Saharan Africa	880	2,248	155	201	29	10	39	53	38	21
World	**6,958**	**9,772**	**403**	**481**	**19**	**100**	**44**	**59**	**34**	**100**

Note: Regions are listed in order of projected daily per capita consumption of total animal-based foods in 2050.
Source: GlobAgri-WRR model with source data from FAO (2019a); UNDESA (2017); FAO (2011c); and Alexandratos and Bruinsma (2012).

up "planetary space" for additional consumption of animal-based foods by the world's poor.

The consequences of the dietary convergence for health and nutrition

When incomes first rise above poverty levels, dietary changes have health benefits, including some additional consumption of meat and dairy. These diet shifts can reduce chronic shortages of calories and many important nutrients, reducing the numbers of stunted and underweight children, and providing a range of health benefits, particularly for children.[71] (The production of modest levels of livestock products by the rural poor also plays a valuable economic role in reducing poverty and therefore helps avoid hunger through that pathway, too.)[72]

However, shifts toward Western-style diets can cause a range of health problems. Overconsumption—combined with sedentary lifestyles—affects nutritional and health outcomes, including weight, and the prevalence of noncommunicable diseases.[73] Diet-related noncommunicable diseases include hypertension, type 2 diabetes, stroke, cardiovascular diseases, and certain types of cancer.[74]

The clearest evidence of diet-related health risks involves obesity, which is linked to all of the illnesses listed above[75] and to an increased risk of premature death.[76] Obesity causes large increases in health care costs.[77] Obesity also adversely affects productivity, with costs estimated in the tens of billions of dollars per year in the United States and Europe.[78] The McKinsey Global Institute estimated the worldwide economic impact of obesity in 2012 to be around $2 trillion, or 2.8 percent of global gross domestic product (GDP), roughly equivalent to the global cost of armed conflict or smoking.[79]

The global obesity rate continues to grow. In 2013, 2.1 billion people were overweight or obese[80]—more than two and a half times the number of chronically undernourished people in the world.[81] Once considered a high-income country problem, the number of obese and overweight people is now rising in low- and middle-income countries.[82] In China, obesity rates tripled between 1991 and 2006.[83] Obesity is growing even in countries that have high levels of child stunting from insufficient food, such as Egypt, South Africa, and Mexico.[84]

Globally, there is some evidence that obesity rates may decline at high-income levels,[85] and may be nearing peaks in developed countries (in the neighborhood of 60% overweight or obese).[86] Using a variety of trends and association, Ng, Fleming, et al. (2014) suggest a global increase of roughly 10 percent from 2010 to 2050 in the rate of overweight and obesity.[87] This trend would bring the number of overweight and obese people to 3.1 billion by 2050.[88]

Another major area of health concern with Western-style diets is the link between high consumption of animal-based foods and a variety of diseases. For many years, the primary focus of attention was cholesterol and saturated fats and the linkages between their consumption and heart disease.[89] Although more recent studies call into question the links between high levels of saturated fats in diets and heart disease,[90] there still appears to be evidence that switching to other fats—including certain polyunsaturated fats more present in vegetable oils—can have some health benefits related to heart disease and diabetes.[91] Several studies have also linked red meat[92] consumption directly to type 2 diabetes, cardiovascular disease, and colorectal cancer.[93] The exact causal connections remain debated, with some research focusing the concern more on processed meats such as bacon and sausages.[94] The International Agency for Research on Cancer has classified processed meat as “carcinogenic to humans,” while listing red meat as “probably carcinogenic.”[95]

Because of these links, the World Cancer Research Fund recommends a population-wide limit of no more than 300 grams (or about three servings) of cooked red meat per person per week, a limit incorporated into the Dutch and Swedish national dietary guidelines.[96] Other researchers recommend even lower limits. Micha et al. (2017) propose 100 grams of red meat (about one serving) per person per week as the maximum “optimal” consumption level.[97]

Dietary implications for health remain contentious because it is difficult to distinguish the effects of diets on human health from the effects of other behaviors. Yet overall, there is good reason to believe that moderating the shift toward Western-style diets would be beneficial to human health.

The low feed and natural resource efficiency of meat and dairy

Animal-based foods have much greater environmental consequences than plant-based foods. Production of animal-based foods accounted for more than three-quarters of global agricultural land use and around two-thirds of agriculture’s production-related GHG emissions in 2010, while contributing only 36 percent of total protein and 16 percent of total calories consumed by people in that year.[98]

These consequences result from the inefficiency of animal-based foods, which has long led to calls to reduce their consumption for environmental reasons. Back in 1971, the book *Diet for a Small Planet* made these recommendations and became a best seller.[99] Many studies (Appendix B) since then have estimated large potential land and GHG benefits from reducing meat and dairy in diets because of their relative inefficiency in converting feed and other natural resources to provide a given quantity of human-edible food. The efficiency of meat and dairy production also has its defenders, whose arguments were cogently presented in a report by the Council for Agricultural Science and Technology (CAST) in 1999.[100] How inefficient, then, are animal-based foods and how do they differ from each other?

Although we agree with meat's defenders that many estimates incorporate some assumptions that overstate the inefficiency of animal-based foods, in more significant ways most calculations tend to understate that inefficiency.

- **Overestimates: Failure to compare the effects of meat consumption with realistic alternative diets**. Studies that fail to compare meat-heavy diets with realistic alternative diets can *overestimate* the possible environmental benefits of eating less meat. Many crops used for animal feeds—such as maize, wheat, alfalfa, and soybeans—have higher caloric and protein yields per hectare than many crops that people consume as alternatives to meat, such as beans, chickpeas, lentils, and vegetables. For example, global maize yields per hectare are roughly five times those of pulses. Some papers have incorrectly assumed that, if people ate less meat, they would instead consume these high-yielding animal feeds, rather than lower-yielding alternative foods that, in practice, they are more likely to eat.[101]

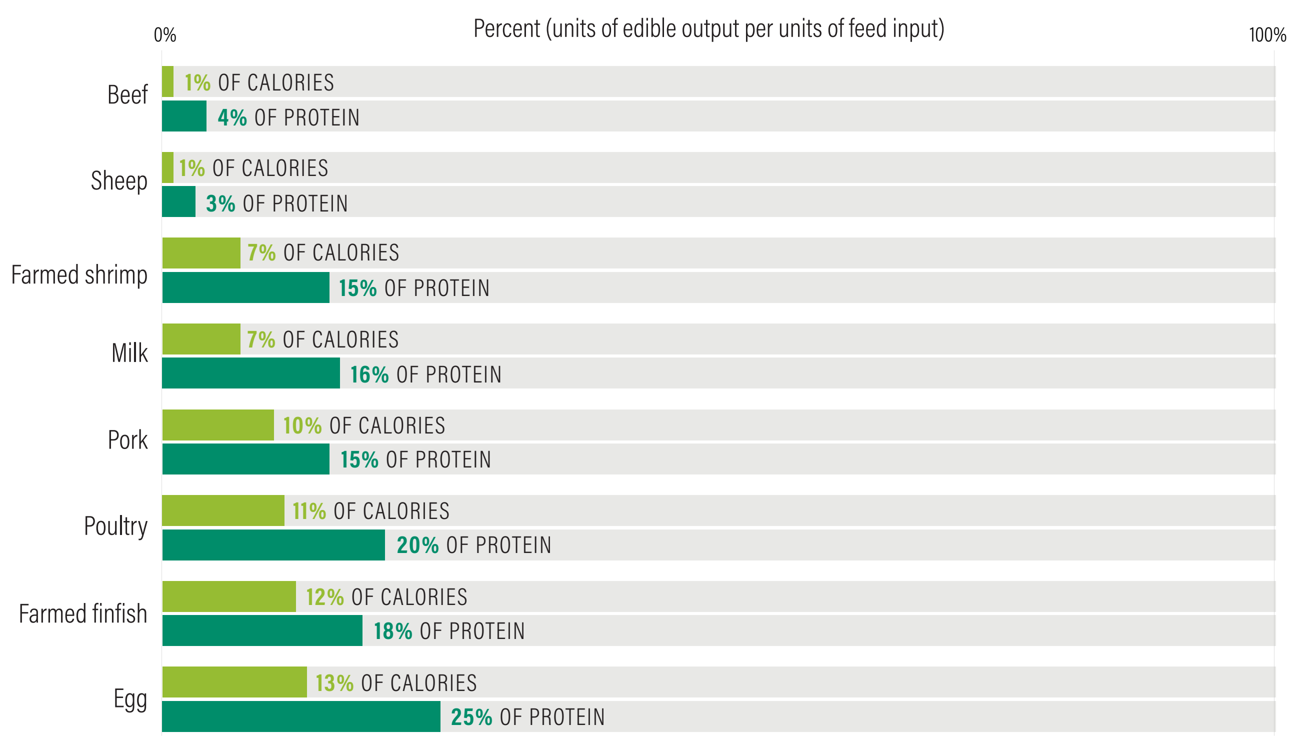
- **Underestimates: Calculating efficiency by weight instead of calories or protein and counting only some stages of production.** Some "feed conversion ratios" show the weight of meat out versus the weight of feed in.[102] This practice improperly compares the weight of a relatively wet output (meat) to the weight of a relatively dry input (feed grains). Focusing only on the feedlot stage of beef production and using weight measures, even critics of meat will often quote efficiency figures of 15 percent for beef (roughly a 7 to 1 ratio of feed in to food out),[103] which is far higher than the true efficiency of beef production (as we show below). A proper analysis should count all stages of production and compare feed calories in to food calories out, or protein in to protein out.

- **Underestimates: Failure to fully account for all animal feeds**. The most significant underestimate results from methods that count the environmental consequences of only "human-edible" animal feeds.[104] This approach excludes animal feed provided by crop residues and food processing wastes, which is defensible because they do not require additional land. But the approach also excludes grasses—whether hayed or grazed—which together constitute more than half of all livestock feed.[105] Counting only "human-edible" animal feeds means that if an animal eats primarily grasses, it may be seen as producing *more* than one calorie food out for each calorie of feed in.[106] This approach also ignores grazing land as a land-use input to food production. Even for most beef raised primarily in feedlots, this approach underestimates environmental consequences because it excludes all the grasses eaten by mother cows and their calves before calves are moved from pastures to feedlots.

Those analyses that count only human-edible feeds contend that only these feeds compete directly with human food supplies. However, of grasslands, those that produce the bulk of animal products are lands converted to pasture from forests and woody savannas. Some of these lands could be used instead to produce crops for direct human consumption and others could remain as natural vegetation to store carbon and provide other ecosystem services.

It is true that if people consumed no animal-based foods at all, many natural grazing lands would go unused for food production, and many residues and wastes would probably be underused or thrown out. But holding down growth in demand is not the same as eliminating consumption of animal-based foods altogether. Even with large reductions in demand for animal-based foods, those otherwise unused residues and wastes will still be used because they are cheap, and the consequence is likely to be less clearing of forests and savannas.

Figure 6-5 | Beef and other ruminant meats are inefficient sources of calories and protein



Notes: "Edible output" refers to the calorie and protein content of bone-free carcass. "Feed input" includes both human-edible feeds (e.g., grains) and human-inedible feeds (e.g., grasses, crop residues).
Sources: Terrestrial animal products: Wirsenius et al. (2010); Wirsenius (2000). Finfish and shrimp: WRI analysis based on USDA (2013a); NRC (2011); Tacon and Metian (2008); Wirsenius (2000); and FAO (1989).

BOX 6-2 | Modeling the greenhouse gas consequences of land required for different diets: Comparing GlobAgri-WRR with other approaches

The GlobAgri-WRR model estimates the GHG emissions from the additional area of agricultural land conversion required to produce each person's diet. Because land use is increasing, every change in diet that reduces (or increases) land-use demands avoids (or adds) that amount of land conversion.

Although this approach seems basic, other analyses have used a variety of approaches (Schmidinger and Stehfest 2012):

1. Land-use-change emissions are not estimated. Most conventional life-cycle assessments of agriculture (including most studies cited in Appendix B) estimate the land area required to produce the foods being studied but do not estimate the emissions associated with this land-use demand. Such studies limit estimates of GHG emissions to production emissions, such as methane from livestock and energy used to run farm machinery.

2. Only new land-use-change emissions are counted each year, and they are averaged over total agricultural production. Some studies count land-use-change emissions for a crop only in countries where both that crop and agricultural land overall are expanding. For example, if soybean area were to expand by 100,000 hectares per year during a study time frame in Brazil, and if total agricultural land in Brazil expanded by 100,000 ha or more, then the emissions from these 100,000 ha would be assigned to soybeans in Brazil. To obtain the emissions per ton of soybeans, the emissions would be divided by the millions of tons of soybeans produced in Brazil over its more than 20 million hectares of cropland. As a result, the emissions per ton of crop would be low. By contrast, in the United States, if soybeans' crop area was not expanding, or if it was expanding but agricultural land overall was not because other crop areas were shrinking, U.S. soybeans would have no land-use cost. As a result, if a European pork producer in Europe switched from using Brazilian to U.S. soybeans, that would be counted as eliminating its emissions from land-use change.

Of course, switching from Brazilian to U.S. soybeans does not reduce the total demand for global soybeans or the total demand for land (at least if the yields are the same). In fact, if some consumers switched from purchasing Brazilian soybeans to U.S. soybeans, either other consumers would switch from the United States to Brazil or the United States would need to devote more land area to soybeans. To avoid the consequences of counting GHG savings where none are likely to occur in reality, other studies do a similar calculation but on a global basis. For example, if we assumed for simplicity that all the world's soybeans were produced only in Brazil and the United States, all soybeans produced in both countries would be assigned emissions from Brazil's 100,000 hectares of land-use-change emissions. That would then divide the responsibility for Brazil's land-use change among all soybeans, but the cost assigned to each ton of soybeans would be even smaller than for Brazil's soybeans alone. To further illustrate this method, in a study period with no expansion of soybeans in Brazil, or if other cropland were shrinking by the same amount as soybeans were expanding, global soybean consumption would be viewed as having no land-use cost at all.

3. Land-use-change emissions are attributed to marginal (additional) agricultural production. This approach—which is what GlobAgri uses—focuses on the additional emissions from the additional land required to produce any additional amount of a crop or other food. For example, if consuming one ton of soybeans requires one-third of a hectare of additional cropland, each ton of soybeans is responsible for one-third of a hectare of cropland. Under this approach, land-use-change emissions per unit of food produced are much higher than in approach 2 and are never zero.

The problem with system 1 is simply that there are no land-use-change emissions assigned to foods.

One major problem with system 2 is that it does not mathematically assess the incremental, or "marginal," consequences of consumption. To understand the incremental effects of demand, imagine if there were no yield gains in one year and no changes in demand. As a result, agricultural land area would not change. If one person then switched to a diet that required one more hectare of land, the incremental effect of that dietary change would be one hectare. Yet, in that case, every person's consumption would incrementally contribute to this land-use change whether it existed in the previous year or not: If any other person or group of people shifted diets that required one hectare less to produce, there would be no land expansion. Averaging that hectare of land-use change instead to the total food consumption from every person's diet vastly undercounts the consequence of each person's consumption and the change in emissions that would result from that person's diet.

A simplified mathematical example also helps to illustrate this basic difference between incremental and average costs. Imagine a world with 100 people, each person eating only one ton of wheat, where each ton of wheat requires one hectare. In this world, there are therefore 100 hectares of wheat. Now imagine that in year two consumption goes up by 1 percent (perhaps from population growth or dietary changes), so there is now a demand for 101 tons of wheat. Farmers therefore clear one more hectare of land resulting in 100 tons of carbon dioxide emissions. The additional consumption of one ton of wheat therefore incrementally causes 100 tons of emissions.

BOX 6-2 | Modeling the greenhouse gas consequences of land required for different diets: Comparing GlobAgri-WRR with other approaches (continued)

GlobAgri-WRR counts one ton of wheat in this example as causing that level of emissions although it amortizes these emissions over 20 years of consumption. This approach recognizes that dietary change by any group of people to reduce consumption by one ton of wheat would save 100 tons of emissions. But under method 2, the 100 tons of emissions from one hectare of land-use change would be divided by the 101 tons of wheat consumed by everyone, so each ton of wheat is assigned 0.99 tons of emissions. That is a large underestimate of the consequences of dietary change, and the problem is not merely conceptual but, in this example, mathematically incorrect.

A likely reason some researchers have embraced system 2 is that standard GHG accounting methods assign the GHG costs of previous land-use change to the past. Under this approach, ongoing food consumption, unless it causes more land-use change, has no land-use costs. Yet even with such an assumption, the incremental costs of land-use change should be assigned to the incremental change in consumption that causes this change, not the total consumption.

Another way of viewing the problem with system 2 is that it does not assign any carbon cost to continued consumption of food produced on existing agricultural land—this land has no opportunity cost in lost carbon storage. Yet continuing to use existing agricultural land each year to meet even long-existing demand has costs. If not used to meet that preexisting demand, it could be used to meet new demand, avoiding land-use change. For this reason, reducing even preexisting demand enough to reduce agricultural area by one hectare still saves a hectare of expansion.

In fact, even if the world were experiencing a decline in agricultural land, each ton of food demand would still keep more land in agricultural use and therefore reduce the amount of abandoned land that would regrow forest and other native vegetation and sequester carbon. In such a world, the carbon cost of consumption would then be this forgone carbon sequestration. As we discuss in Course 3, as the locations of agricultural land shift around the world, the regrowth of carbon stocks on abandoned agricultural land already plays an important role in holding down net deforestation and therefore net emissions from land-use change. Devoting land to agricultural use, therefore, always has a carbon opportunity cost, and this cost is physical and real, not merely conceptual.

Although GlobAgri-WRR focuses on the incremental effects of each person's consumption, it does not factor in economic feedback effects, which could alter those incremental effects. As prices change as a result of any one person's consumption, that might affect how farmers farm or the amount of consumption by others. But when GlobAgri-WRR evaluates the consequences of any one person's change in diet, it holds other people's consumption constant and keeps yields and other production systems the same. The reasons, which we explain more thoroughly in Chapter 2, Box 2-1, include the large uncertainties in those estimates.[a] But a more fundamental reason is the need to analyze separately the effects of each menu item. For example, if increased food consumption were credited with increased yields, then we could not separately evaluate the effects of increased yields alone.

The same is true for possible feedback effects on consumption by others. Some economic models estimate that an increase in consumption of food by any one person will increase prices and force other people to consume less, leading to less land-use change, an effect that occurs for rich and poor alike (and generally more for the poor). The ultimate calculation of the GHG consequences of a person's high-beef diet, for example, are lower than they otherwise would be because that person's consumption is credited with the lower land-use requirements and emissions by others. This kind of model does not estimate the GHG costs of supplying all the food in one person's diet; it estimates the net GHG costs of supplying that food while also supplying less food for others. Because meeting the dietary requirements of everyone is a requirement for a sustainable food future, this type of economic model cannot tell us the GHG contribution of any one person's dietary changes toward a sustainable food future, which requires meeting others' food demands as well.

Note:
a. Searchinger, Edwards, Mulligan, et al. (2015) and supplement; Berry (2011).

Overall, the most appropriate methods to estimate efficiencies of diets should compare animal-based diets to reasonable alternatives; measure costs based on calories or protein "in" through feed and calories or protein "out" through meat, fish, or milk; count all stages of animal production; and count both human-edible and human-inedible feeds.

Wirsenius et al. (2010) provides a comprehensive analysis of meat and dairy conversion efficiencies that meets our criteria (Figure 6-5). As a global average, energy conversion efficiencies range from 13 percent for eggs to 1 percent for beef. One percent efficiency means that 100 calories of feed are needed to produce just one calorie of beef. Protein efficiencies range from 25 percent for eggs to 3–4 percent for ruminants, such as sheep and cattle.[107] This calculation is broadly consistent with other analyses that count both human-edible and human-inedible feeds.[108]

One key insight from this analysis is that all livestock products are inefficient; a second insight is that beef and other ruminant meats are particularly inefficient. Counting these efficiencies reasonably, plus counting the land-use consequences of each additional unit of food production, has major implications for our results.

Comparing land-use and greenhouse gas consequences of different foods

Low production efficiencies are the principal reason that meat and dairy require more land and water than plant-based foods—and generate more GHG emissions—per calorie or gram of protein produced. Yet how analysts count the GHG consequences of this land use itself has great consequences.

The approach to land in the dietary analysis by GlobAgri-WRR is conceptually simple. With modest adjustments, we basically ask: Holding agricultural production systems constant, how much additional land would farmers use and how many additional GHG emissions would the associated land clearing generate to produce an additional quantity of calories or protein from different foods?[109] Because land-use change is a one-time event, but food production will continue on the land for years, we also amortize the land-use-related emissions over 20 years when we wish to express annual emissions (Figures 6-6a through 6-6d).[110]

As discussed in Box 6-2, this approach of looking at the "incremental" consequences of dietary change—the amount of additional land required to produce each person's diet—differs from many other approaches. We believe this approach is necessary to truly measure the consequence of a given dietary shift scenario. Consistent with virtually all other studies (Appendix B), we find that animal-based foods require more land and generate more GHG emissions than plant-based foods (Box 6-2 and Figure 6-6). But because we count these full incremental consequences of dietary choices on carbon storage in vegetation and soils, our results show dietary choices to be more important than typical other estimates.

We reach the following conclusions:

- Meat from ruminants (beef, sheep, and goat) is by far the most resource-intensive food. It requires over 20 times more land and generates over 20 times more GHG emissions than pulses per gram of protein. Relative to dairy, it requires four to six times more land and generates four to six times more GHG emissions per calorie or gram of protein ultimately consumed by people.
- Dairy's land-use and GHG emissions are slightly higher than those of poultry per calorie and significantly higher than those of poultry per gram of protein.
- Poultry and pork are responsible for similar GHG emissions and land use per gram of protein consumed, but poultry requires more land and generates more emissions than pork per calorie, mainly because of the high energy content of pork fat.
- Pulses, fruits, vegetables, and vegetable oils are generally more resource-intensive to produce than sugars and staple crops because of their lower yields; yet they are still favorable compared to meat, dairy, and farmed fish.

Figure 6-6a | Foods differ vastly in land-use and greenhouse gas impacts

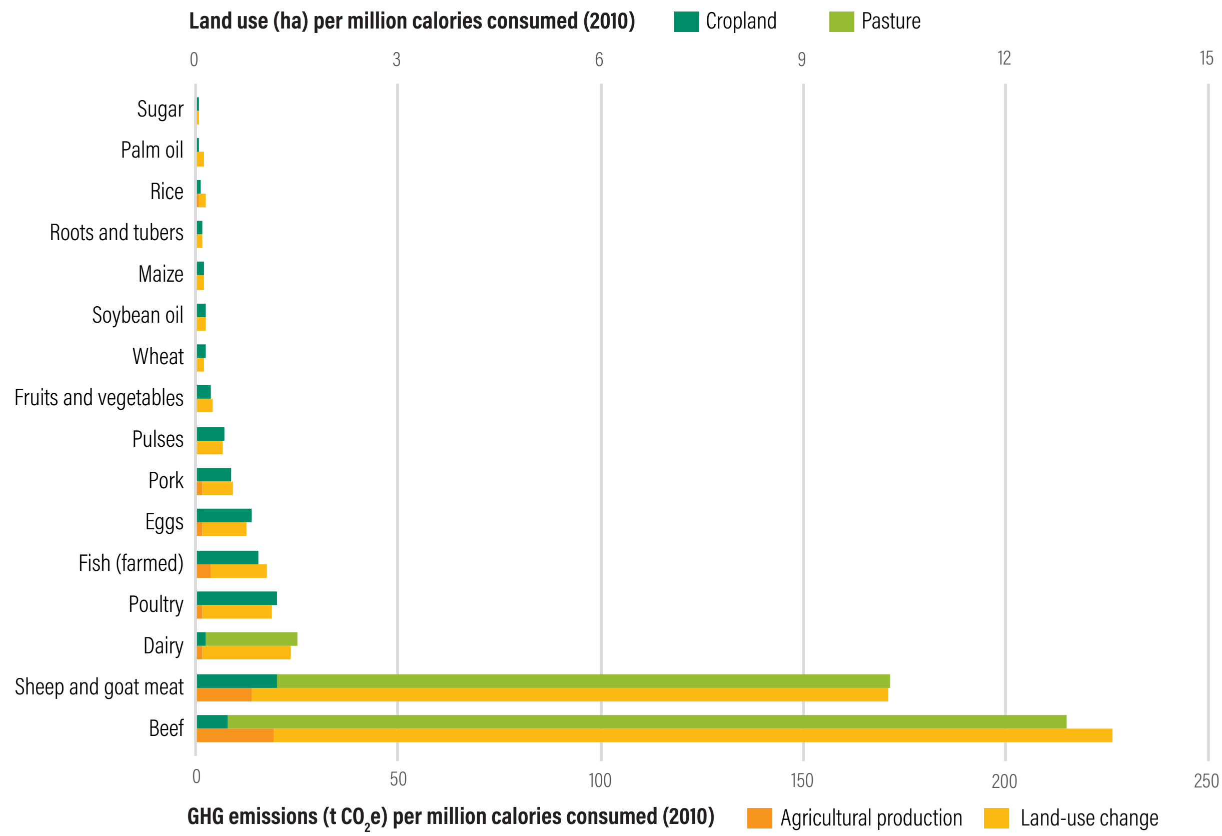


Figure 6-6b | Foods differ vastly in land-use and greenhouse gas impacts

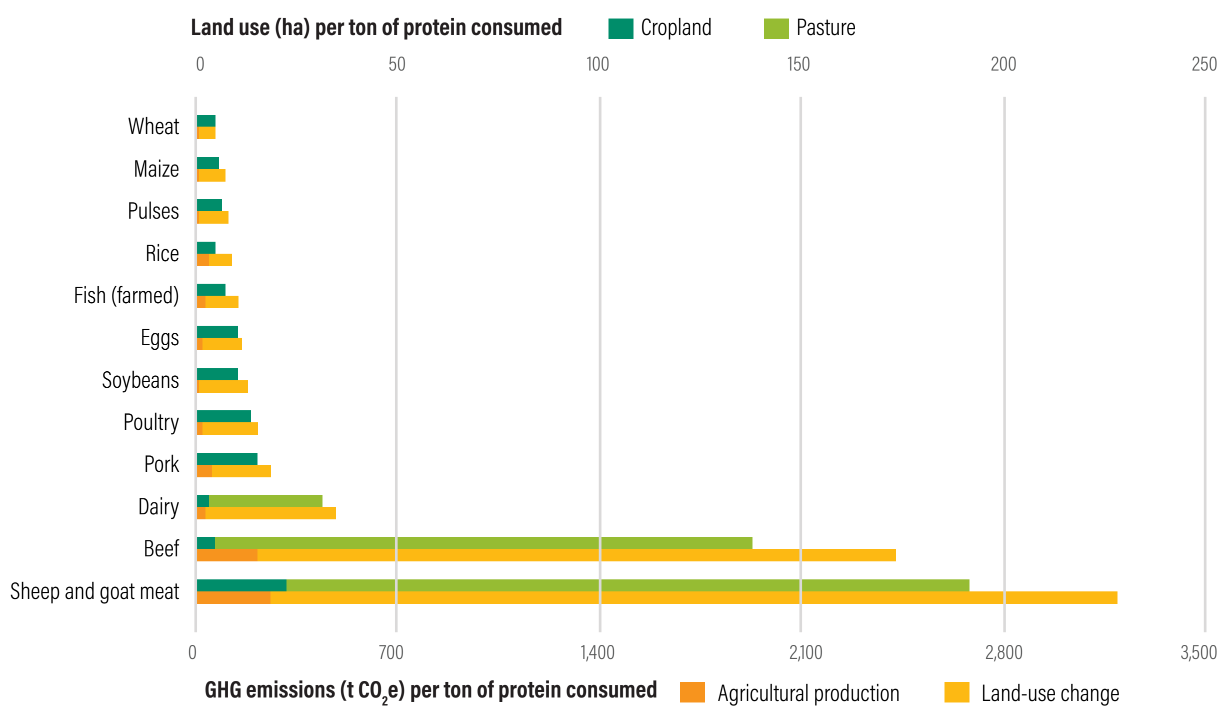


Figure 6-6c | Foods differ vastly in greenhouse gas impacts

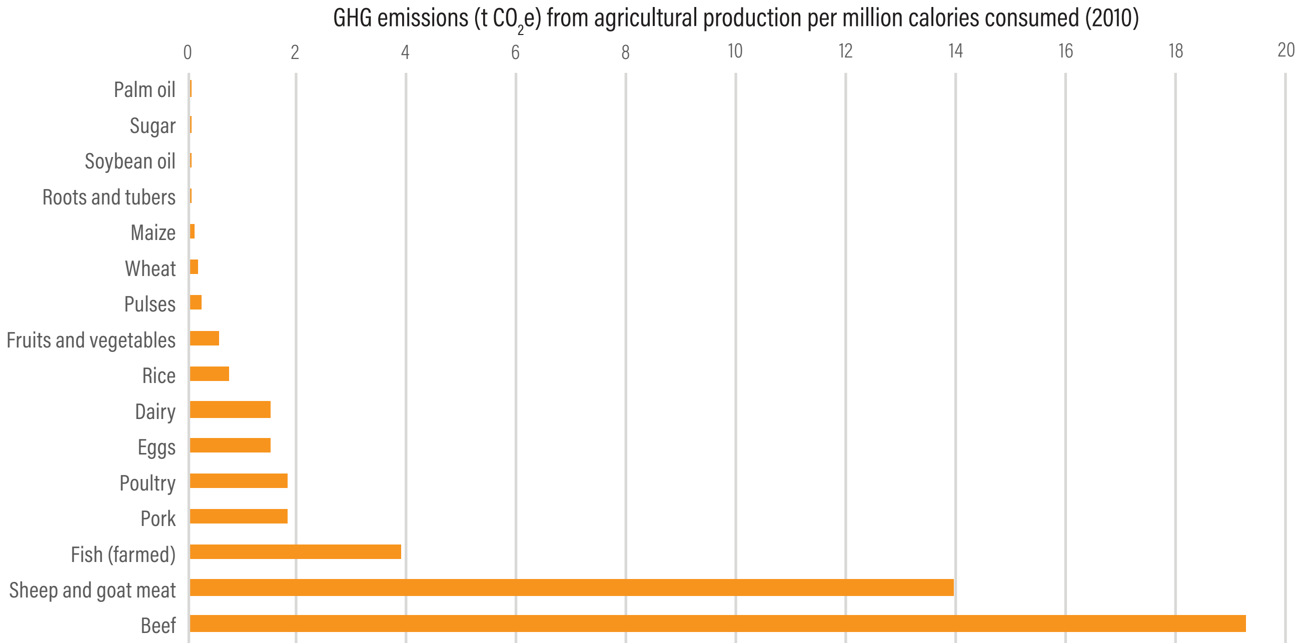
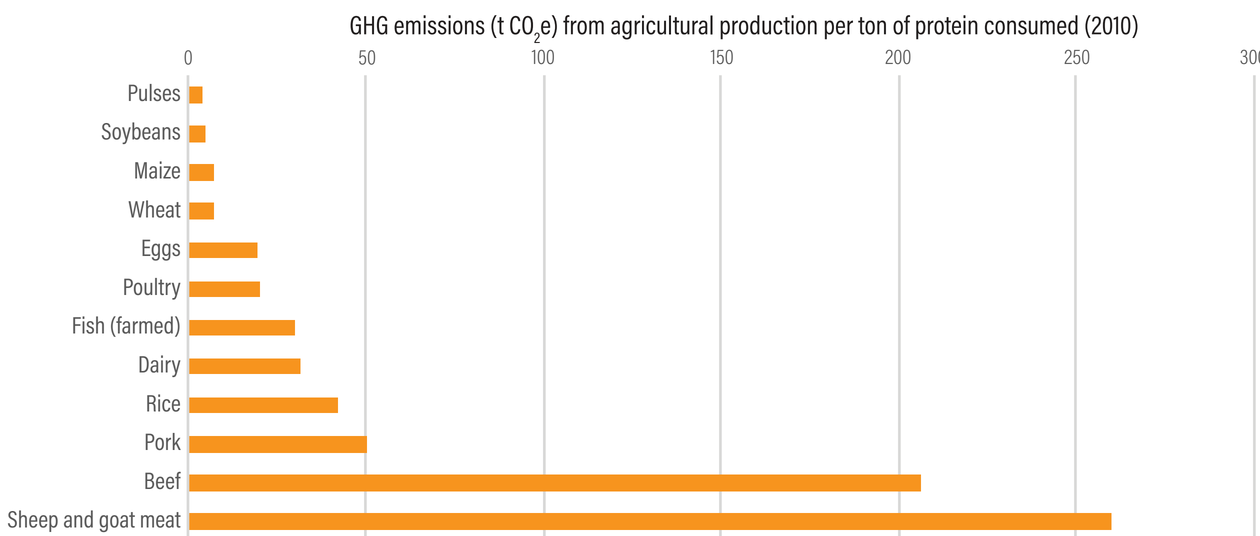


Figure 6-6d | Foods differ vastly in greenhouse gas impacts



Notes for Figure 6-6a through 6-6d: Data presented are global means, weighted by production volume. Indicators for animal-based foods include resource use to produce feed, including pasture. Tons of harvested products were converted to quantities of calories and protein using the global average edible calorie and protein contents of food types as reported in FAO (2019a). "Fish" includes all aquatic animal-based foods. Land-use and GHG emissions estimates are based on a marginal analysis (i.e., additional agricultural land use and emissions per additional million calories or ton of protein consumed). Based on the approach taken by the European Union for estimating emissions from land-use change for biofuels, land-use-change impacts are amortized over a period of 20 years and then shown as annual impacts. Land-use and GHG emissions estimates for beef production are based on dedicated beef production, not beef that is a coproduct of dairy. (Dedicated beef is 85 percent of total beef produced in 2010, 88 percent in 2050, and likely even more of the marginal source of meeting beef demand.) Dairy figures are lower in GlobAgri-WRR than in some other models because GlobAgri-WRR assumes that beef produced by dairy systems displaces beef produced by dedicated beef-production systems.

Source for Figure 6-6a through 6-6d: GlobAgri-WRR model.

Comparing land-use and greenhouse gas consequences of different complete diets

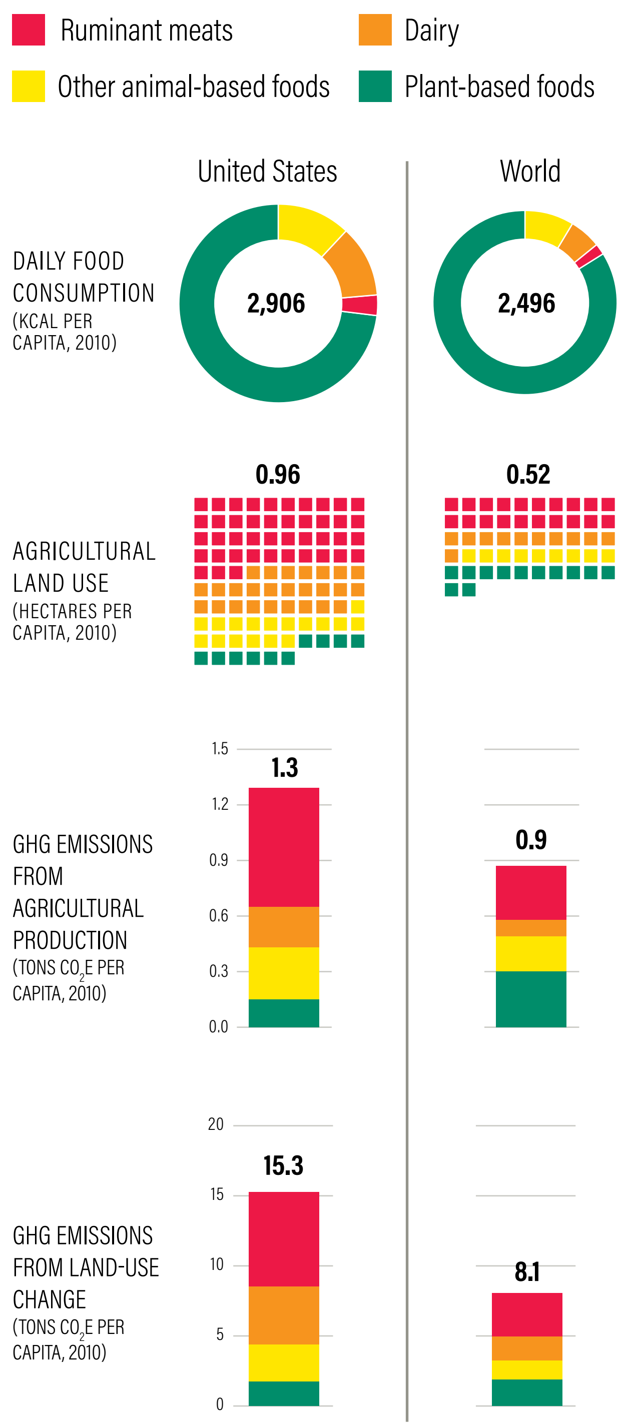
The large differences in land-use and GHG consequences of different foods explain why the global convergence toward Western-style diets has important implications for the resource needs and environmental impacts of agriculture. The average diet of the United States provides a good illustration because it contained nearly 500 more calories than the average world diet in 2010, including nearly 400 additional animal-based calories. In short, it is high in calories and high in animal-based foods, especially ruminant meat. As Figure 6-7 shows, the agricultural land use and GHG emissions associated with the average daily U.S. diet were almost double those associated with the average daily world diet.[111]

Animal-based foods accounted for nearly 90 percent of the production-related GHG emissions and agricultural land use associated with the average U.S. diet in 2010.[112] Beef had a disproportionately large impact relative to other food types. While beef contributed only around 3 percent of the calories and 12 percent of the protein in the average U.S. diet, it accounted for 43 percent of the annual land use and nearly half of the production emissions associated with the diet.[113]

Our calculations of GHG emissions from food consumption are larger than those of nearly all other previous estimates mainly because we take full account of the implications for agricultural land use of that consumption and the resulting loss of carbon storage in vegetation and soils on that land. Even the relatively modest average world diet in 2010 resulted in annualized emissions from land-use change and agricultural production equivalent to 8.4 tons of carbon dioxide. This amount is close to double the average world citizen's emissions that were attributable to energy use that year.[114]

Based on our method of averaging land-use emissions over 20 years, the average U.S. diet causes emissions that are more than 90 percent of the average U.S. person's energy use and equivalent to three-quarters of the emissions typically attributed to each U.S. person's consumption of all goods. (Without annualizing, the carbon cost of converting land from natural ecosystems to produce this diet equals 18 years of an average U.S. person's energy emissions.)[115]

Figure 6-7 | Land-use and greenhouse gas emissions associated with the average U.S. diet were nearly double the world average in 2010



Note: Calculations assume global average efficiencies (calories produced per hectare or per ton of CO_2e emitted) for all food types. Land-use-change emissions are amortized over a period of 20 years and then shown as annual impacts. "Other animal-based foods" includes pork, poultry, eggs, and fish.
Source: GlobAgri-WRR model, based on FAO (2019a).

The magnitude of diet-related GHG emissions may seem odd because the total emissions from energy use reported in national energy accounts are typically much larger than the total emissions from agriculture. How then can each person's diet have comparable significance? One way to understand this point is that each person, by eating differently, can substantially alter the amount of additional agricultural conversion that occurs each year.

The Opportunity

How much could plausible global shifts away from the diets expected in 2050 help to close the food, land, and GHG mitigation gaps?

Designing diet shift scenarios

Any realistic answer must recognize that most people in the world eat few animal-based foods and even less ruminant meat. To estimate the potential of shifting diets in a reasonable and fair way, we therefore adopt a principle of equity that assigns reductions first to high consumers until they reach the threshold needed to achieve the percentage reduction in global per capita consumption desired in each scenario. To explore options for diet shifts, we construct and evaluate four categories of alternative diet scenarios in 2050. Figures 6-8 through 6-10[116] show the distribution of dietary changes across countries. Table 6-2 shows the full results. All diet scenarios can help to close our gaps, and some by a great deal. But we believe that, given the scope of the changes needed, changes in ruminant meat consumption stands out as the most promising strategy.

Model Results

Skinny Diet: The 2050 baseline projection indicates a global population where 2.1 billion people are overweight and 1 billion are obese. The Skinny Diet scenario, the only scenario to include a net reduction in calories, explores a 50 percent reduction in the numbers of obese and overweight people below this baseline.[117]

Because even obese people probably consume on average only 500 more calories per person per day, this scenario would reduce caloric consumption by only 2 percent globally[118] and would thus close the crop calorie gap by only 2 percent (which is consistent with simpler analyses from earlier reports in this series).[119] The contribution to the land target is more significant, however, as reduced calorie consumption leads to agricultural land area in 2050 growing by 84 Mha less than projected in the baseline scenario, thus achieving 14 percent of the land target.

Despite some potentially meaningful benefits, reducing obesity by 50 percent would be extremely challenging; despite more than three decades of effort, there are no success stories of any national reductions.[120] Even after substantial efforts to reduce child obesity in the United States, U.S. childhood obesity is still increasing.[121] Although health benefits warrant major efforts to reduce obesity, the scope of the challenge is daunting relative to the land and GHG benefits, and we do not consider obesity reduction to be an important strategy for closing food, land, or GHG mitigation gaps.

Less Animal-Based Foods Diet (Figure 6-8). By 2050, we project that 3.6 billion people will live in regions where average consumption of animal-based foods (meats, dairy, fish, and eggs) is at or above 600 kcal per day, which is roughly the level of consumption of Brazil in 2010.[122] We explore scenarios in which we cut back total global consumption of all animal-based foods by 10 percent and 30 percent and shift this consumption to plant-based foods.[123]

The consequences could be large. By 2050, the 10 percent cut would reduce the food gap by 4 percent, the land gap by 44 percent, and the GHG mitigation gap by 22 percent. The 30 percent cut would be enough to close 12 percent of the food gap, nearly eliminate new net cropland expansion, cause a net *reduction* of 289 Mha in grazing area from 2010 levels, and close 59 percent of the GHG mitigation gap.[124]

Despite these large benefits, achieving this global 30 percent reduction in consumption of animal-based foods would be extremely difficult, and vegetarian diets illustrate the challenge. To achieve this reduction fairly, because roughly 6 billion people would still eat few animal products in 2050 under our baseline, a 30 percent global average reduction would require a roughly 50 percent reduction by people in North America and Europe. Although the actual diets of vegetarians are surprisingly little understood, our best efforts to estimate vegetarian diets using a U.K. sample from the 1990s suggests that consumption of total animal-based foods

Table 6-2 | Global effects of alternative 2050 diet scenarios on the food gap, agricultural land use, and greenhouse gas emissions

SCENARIO	FOOD GAP, 2010–50 (%)	CHANGE IN AGRICULTURAL AREA, 2010–50 (MHA)			ANNUAL GHG EMISSIONS, 2050 (GT CO_2E)			GHG MITIGATION GAP (GT CO_2E)
		Pastureland	Cropland	Total	Agricultural production	Land-use change	Total	
2050 BASELINE	**56**	**401**	**192**	**593**	**9.0**	**6.0**	**15.1**	**11.1**
SKINNY DIET								
Obesity/overweight reduced by 50%	54	350 (-52)	159 (-32)	509 (-84)	8.9	5.4	14.3	10.3 (-0.8)
LESS ANIMAL-BASED FOODS DIET								
10% shift to plant-based foods	52	195 (-207)	36 (-56)	330 (-263)	8.5	4.1	12.6	8.6 (-2.5)
30% shift to plant-based foods	44	-289 (-690)	18 (-173)	-271 (-864)	7.5	1.1[a]	8.6	4.6 (-6.5)
LESS MEAT DIET								
10% shift to legumes	55	276 (-126)	181 (-11)	456 (-137)	8.8	5.0	13.7	9.7 (-1.3)
30% shift to legumes	48	-16 (-418)	123 (-69)	106 (-487)	8.1	2.2	10.3	6.3 (-4.8)
10% shift to U.K. vegetarian diet	55	368 (-33)	179 (-14)	547 (-46)	8.8	5.7	14.5	10.5 (-0.6)
30% shift to U.K. vegetarian diet	49	248 (-154)	137 (-54)	385 (-208)	8.3	4.3	12.6	8.6 (-2.5)
LESS RUMINANT MEAT DIET								
10% shift to legumes *(Coordinated Effort)*	56	220 (-181)	188 (-4)	408 (-185)	8.7	4.4	13.2	9.2 (-1.9)
30% shift to legumes *(Highly Ambitious, Breakthrough Technologies)*	55	-154 (-555)	171 (-21)	18 (-576)	8.1	1.4	9.4	5.4 (-5.6)
50% shift to legumes	53	-573 (-974)	154 (-38)	-418 (-1,012)	7.4	1.1[a]	8.5	4.5 (-6.6)
10% shift to poultry/pork	57	221 (-181)	206 (14)	426 (-167)	8.8	4.6	13.3	9.3 (-1.7)
30% shift to poultry/pork	58	-153 (-555)	225 (33)	71 (-522)	8.2	1.7	9.9	5.9 (-5.1)
50% shift to poultry/pork	59	-573 (-975)	237 (45)	-336 (-930)	7.6	1.1[a]	8.7	4.7 (-6.4)

Notes: "Cropland" includes cropland plus aquaculture ponds. Numbers not summed correctly are due to rounding. Numbers shown in parentheses are changes relative to 2050 baseline.

a. Indicates a scenario that led to an overall agricultural land-use reduction between 2010 and 2050. To be conservative, we set land-use-change emissions between 2010 and 2050 to zero, and kept only ongoing peatland emissions (1.1 Gt/year).

Source: GlobAgri-WRR model.

declines by only about 25 percent because vegetarians mostly substitute dairy and eggs for meat.[125] As a result, even if every person in North America and Europe became a vegetarian—which is unlikely—that shift would still achieve only half of those regions' responsibility for achieving the 30 percent global reduction in animal-based foods.

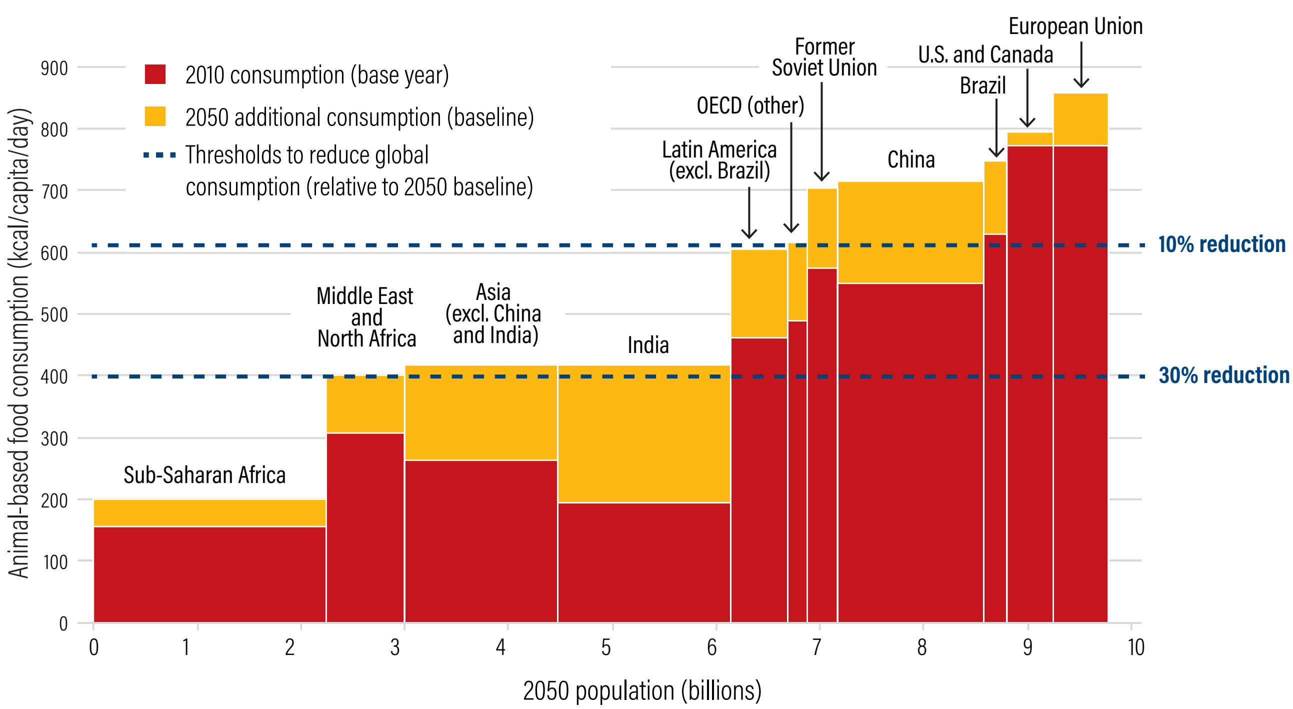
Less Meat Diet (Figure 6-9). We explore scenarios in which people cut back their consumption of all meats (but not other animal-based foods), by 10 or 30 percent (to a maximum of 372 or 238 kcal/person/day, respectively). In one variation for each level of cut, people substitute their meat with a 50/50 combination of pulses and soy. In the other variation, they switch to a combination of more plant-based foods, dairy, and eggs that reflects the experience of self-reported vegetarians[126] as observed in the United Kingdom in the 1990s.[127]

The switch from meat to plant-based foods only would achieve roughly half the savings in land and emissions achieved by the reduction in all animal-based foods. For example, the 30 percent meat reduction would reduce the food, land, and mitigation gaps by 8 percent, 82 percent, and 43 percent, respectively. If these meat reductions were accomplished by shifting not only to vegetables but also to dairy and eggs, which is what vegetarians typically do, they would produce only half this level of reductions in land and GHG mitigation gaps (Table 6-2).

One lesson is the significance of dairy and eggs in a standard vegetarian diet. Dairy in general has modestly greater land-use demands and emissions than poultry and pork, and eggs only slightly less. A simple shift from meat to dairy and eggs has much less consequence than one from meat to plants.

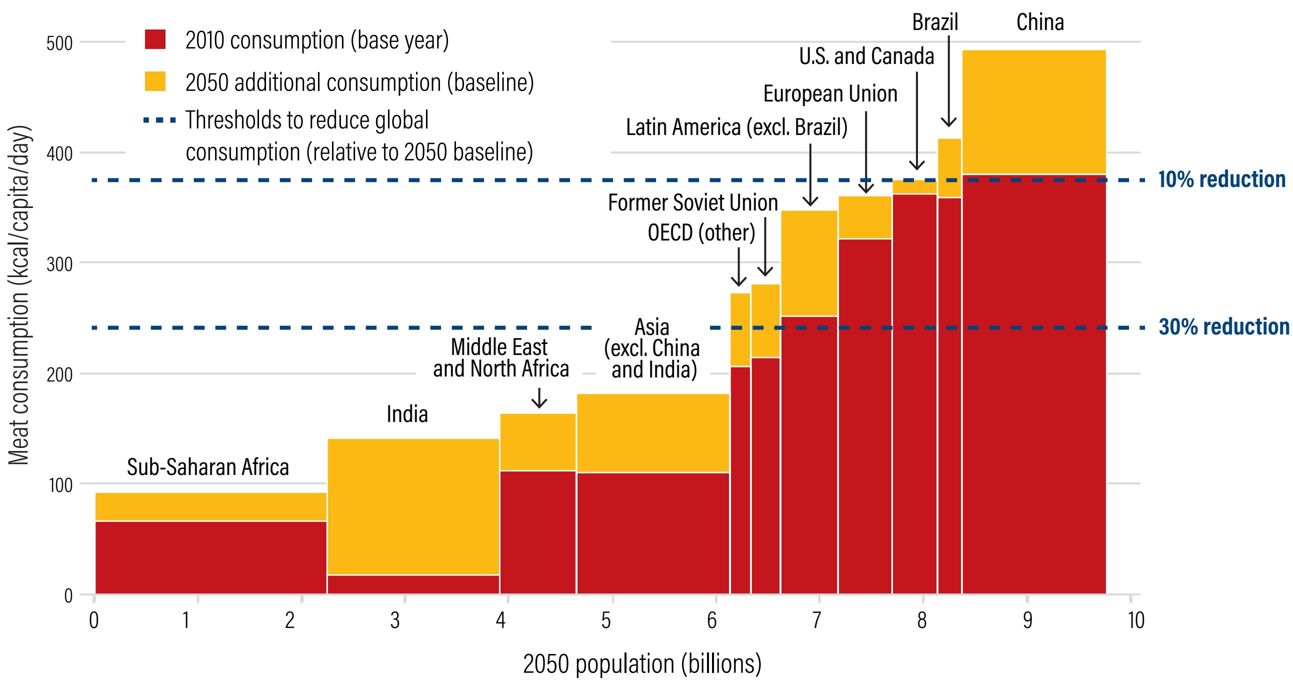
Less Ruminant Meat Diet (Figure 6-10). A fourth category of alternative diets focuses on reducing consumption of ruminant meats only (beef, sheep, and goat). These changes require large reductions in consumption but only by people in the United States, Canada, Europe, Latin America, and the former Soviet Union because, in 2010, they consumed more than half of the world's ruminant

Figure 6-8 | Less Animal-Based Foods Diet scenarios reduce consumption of animal-based foods in 2050



Source: GlobAgri-WRR model, with source data from FAO (2019a); UNDESA (2017); FAO (2011c); and Alexandratos and Bruinsma (2012).

Figure 6-9 | Less Meat Diet scenarios reduce meat consumption in 2050



Source: GlobAgri-WRR model, with source data from FAO (2019a); UNDESA (2017); FAO (2011c); and Alexandratos and Bruinsma (2012).

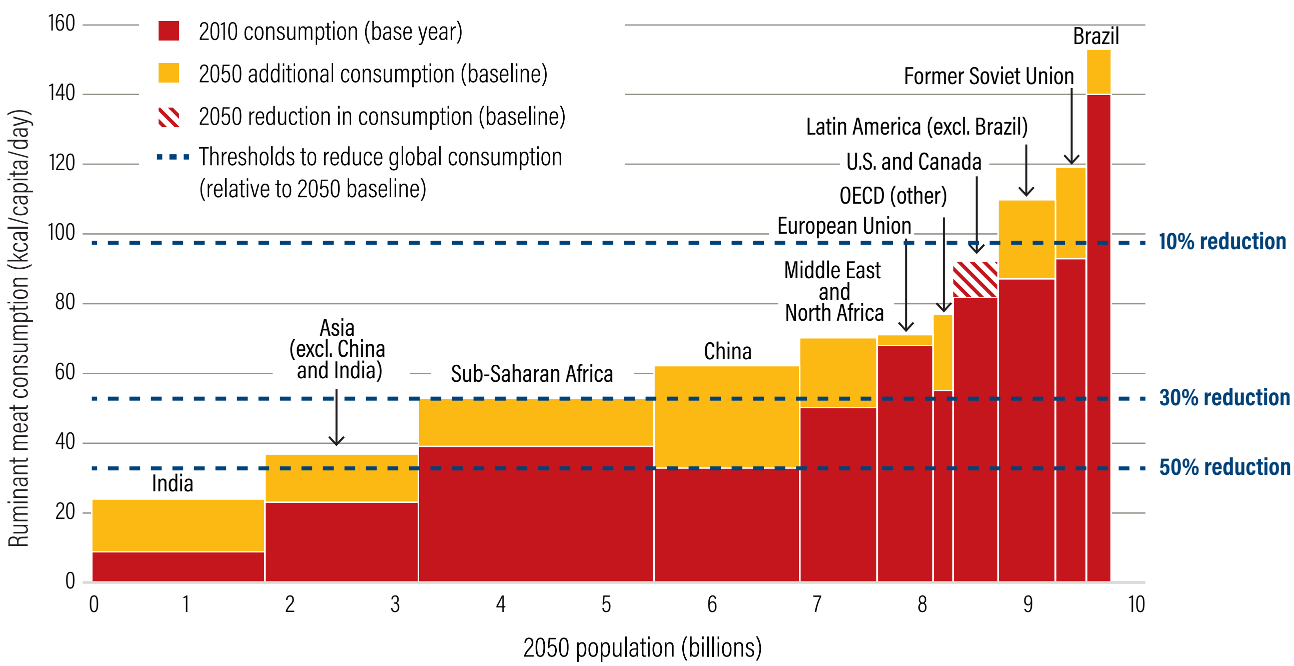
meat, although they comprised just one-quarter of the world's population.[128] Using our threshold approach, we explore three levels of cuts in global ruminant meat consumption relative to predicted 2050 levels:

- A 10 percent cut, which would require that each person in Brazil, countries of the former Soviet Union, and the United States eat no more ruminant meat than the average person in the United States today.
- A 30 percent cut, which would require that all countries limit their consumption to no more than present levels in the Middle East and North Africa in 2010.
- A 50 percent cut, which would require all countries limit their per capita consumption to China's levels in 2010.

For each scenario, we examined shifting the food consumption to pork and chicken,[129] and alternatively to legumes comprising an equal mix of pulses and soy.

In all scenarios, the effects of all these shifts on the crop calorie gap are small—because only modest amounts of crops are fed to ruminants—but the effects on land use and GHG emissions are large. These effects are similar whether the shift occurs to other meats or to pulses and soy. The 10 percent cut would reduce the land gap by roughly 30 percent and the GHG mitigation gap by roughly 16 percent. The 30 percent cut would virtually eliminate the land gap and cut the GHG mitigation by more than half. The 50 percent cut would free up more than 300 Mha of agricultural land.

Figure 6-10 | Less Ruminant Meat Diet scenarios reduce ruminant meat consumption in 2050



Note: Per capita ruminant meat consumption in the United States and Canada is projected to decline between 2010 and 2050. Declines are shown as hatched bars.
Source: GlobAgri-WRR model, with source data from FAO (2019a); UNDESA (2017); FAO (2011c); and Alexandratos and Bruinsma (2012).

Although not analyzed here, an additional category of alternative diets could draw more heavily from nutritional recommendations. Papers such as Springmann, Godfray, et al. (2016) have used global dietary recommendations to analyze not only a reduction in red meat (ruminant meat plus pork) consumption, but also reduced sugar consumption and increased fruit and vegetable consumption—finding sizable reductions in agricultural production emissions relative to baseline diets.[130] The EAT-*Lancet* Commission analyzed even more pronounced dietary shifts away from animal-based foods and toward a healthy mix of plant-based foods, again finding large agricultural production emissions reductions relative to baseline diets, although cropland and irrigation water use remained relatively constant with baseline levels.[131] All told, the overwhelming majority of emissions reductions in these researchers' "healthy diet" scenarios are driven by the decreases in ruminant meat consumption,[132] which is not surprising when considering the data in Figures 6-6a through 6-6d.

Per capita effects of the diet shifts in a high-consuming country

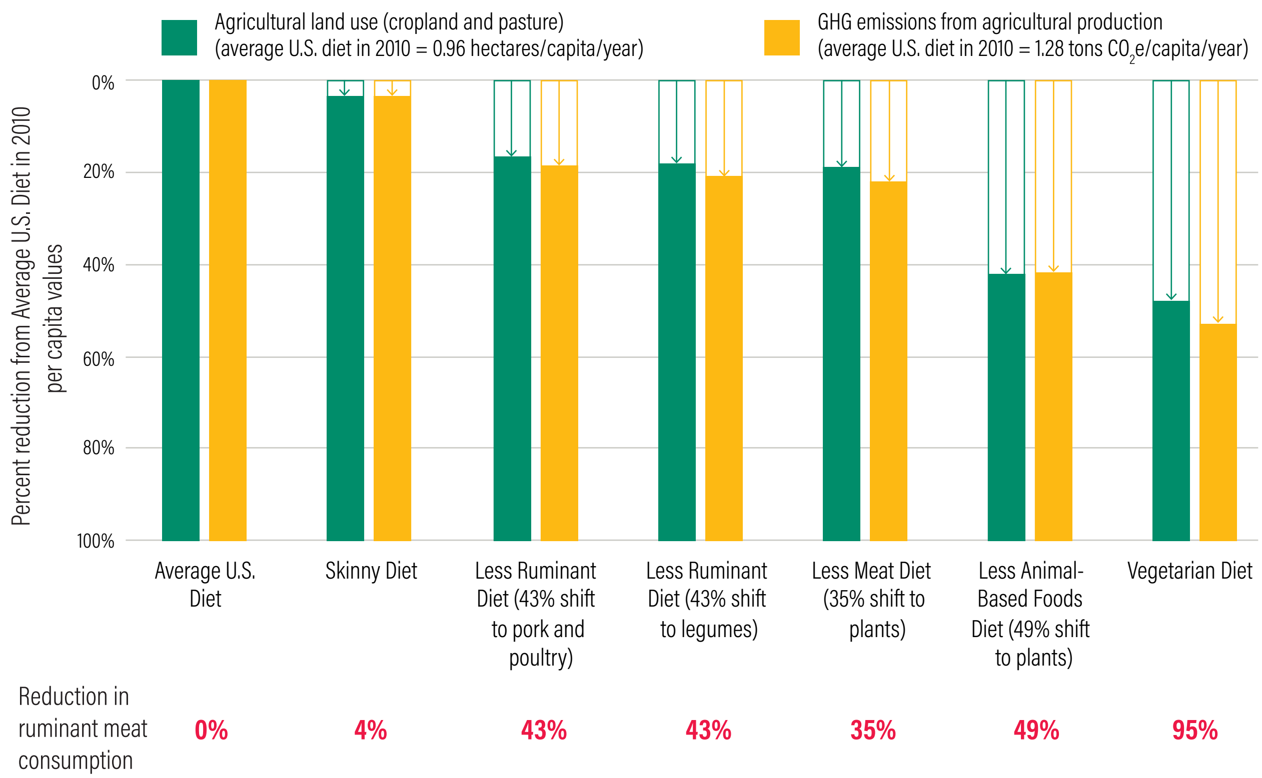
To better understand the feasibility and importance of the various global diet shifts we analyzed, Table 6-3 explains the dietary changes that would be required in the United States (a high meat-consuming country) in 2010, according to our principle of equity, and Figure 6-11 shows the per capita implications of each diet for land use and GHG emissions.[133] We also simulated one completely vegetarian diet[134] as an "upper bound" against which the other diet shifts could be compared.

The main lesson that emerges again is that a reduction in consumption of ruminant meat largely determines the environmental results.

Table 6-3 | Applying selected diet shift scenarios to to the average U.S. diet in 2010

SCENARIO	COMMENT
Average U.S. Diet	Animal-based foods account for 27% of all caloric consumption; ruminant meat (overwhelmingly beef) for 3%.
Skinny Diet	Reduces per capita consumption of calories by 4% across all food types.
Less Animal-Based Foods Diet, 30% global reduction	Reduces U.S. consumption of animal-based foods by 49%, shifts to plant-based foods.
Less Meat Diet, 30% global reduction	Reduces U.S. consumption of meat by 35%, shifts to plant-based foods.
Less Ruminant Meat Diet, 30% global reduction (shift to legumes)	Reduces consumption of ruminant meat by 43%, shifts to pulses and soy.
Less Ruminant Meat Diet, 30% global reduction (shift to pork and poultry)	Reduces consumption of ruminant meat by 43%, shifts to pork and poultry.
Vegetarian Diet	Simulates the U.K. vegetarian diet observed by Scarborough et al. (2014) scaled to 2010 per capita U.S. calorie consumption levels. Meat and fish consumption falls to nearly zero, but dairy and egg consumption rises along with consumption of fruits, vegetables, and legumes.

Figure 6-11 | Shifting the diets of the world's "high consumers" could significantly reduce per person agricultural land use and GHG emissions



Source: GlobAgri-WRR model. The Vegetarian Diet scenario, which uses data from Scarborough et al. (2014), includes small amounts of meat, as "vegetarians" were self-reported.

Key Lessons from Our Analysis of Potential Diet Shifts

We draw four principal lessons from our analysis of the GlobAgri-WRR model's projections:

- Reducing overconsumption of calories would have large health benefits but would have only a modest impact on land use and GHG emissions relative to the challenge.
- Reducing consumption of all animal products would have large benefits, and is important for the wealthy, but is hard to achieve globally because even vegetarians shift much of their consumption to dairy and eggs, and because our baseline assumes that 6 billion people already eat so few animal products and they could quite possibly eat more.
- Reducing consumption of all meat alone could close our gaps but primarily through the effects of eating less ruminant meat, and assuming that much of that meat consumption shifts to dairy and eggs.
- Reducing ruminant meat consumption by the world's highest consumers of these foods is a particularly promising strategy to achieve the land and GHG emissions targets. Although a 30 percent global cut in ruminant meat would require 40–60 percent reductions in ruminant meat in the United States and Brazil, ruminant meat today provides only 3–5 percent of their diets. Europeans would have to cut their ruminant meat consumption by only 22 percent relative to 2010 levels.

Although switching to plant-based foods would provide many additional environmental benefits and benefits for animal welfare, most of the climate and land-use benefits would occur even if consumption switched from beef to chicken and pork.

Since its peak levels in the mid-1970s, per capita beef consumption has dropped by roughly one-third in the United States and Europe, and it has dropped by 27 percent in Japan since the 1990s.[135] This history provides real evidence of an ability to shift at least from beef to other animal products.

BOX 6-3 | The potential of shifting diets to reduce agricultural freshwater consumption

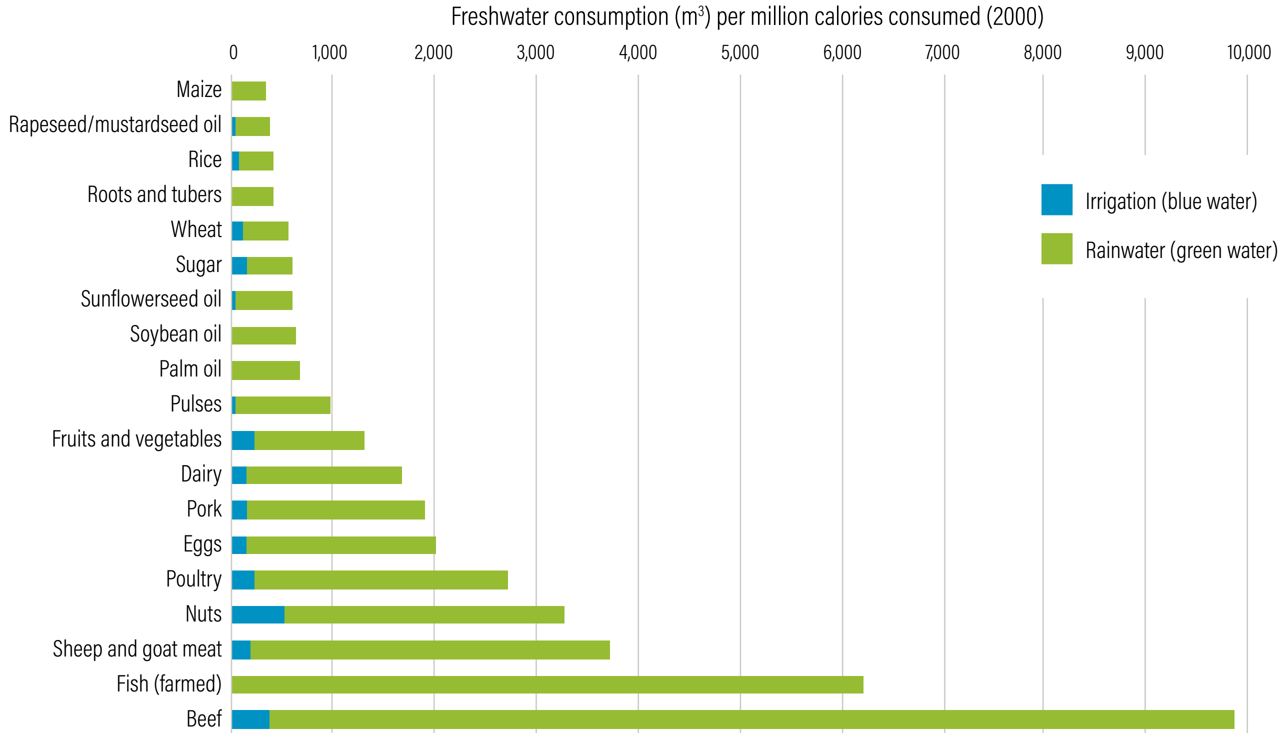
Just as with land use and GHG emissions, increasing demand for animal-based foods will likely increase pressure on the world's freshwater resources—and shifting to diets with a greater share of plant-based foods will likely reduce that pressure. Mekonnen and Hoekstra (2011, 2012) provide a comprehensive global analysis of the "water footprint" of plant- and animal-based foods (Figure 6-12), which displays a similar pattern to GlobAgri-WRR's findings for land use and GHG emissions, shown in Figure 6-6. In general, animal-based foods are more water-intensive, with the ruminant meats being especially water-intensive. These authors estimate that beef accounted for one-third of the global water footprint of livestock production in 2000.[a]

The majority of agricultural water consumption is rainwater or "green" water. A product's "green water footprint" tracks quite closely to GlobAgri-WRR's estimate of land use. Water managers, however, tend to be most concerned with irrigation water or a food's "blue water footprint," which represents the volume of surface and groundwater consumed. When comparing just irrigation water values (shown in blue in Figure 6-12), the picture of water intensity per calorie or gram of protein across plant-based and animal-based foods is more mixed. Nuts, for example, stand out as even more irrigation-water-intensive than beef at the global average level, and fruits and vegetables are globally on par with animal-based foods other than beef.

In contrast to GHG emissions, whose significance does not vary depending on geographic location, the consequences of high agricultural water use for sustainability are location-specific.[b] "Water footprint estimates" of total water consumption therefore become especially useful when overlaid with maps of water stress, such as those produced by WRI's Aqueduct and shown in Figures 1-5 and 3-1 of this report. Such maps allow water managers to identify "hotspots" where water footprint reduction is most urgent.[c]

Sources:
a. Mekonnen and Hoekstra (2012).
b. Putt del Pino et al. (2016).
c. Hoekstra et al. (2011).

Figure 6-12 | Foods differ vastly in freshwater requirements



Source: Authors' calculations from Mekonnen and Hoekstra (2011, 2012) (freshwater consumption) and Waite et al. (2014) (farmed fish freshwater consumption—shown as rainwater and irrigation combined).

Finally, a shift away from ruminant meat consumption would also still leave plenty of business for cattle farmers and use of pasture lands. Even a 30 percent decline in global ruminant meat demand (relative to our 2050 baseline) would mean that demand would still rise by 32 percent from 2010 to 2050. This is a significant increase—just far less than the 88 percent growth anticipated under our baseline scenario.

Based on this analysis, in the penultimate section of this report, "The Complete Menu: Creating a Sustainable Food Future," we include the Less Ruminant Meat Diet (10 percent reduction, shifting to plant proteins) in the "Coordinated Effort" scenario of combined menu items, and the Less Ruminant Meat Diet (30 percent reduction, shifting to plant proteins) in the "Highly Ambitious" and "Breakthrough Technologies" combination scenarios.

Recommended Strategies

Despite the potential benefits of diet shifts, the current trend of rising global consumption of animal-based foods will likely continue, absent significant actions to shift demand.

Food choices are influenced by a variety of interacting factors, including price and taste of the food, and the age, gender, health, income, geography, social identity, and culture of the consumer. Marketing, media, and ease of access to supermarkets and restaurants also play a role. What can be done to influence people's food choices on a large enough scale to achieve the scenarios analyzed in the previous section and contribute to a sustainable food future?

We recommend a new approach that focuses on what influences purchasing decisions. It includes four strategies: move beyond reliance on information and education campaigns to effective marketing, engage the food industry, improve plant-based substitutes, and leverage government policies.

Move beyond a reliance on information and education campaigns to effective marketing

Typical strategies to shift diets rely on nutrition labeling or public health campaigns about the benefits of different food types or diets. Public health campaigns range from advocating for abstinence (e.g., vegetarianism or Meatless Mondays), recommending balanced diets (e.g., the UK Eatwell plate, Chinese Pagoda, U.S. ChooseMyPlate, Canadian Food Rainbow), promoting fruits and vegetables, and warning against excessive consumption of particular food types.

There is limited evidence, however, that consumers regularly use information labels or are influenced by education campaigns when buying food.[136] A review of the influence of nutritional labeling, for example, found information to have at best a modest impact on purchasing behavior.[137] In addition, a review of the effectiveness of education campaigns to increase fruit and vegetable consumption in Europe has reported a small impact.[138] Analysis published in the *British Medical Journal* in 2011 found a similar pattern in the restaurant environment. Calorie and nutritional information about food served at fast-food chains in New York City resulted in no change in average calories bought, and only one in six people said they used the information.[139]

In light of how consumers shop, the limited effectiveness of information and education strategies is not surprising. Consumers are bombarded with messages every day from multiple sources and, as a result, the information is likely to be screened out or quickly forgotten.[140] Consumers tend to follow a shopping routine and rarely evaluate the products they buy.[141] What ends up in the shopping cart is usually based on habit and unconscious mental processing rather than on rational, informed decisions.

Interventions to change food consumption behavior, therefore, need to affect not only consumers' rational, informed decisions but also their automatic or unconscious decisions. This insight suggests that interventions must go beyond information and education campaigns and attempt to alter consumers' choices and the ways those choices are presented.[142] For example, fishers, processors, and retailers in the United Kingdom have worked together to rebuild demand for pilchards. The fish were renamed "Cornish sardines." Sardines are regarded favorably as a Mediterranean dish and preferable to the humble pilchard, traditionally sold in cans. Since this repositioning in the late 1990s, catches of pilchards in Cornwall increased from 6 tons per year in the early 1990s to 2,000 tons in 2008.[143]

Engage the food industry, especially major food retailers and food service providers

Global food consumption patterns are converging as the food industry consolidates and creates large-scale food processors, wholesale food companies, supermarkets and other retail store chains, and restaurant chains.

Supermarkets accounted for 70 to 80 percent of food retail sales in the United States and France in 2000,[144] and they are playing an increasingly important role in developing countries. Between 1980 and 2000, supermarkets grew their share of food retail sales from an estimated 5–20 percent to 50–60 percent in East Asia, Latin America, urban China, South Africa, and Central Europe.[145] This expansion continued through the first decade of the 2000s; supermarket sales grew at a 40 percent compound annual growth rate in China, India, and Vietnam between 2001 and 2009.[146] New supermarkets typically open in urban areas with concentrations of affluent consumers before diffusing to middle- and lower-income consumers and expanding from urban to rural areas.[147] Supermarkets increase consumers' access to foods more common in developed countries, such as meat, dairy products, temperate fruits and vegetables, and processed foods and drinks.[148]

People are also increasingly choosing to dine out—in restaurants, cafeterias, and other food service facilities. In the United States, expenditures on "food away from home" as a share of total food expenditures grew from 25 percent in 1954 to 50 percent in 2013.[149] In China, out-of-home food consumption grew by more than 100-fold between 1978 and 2008, as people increasingly eat food from street stalls, traditional restaurants, and fast-food outlets.[150] This trend is driven by the growing share of women in the workplace, higher incomes, smaller households, more affordable and convenient fast-food outlets, and increases in advertising by large restaurants.[151] Given that these drivers are increasingly relevant worldwide, restaurants and other food service facilities will likely capture a still higher share of global food sales in coming decades.

Until now, efforts to shift diets have primarily been led by governments and nongovernmental organizations. However, consumers make the majority of their food choices in stores and restaurants; influencing these choices to shift diets will require the engagement of the food industry, particularly large-scale actors in the retail and food service sectors. What strategies can they use?

SHIFT WHEEL: A FRAMEWORK FOR SHIFTING CONSUMPTION

Little is known about alternative strategies that could be used to reduce high consumption of animal-based food products, especially beef. To help address this knowledge gap and design more effective strategies, we looked across the field of fast-moving consumer goods—not just food—and examined a number of specific consumption shifts that have been successfully orchestrated by industry, NGOs, and government. Notable examples include the shifts from incandescent to long-life light bulbs, from caged to free-range eggs in the United Kingdom, from big box to compact washing powder, from high- to low-alcohol beer in Europe, from butter to plant-based spreads, from trans fats to healthier fats, and a shift away from shark fin in China. While these examples draw primarily on experience in developed countries, the resulting insights are likely to be relevant to developing countries, given their trends toward shopping in supermarkets and eating outside the home. We analyzed these shifts by reviewing published literature and market data reports, commissioning sales research, and consulting marketing strategy professionals and academic behavior specialists.

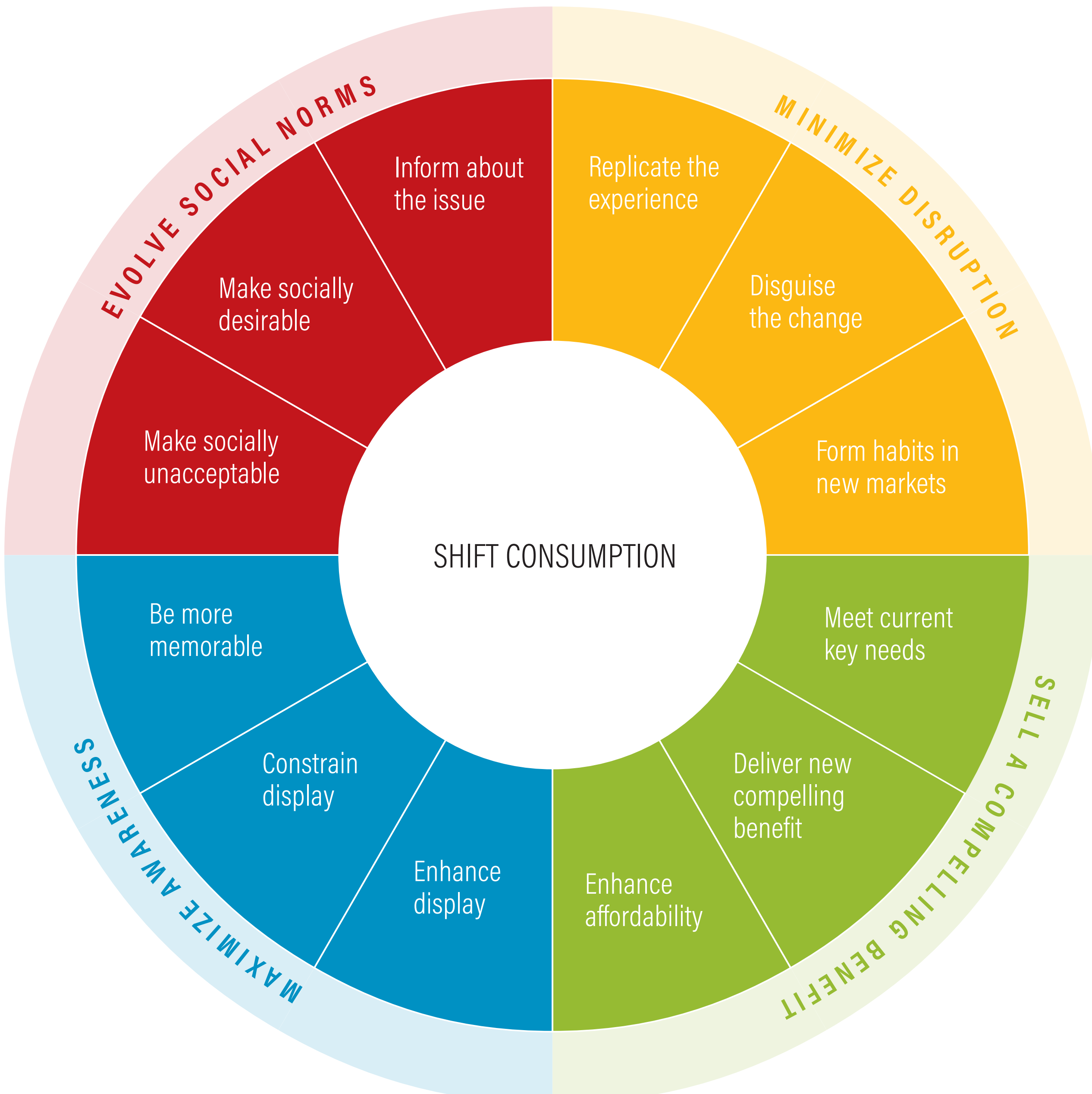
Based on this analysis, we developed the "Shift Wheel" (Figure 6-13), a suite of strategies and tactics that appear to have underpinned some of the historical shifts in consumption patterns. Given their efficacy in the past, we suggest that elements of the Shift Wheel will be important for shifting diets in the future. The Shift Wheel includes four complementary strategies: minimize disruption, sell a compelling benefit, maximize awareness and optimize display, and evolve social norms.

Minimize disruption

Changing food consumption behavior is challenging because it requires breaking current habits and investing time and effort to establish new ones. Changes in taste, look, texture, smell, packaging, and even in-store location can be major barriers to changing a consumer's food-buying decisions. An effective strategy is to minimize the consumer's perception of differences:

- **Replicate the experience.** Brands such as Quorn (a meat substitute made from mycoprotein) have, over the years, evolved their chicken, minced and ground beef, and tuna products to replicate the familiar texture of the meat as closely as possible. Other products

Figure 6-13 | The Shift Wheel comprises four strategies to shift consumption



Source: Ranganathan et al. (2016).

are replicating packaging formats and product placement. For example, several brands of soy milk have launched packaging that looks similar to that of fresh cow's milk and, rather than being stored at room temperature near long-life ultra-high temperature processed (UHT) milk, are being placed in retailers' chillers alongside fresh milk.

- **Disguise the change.** A number of products have blended in new ingredients within current formats to help disguise the shift toward plant-based ingredients. For example, the "Lurpak" Danish brand of butter has released a number of variants, such as "Lurpak Lighter," which has around 30 percent vegetable fat blended into the butter. These inclusions are listed in the ingredients label, but the marketing leads with messaging about its buttery taste and spreadability, a result of the vegetable fat. Change can also be disguised through small, imperceptible steps (sometimes referred to as "stealth changes"). This approach has been used by food companies to steadily cut sodium and sugar levels in food. For example, manufacturers have reduced salt levels in UK bread by an average of 20 percent over the past decade.

- **Form habits in new markets.** Getting consumers to purchase healthy and more sustainable products is less disruptive if they have yet to form buying habits. This approach is especially relevant to countries where consumption of animal-based protein and beef is rapidly rising or is projected to do so by 2050. Introducing programs that limit consumers' shift toward buying more animal-based food products in geographies or social groups without a prior history or unformed buying norms can be an effective strategy.

Sell a compelling benefit

Not all food consumption shifts are disguisable; selling a compelling benefit requires defining and communicating attributes that are sufficiently motivating to stimulate behavior change among the majority of consumers. This can mean selling factors other than the environment.

- **Meet current key needs.** The UK egg industry has built upon and reinforced the consumer perception that eggs from free-range chickens taste better than those from cage-reared chickens. Brands such as "Happy Eggs," with their tagline "happy hens lay tasty eggs," demonstrate this approach. Although free-range eggs are 30–50 percent more expensive than conventional eggs, this quality association has helped capture around 45 percent of the UK market.[152]

- **Deliver new compelling benefit.** Although much current messaging around the benefits of plant-based foods relates to health and nutrition—which can be effective in certain circumstances—health-related messaging can be a double-edged sword. Studies have found that calling plant-based dishes "healthy" can actually create negative connotations for consumers, with many experiencing "healthy" dishes as less enjoyable, less tasty or less filling.[153] Rather than leading with a health message, certain food service outlets emphasize the unique taste sensations of plant-based food. For example, restaurants such as Dirt Candy in New York champion the natural sweetness of plant-based foods in their description of main dishes (e.g., Tomato Cake). And Stanford University found that giving vegetable-based dishes flavorful, indulgent, or exciting names (e.g., "twisted citrus-glazed carrots") boosted sales of those dishes in cafeterias by 25 to 41 percent relative to less-appealing names.[154] The converse is also true. Research from the London School of Economics has shown that placing plant-based dishes within a vegetarian box on a menu can reduce the chances a nonvegetarian will order these dishes by more than half because it is not based on offering a compelling benefit except to vegetarians.[155]

- **Enhance affordability.** Price is an influential factor in food purchases. When comparing how much protein is derived from animal-based foods in different countries, it is estimated that income explains 65 to 70 percent of the variation.[156] That is why the falling price of chicken, relative to the price of beef, has played a role in the rise of per capita chicken consumption in the United States (and the decline in per capita beef consumption) since the 1970s.[157] Because plant-based ingredients can be cheaper than animal-based ones,[158] companies may be able to sell reformulated products with a greater share of plant-based ingredients at a lower price point and/or an increased profit.

Maximize awareness

The more consumers are exposed to a product, the greater the chance they will consider purchasing it. Repetition, memorability, and product display techniques can all influence food-purchasing decisions.

- **Enhance display.** One study in New York City found that when supermarket checkout lines were stocked with more healthy foods, customers purchased more healthy items and fewer unhealthy ones, relative to standard checkout lines.[159] In a retail environment, food manufacturers can encourage retailers to increase the amount and quality of space given to displaying their products by providing greater margins to retailers or running promotional campaigns, such as offering discounts or engaging celebrity chefs to feature their products. In a food service environment, layout and design of menus, buffets, and cafeteria spaces can all enhance the success of target dishes by increasing their visibility.

- **Constrain display.** In some cases, undesired food choices can be curtailed by limiting product distribution and display. Public food procurement policies in schools, hospitals, prisons, and government offices have been used to influence consumption habits. The complete removal or "choice editing" from stores is possible, but it is sensitive; 46 percent of British shoppers are in favor of more choice editing for ethical reasons but 26 percent object, and 73 percent were against editing for health reasons.[160] Some countries also are experimenting with limiting marketing of undesirable foods. Chile passed a law in 2012 that limits children's exposure (through marketing and sales) to foods that are high in calories, salt, sugar, and fat—and began implementing the law in 2016.[161]

- **Be more memorable.** Consumers shop quickly, and the majority screen out information about new products. Companies can disrupt these predetermined choices by making products more noticeable in a purchasing situation or by increasing their prominence in consumers' thoughts. Creating memorable advertising campaigns and building consumers' memory associations with the desired food can, over time, increase the probability that it will be remembered and purchased.[162] Coca-Cola, for example, is associated in many consumers' minds with the color red, its distinctive bottle shape, its logo script, and its ability to refresh on a hot day.[163] In the United States, agricultural commodity marketing programs have been responsible for several memorable advertising campaigns, such as "Got Milk?" and "Beef: It's What's for Dinner." Developing memorable marketing programs for plant-based foods could play an important role in shifting consumer behavior.

Evolve social norms

Research has shown that the cultural environment and social norms of the group to which a person belongs can influence what and how much that person eats. A study in the *Journal of the Academy of Nutrition and Dietetics*, for example, reported that people eat more when others around them are eating more, and choose food types based on what they perceive will help them fit in with a given group and gain social approval.[164] A key challenge will be to moderate men's meat consumption and increase their consumption of plant-based foods: studies have shown strong cultural associations between red meat consumption and masculinity,[165] and men are more likely than women to believe that plant-based diets are not nutritious, tasty, or filling.[166]

- **Inform about the issue**. Although evidence shows that information and education alone do not lead to sufficient action,[167] they can sometimes contribute to a broader effort, as demonstrated by their role in the past decade in reducing consumption of trans fats in several countries.[168] In many cases, information can lead to indirect or multiplier effects, by raising the profile of an issue, prompting product reformulation (in the case of labeling), or forming the basis of food and nutrition policy and programs (e.g., national dietary guidelines).[169]

- **Make socially desirable.** In 2012, celebrity chef Delia Smith helped increase UK sales of gammon (ham) nearly threefold relative to the previous year after featuring a recipe for gammon on television. The chef's influence over food sales has been called the "Delia effect," a term coined when sales of cranberries quadrupled the day after she used them on television.[170] Plant-based food companies such as Beyond Meat, Silk, and MorningStar Farms have used athlete or male celebrity endorsements, prominent protein claims, and masculine language like "Beast Burger" to create associations with strength and power to avoid feelings of emasculation. Tossed, a UK-based salad chain, attracts men through naming certain products "Muscle Builders" and forming partnerships with local gyms to offer male personal assistants discounts if they eat in their stores.

- **Make socially unacceptable.** A number of campaigns have helped make a specific food socially unacceptable to consumers. For example, in 2008 the celebrity chefs Hugh Fearnley-Whittingstall and Jamie Oliver both launched high-profile TV programs and campaigns to highlight the issues associated with buying non-free-range chicken. During the campaign, sales of free-range poultry reportedly increased by 35 percent relative to the previous year, while sales of caged birds fell by 7 percent.[171] In another example, WildAid launched a campaign to draw attention to the devastating impacts of shark fishing, helping to reduce consumption of shark fins in China.[172] It is important to note, however, that the long-term impact of these campaigns is unknown.

In nearly all the successful case studies reviewed, a shift in consumption behavior required multiple strategies from the Shift Wheel, and typically involved groups across a range of sectors, including manufacturers, retailers, nongovernmental organizations, and governments.

Improve plant-based or cultured meat substitutes

The size of diet shifts needed among the world's affluent populations suggests that food manufacturers will need to make dramatic progress in their development of plant-based or cultured substitutes for animal-based foods—particularly beef—that truly replicate consumers' experiences.

One possibility is meat cultured in laboratories—called "clean meat" by its proponents. The objective is to create meat without the resource inputs and environmental impacts generated by conventional meat, by harvesting animal stem cells and growing them in a petri dish.[173] In 2013, the first public tasting of this cultured meat at Maastricht University showed success in replicating the texture and density of real meat, although the flavor seemed bland.[174] An even bigger challenge will be producing cultured meat at a competitive cost because "cell culture is one of the most expensive and resource-intensive techniques in modern biology."[175] Companies are working to improve cultured meats while reducing production costs in order to get these meats to market; Memphis Meats and JUST (formerly known as Hampton Creek) both have stated goals of reaching the market within the next five years.[176]

The more immediate alternative is to produce animal-based food substitutes from plant-based products. Leading brands include Quorn, Beyond Meat, Impossible Foods, and JUST. The ingredients in Beyond Meat include soy protein, pea protein, and carrot fiber. Impossible Foods' plant-based ground beef is made from ingredients including wheat, coconut oil, potatoes, and plant-based heme.[177] Heme, a molecule also found in the hemoglobin of animal blood, contributes a meat-like color and flavor to the product. In 2015, Oregon State University researchers patented a new strain of red marine algae that is high in protein and tastes like bacon.[178] The product has yet to be commercialized but is showing potential. Several companies are manufacturing plant-based fish alternatives; Ocean Hugger Foods makes a tomato-based raw tuna substitute and New Wave Foods is producing plant-based shrimp.[179]

In the United States in recent years, the company JUST has made major commercial breakthroughs in alternatives for other animal-based foods. It uses Canadian yellow peas to create an eggless mayonnaise alternative called "Just Mayo," and a similar approach to create egg- and dairy-free cookie dough and powdered scrambled faux eggs. The company is working on plant-based alternatives to ice cream, ranch dressing, and other animal-based foods. Part of JUST's business model is to sell plant-based alternatives that are not only indistinguishable from but also cheaper than conventional animal-based products.[180]

Significant reductions in meat consumption could occur just by blending plant-based ingredients into widely consumed ground meats. In the United States, ground beef accounts for between 55 and 60 percent of total beef consumption.[181] Mixtures of ground beef and plant-based products could be attractive, and several organizations—including the Culinary Institute of America, the U.S. Mushroom Council, the James Beard Foundation, large food service companies like Sodexo, a number of universities, and the national burger chain Sonic Drive-In—are piloting burgers made from a blend of beef and 20 to 35 percent mushrooms that are comparable or superior to all-beef burgers in taste.[182] In the case of blended burgers, low amounts of mushroom (e.g., 20%) can lead to burgers that are indistinguishable in taste from conventional all-beef burgers—constituting another example of "disguising the change."

In recent years, corporate investment and research in alternative meat products has grown rapidly.[183] Food critics appear to confirm that substitutes are coming closer to matching the experience of at least some meats.[184] Because of the inefficiency of meat production, these alternatives have a high potential to become cheaper than meat. Even with a high rate of growth, however, the retail market is only projected to grow from $3.8 billion worldwide in 2015 to $5.2 billion in 2020.[185] By comparison, the retail market for conventional meat and seafood was $741 billion in 2014.[186] The industry will need to grow at a vastly greater rate if it is to have a real effect on global meat consumption.

Leverage government policies

Governments have a wide range of policy options available to influence diets, including procurement, taxes, subsidy reforms, and stronger policy coherence.[187] Diet choices, in turn, affect multiple policy goals, including public health, agricultural production, rural development, climate change mitigation, biodiversity protection, and food and water security.

Procurement

Governments provide meals in schools, hospitals, offices, and to the military. For example, the U.S. National School Lunch Program provided lunches to more than 31 million children each school day in 2012, across more than 100,000 schools. And in Brazil, the National School Feeding program feeds approximately 42 million students each day. These programs could have large impact if they shifted these meals toward less consumption of beef and other meats.[188] For example, in Brazil, São Paulo's public schools serve more than 500,000 vegetarian meals to students every other week.[189]

Taxes

Taxes may provide the strongest and technically most plausible measures that governments could take to influence consumption patterns, although they can be politically challenging to introduce. Available evidence suggests that food taxes imposed at the retail level on certain types of food could work in developed countries. Since around 2010, several countries have established taxes on foods and beverages based on health concerns (e.g., sugary soft drinks, candy, foods high in saturated fats)—including Barbados, Chile, Denmark, Finland, France, Hungary, Mexico, and local governments in the United States.[190] Reviews of these kinds of efforts indicate a significant effect on consumption.[191]

Modeling studies agree that food taxes could have a significant effect on consumption, using a variety of economic methods. These studies generally estimate substantial reductions in specific targeted foods and have emphasized that taxes work best when there are untaxed, appropriate substitutes. Estimated elasticities of consumption for various meats also suggest that a tax on beef, for example, could lead to substantial switching at least to other meats if not vegetable alternatives.[192] In fact, U.S. consumption of beef declined by 12 percent just from 2007 to 2015 as retail prices rose by 51 percent,[193] although with the recession over, and beef production rebounding to prerecession levels, consumption has somewhat rebounded.[194]

Studies on food taxes have also suggested important lessons and caveats:

- Taxes imposed by countries at the production level, such as a beef production tax, are unlikely to work because production will simply move to another country.[195]
- As the Denmark experience suggests, taxes imposed over broader regions are likely to be more effective than those imposed in a single country or municipality if consumers can simply shop elsewhere. In 2011, Denmark imposed taxes on foods based on fat content, but it abandoned the taxes a year later in large part because consumers were able to cross the border into Germany and purchase the same products without a tax.[196]
- Taxes will be more effective when more desirable substitutes are untaxed. For example, it is more likely that people will switch from beef to chicken if beef is taxed more highly than chicken.
- Tax rates will likely have to be substantial to meaningfully reduce consumption. For example, even though one survey of estimated demand elasticities for meats found elasticities often around one (or even modestly higher),[197] such an estimate still implies that roughly a 10 percent tax would be needed to achieve a 10 percent reduction in consumption. In a less encouraging result, another study found that a 40 percent tax on beef would reduce consumption by only 13 percent,[198] a sensitivity to price that could help explain the changes in U.S. beef consumption after 2008.

Except in the case of inherently unhealthy foods and beverages, food taxes designed to change consumption of animal-based foods seem politically unlikely today. To avoid unfair distributional consequences, such taxes should also be rebated through subsidies or reduced taxes on other necessities.

Nevertheless, food taxes deserve more attention and may become more acceptable in the future.

Subsidies

Governments should phase out subsidies that favor meat and dairy production and explore subsidies instead for healthy plant-based foods. Bailey et al. (2014) found that livestock subsidies in Organisation for Economic Co-operation and Development (OECD) countries amounted to $53 billion in 2013, and pork subsidies in China exceeded $22 billion in 2012. The U.S. Department of Agriculture estimated in 2009 that a subsidy lowering retail prices of fruits and vegetables by 10 percent would encourage low-income households to increase their consumption by 2 to 5 percent,[199] and would cost around $600 million to implement annually. A more recent U.S. study also estimating the effects of a 10 percent reduction in fruit and vegetable prices came to a more hopeful conclusion that consumption would rise by 14 percent, preventing or postponing more than 150,000 deaths from heart disease in the United States by 2030.[200]

Stronger policy coherence

Government policies are not always aligned and can work at cross-purposes. As a first step to assuring coherence, governments should establish multidisciplinary cross-agency task forces to identify policies and regulations that influence diet choices, assess whether they are aligned with promoting healthy and sustainable diets, and recommend changes to ensure alignment.

For more detail about this menu item, see "Shifting Diets for a Sustainable Food Future," a working paper supporting this World Resources Report available at www.SustainableFoodFuture.org.

CHAPTER 7

MENU ITEM: AVOID COMPETITION FROM BIOENERGY FOR FOOD CROPS AND LAND

Many governments are calling for large increases in "modern" bioenergy, believing that this will reduce GHG emissions from energy use. In this chapter, we estimate the potential impacts of scaling up the use of bioenergy derived from plants grown on productive land. We conclude that the proportion of plant material diverted from food and fiber to energy would be unacceptably high—and that hopes of climate benefits are misplaced. We recommend phasing out bioenergy targets.

Bioenergy is any form of energy that is derived from recent (as opposed to fossil) plant or animal tissue. For millions of the world's people who cannot afford fossil fuels, bioenergy has long provided and continues to provide the major source of energy in the form of wood, charcoal from wood, and sometimes dung. Traditionally estimated at roughly one-tenth of the world's energy supply,[201] these traditional sources of bioenergy will probably continue for many years to serve millions of people who cannot afford modern alternatives. Even so, reducing this traditional bioenergy use has been a major focus of many international efforts both to preserve forests[202] and to reduce adverse impacts on human health. [203]

In Europe and the United States, wood for heat and grass for working animals once provided the primary energy sources, but they proved incapable of meeting growing energy demands. By the middle and late 19th century, reliance on bioenergy had contributed to extensive deforestation in these regions, even though total energy demand at the time was a modest share of present consumption. The shift to fossil fuels played an important role in allowing many of these forests to regrow.[204]

The Challenge

Some forms of bioenergy represent little or no competition for other uses of land such as producing food or fiber or storing carbon. For example, the use of wood wastes for electricity and heat generation in the production of paper and other wood products has long provided bioenergy from materials that would otherwise be discarded. Various studies suggest potential to expand the use of biomass-based wastes and residues, and we discuss them briefly later in this chapter.

Over the past few decades, however, many governments have made strong pushes to expand "modern" bioenergy that diverts land or plants from alternative uses. These policies encourage liquid biofuels for transportation made from crops. Governments are also encouraging power plants to replace coal, at least in part, with wood pellets or chips generated by additional harvest of trees or diversion of the parts of trees that would otherwise provide pulp and paper. Governments have created incentives to cultivate fast-growing grasses for biomass energy feedstocks on agricultural land, although this has not yet occurred in meaningful volumes.

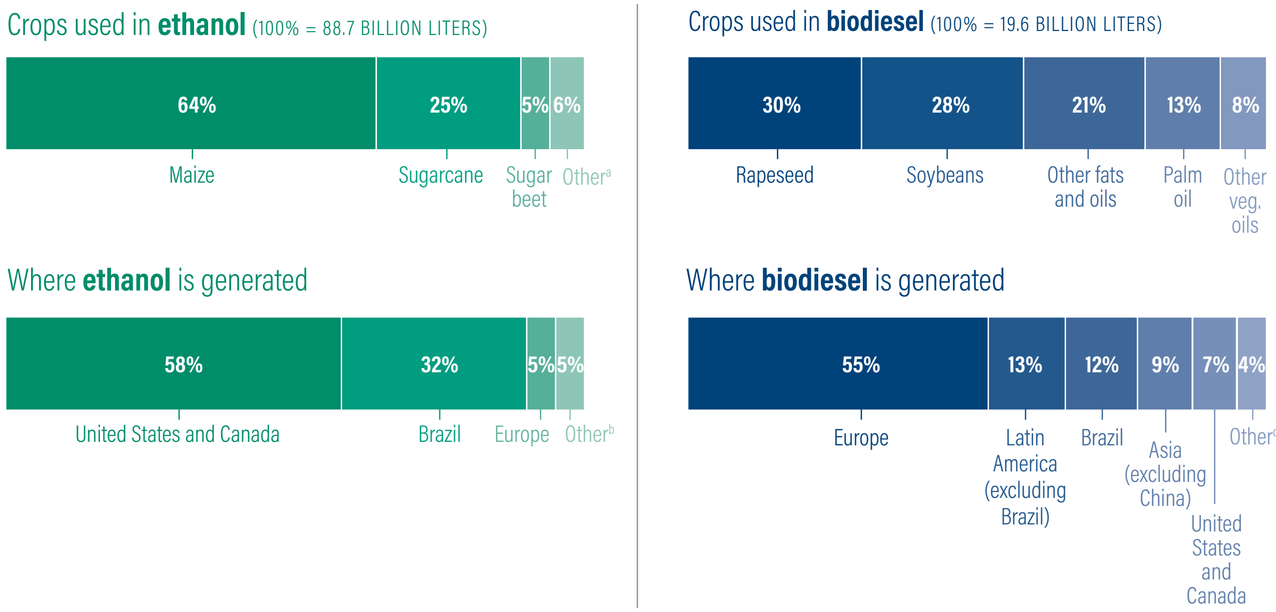
We call these forms of bioenergy "bioenergy from the dedicated use of land" because land must be dedicated to the purpose of producing bioenergy feedstocks. The productive potential of land is thus diverted from food and fiber production or carbon storage to bioenergy. This diversion still occurs, at least in part, even if some of the biofuel crops are used for food or other useful nonfuel by-products.

We find that meeting the more ambitious bioenergy targets and mandates currently in effect would divert and consume plant material equal to large percentages of the crops, grasses, and wood harvested in the world today. We further find that the claimed climate benefits of bioenergy are based primarily on an accounting error that treats biomass as automatically "carbon free," meaning it counts the benefit of using land or biomass for energy without counting the cost of not using them for other purposes.

In 2010, our base year, biofuels provided roughly 2.5 percent of the energy in the world's transportation fuel (the fuel used for road vehicles, airplanes, trains, and ships). The source of these biofuels was, overwhelmingly, food crops.[205] They include ethanol distilled mainly from maize, sugarcane, sugar beets, or wheat (88.7 billion liters),[206] and biodiesel refined from vegetable oils (19.6 billion liters). The United States, Canada, and Brazil accounted for about 90 percent of ethanol production, while Europe accounted for about 55 percent of biodiesel production (Figure 7-1).[207] Excluding feed by-products, about 4.7 percent (3.3 exajoules [EJ][208]) of the energy content in all crops grown worldwide was used for biofuels in 2010.[209]

For our 2050 baseline scenario, we used the FAO assumption that biofuels in 2050 will continue to provide the same 2.5 percent share of transportation fuel as they did in 2010. Because transportation energy demand will grow, this assumption leads to relatively modest growth in biofuels.

Figure 7-1 | Biofuel production in 2010 was concentrated in a few regions and a few crops



Notes:
a. Includes wheat (4%), cassava (1%), and other feedstocks (1%).
b. Includes China (2%) and other regions (3%).
c. Includes China (2%) and other regions (2%).
Source: EIA (2014a).

Biofuel policy becomes more consequential because many nations have established, or are establishing, targets and mandates that call for biofuels to make up a greater share of transportation fuel by 2030 or before (Table 7-1). Common targets are at least 10 percent, and many countries view these targets as just steps toward even larger targets.

What are the implications of a global 10 percent biofuels share of transportation fuels for the crop calorie gap? One way to answer this question is to determine the share of the world's existing annual crop production that would be required to meet such a target. (The share of *existing* crop calorie production, rather than future crop production, conveys how much additional crop production is needed to supply these biofuels, which contributes to the crop calorie gap.) For 2050, the answer is roughly 30 percent of all the energy in today's (2010) crop production (Figure 7-2).

Because transportation fuel is only one part of the world's energy use, 30 percent of all today's crop energy would provide only around 2 percent of final, net delivered energy in 2050.[210]

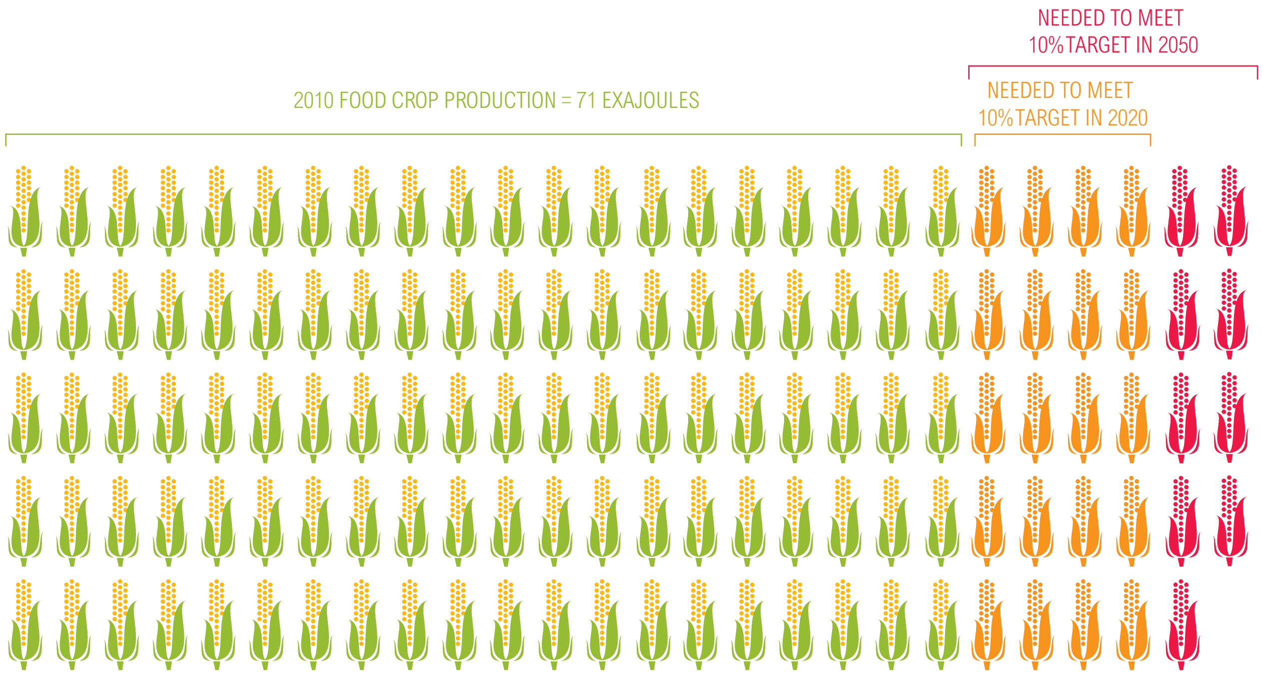
These numbers can be used to show the implications for the crop calorie gap of increasing biofuel production to 10 percent of transportation fuels from the 2.5 percent we already factor into our baseline. In that event, the crop calorie gap between 2010 and 2050 would widen from 56 to 78 percent (Table 7-3).[211] Yet, if the world were to eliminate crop-based biofuels, the crop calorie gap would decline from 56 to 49 percent.

Table 7-1 | Biofuel targets and mandates around the world, 2016

COUNTRY	MANDATE/TARGET
Angola	E10
Argentina	E10, B10
Australia: New South Wales (NSW), Queensland (QL)	NSW: E6, B2; QL: E3 (by 2017), E4 (by 2018), B0.5
Belgium	E4, B4
Brazil	E27 and B8 (by 2017), rising to B10 (by 2019)
Canada	E5, B2 (nationwide), E5–E8.5 (in 5 provinces), B2–B4 (in 5 provinces)
Chile	E5, B5 (target, no mandate)
China	E10 (9 provinces), B1 (Taipei)
Colombia	E8, B10
Costa Rica	E7, B20
Dominican Republic	E15, B2 (target, no mandate)
Ecuador	E10, B5
European Union	10% renewable energy in transport by 2020 with 7% cap on crop-based fuels[a]
Ethiopia	E10
Fiji	E10, B5 (approved target in 2011, mandate expected)
Guatemala	E5
India	E22.5, B15
Indonesia	E3, B20
Italy	0.6% advanced biofuels blend by 2018, 1% by 2022
Jamaica	E10
Kenya	E10 (in Kisumu)
Malawi	E10
Mexico	E5.8
Malaysia	E10, B10
Mozambique	E15 (2016–20), E20 (from 2021)
Norway	B3.5
Panama	E10
Paraguay	E25, B1
Peru	E7.8, B2
Philippines	E10, B2
Republic of Korea	B2.5, B3 (by 2018)
South Africa	E2, B5
Sudan	E5
Thailand	E5, B7
Turkey	E2
Ukraine	E5, E7 (by 2017)
United States	136 billion liters of any biofuel, equivalent to ~12% of total transportation fuel demand in 2020–22[b]
Uruguay	E5, B5
Vietnam	E5
Zimbabwe	E15

Notes:
E= ethanol (e.g., "E2" = 2% ethanol blend); B = biodiesel (e.g., "B2" = 2% biodiesel blend)
a. Lignocellulosic biofuels, as well as biofuels made from wastes and residues, count twice and renewable electricity 2.5 times toward the target.
b. The U.S. mandate is for a volume, not a percentage, and this volume may be met either by ethanol or biodiesel, despite their different energy contents. The estimated percentage of U.S. transportation fuel in 2020-22 is based on the assumption of 34 billion gallons of ethanol and 2 billion gallons of biodiesel and a U.S. Energy Information Administration projection of 2020 U.S. transportation energy demand. The U.S. mandate includes a goal that 16 billion gallons of the 36 billion gallons (136 billion liters) come from cellulosic sources, but that requirement can be waived and all 36 billion gallons could come from crops as long as maize-based ethanol does not exceed 15 billion gallons.
Source: IEA (2016a) in REN21 (2017).

Figure 7-2 | If crop-based biofuels provided 10 percent of the world's transportation fuels in 2050, they would require an amount of energy equal to roughly 30 percent of the energy contained in global crop production in 2010



Source: Authors' calculations based on EIA (2013), FAO (2013), and Wirsenius (2000).

Biofuel from cellulose?

Some biofuel advocates argue that producing biofuels from various forms of cellulose or noncrop biomass rather than from food crops would avoid competition with food. Cellulose forms much of the harder, inedible structural parts of plants, and researchers are devoting great effort to find ways of converting cellulose into ethanol more efficiently. In theory, almost any plant material could fuel this cellulosic ethanol, including crop residues and urban organic wastes. Yet the potential for wastes to provide energy on a large scale is limited (as discussed below). Virtually all analyses for future large-scale biofuel production assume that most of the cellulosic biomass for bioenergy would come from fast-growing grasses and trees planted for energy.[212]

Unfortunately, growing trees and grasses well requires fertile land, resulting in potential land competition with food production. In general, growing grasses and trees on cropland generates the highest yields but is unlikely to produce more biofuel per hectare than today's dominant ethanol food crops. For example, a hectare of maize in the United States currently produces roughly 1,600 gallons (about 6,000 liters) of ethanol after deducting the part of the land that produces feed products.[213] For cellulosic ethanol production to match this figure, the grasses or trees must achieve almost double the national cellulosic yields estimated by the U.S. Environmental Protection Agency (EPA),[214] and two to four times the perennial grass yields farmers actually achieve today.[215] Although there are optimistic projections for even higher yields, they are unrealistically predicated on small plot trials by scientists—sometimes only a few square meters,[216] which scientists can tend more attentively than real farmers.

Yields on poorer, less fertile land tend to be substantially lower.[217] More fundamentally, using poorer land for bioenergy still uses land. Land that can grow bioenergy crops reasonably well will typically grow other plants well, too—if not food crops, then trees and shrubs that provide carbon storage, watershed protection, wildlife habitat, and other benefits.

The implications of possible bioenergy targets for all forms of energy

Targets for transportation fuel are actually only part of much larger targets for bioenergy. Some governments and researchers are promoting bioenergy for heat and electricity generation, using not only food and energy crops but also wood harvested from forests. Both the goals and claims about the potential "sustainable" supply of biomass are ambitious. Today, the world uses around 575 exajoules (EJ) of energy,[218] and some researchers claim that biomass could sustainably supply almost the whole of this amount.[219] The International Energy Agency has at times called for a bioenergy target of 20 percent of global energy by 2050,[220] which—at projected 2050 levels of energy consumption—would require around 230 EJ of bioenergy.[221] This quantity of biomass also features in many other strategies to stabilize climate.[222]

How much of today's world biomass harvest would be required to supply 230 EJ? The answer is roughly all of it: all the crops, plant residues, and wood, and all the biomass grazed by livestock around the world, probably amounts to roughly 225 EJ[223] (Figure 7-3). Yet the world would still need all this biomass for food, livestock, wood, and other uses. To meet this bioenergy demand while also meeting projected food demand, the world would therefore have to approximately double the present total harvest of plant material and produce roughly 50 percent more food at the same time.

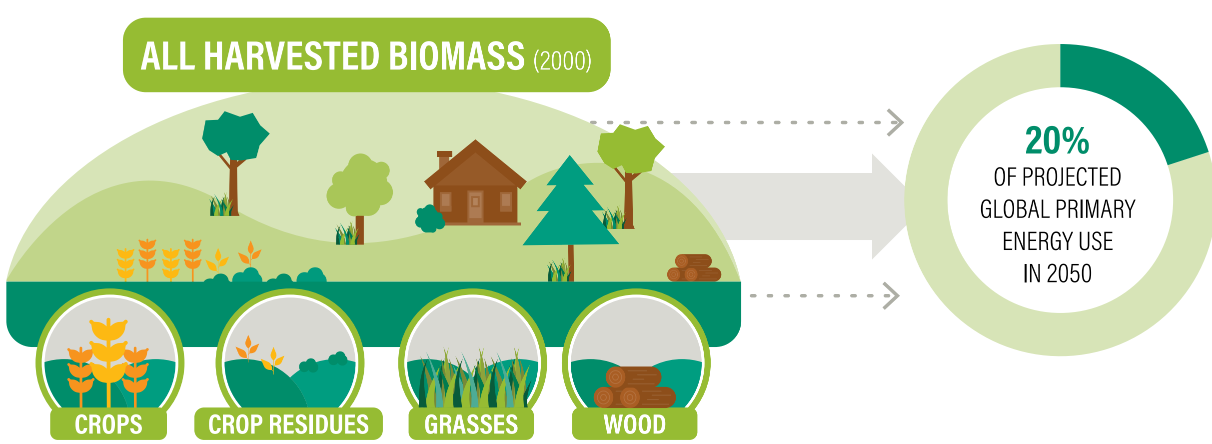
The Opportunity

Phasing out biofuels from the dedicated use of land provides an opportunity to close food, land, and agricultural GHG mitigation gaps. Yet bioenergy supporters believe that land-based bioenergy reduces GHG emissions, is a necessary replacement for fossil energy, and therefore must be pursued despite its high land requirements. Because the sustainability criteria in this analysis are designed in part to stabilize the climate, we might agree—*if* bioenergy from the dedicated use of land truly reduced emissions. Yet, in this section, we explain our view that arguments in favor of these sources of bioenergy are based on a fundamental accounting error. Solar energy and some smaller alternative sources of biomass provide far superior options.

Estimates of the energy potential of bioenergy grown on dedicated areas of land lead to double counting of land

How can some researchers estimate that the world could reduce GHG emissions while harvesting double the quantities of biomass already harvested in the world, given that producing existing levels of biomass has already required conversion of enough forests and other natural vegetation to contribute roughly one-third of the extra carbon in the atmosphere? The answer, we believe, is that they simultaneously count the land or biomass as available to produce bioenergy while assuming that the same

Figure 7-3 | If the world's entire harvest of crops, crop residues, grasses, and wood in 2000 were used for bioenergy, it would provide only 20 percent of energy needs in 2050



Note: Assumes primary to final energy conversion for biomass is 24% lower than for fossil energy.
Source: Authors' calculations based on Haberl et al. (2007), IEA (2017), and JRC (2011).

land or biomass continues to serve its existing uses, including food production or carbon storage.

The world's lands are already growing plants every year, and these plants are already being used. Some uses involve the production of food, fiber, and timber—which people directly "consume." Other uses include replenishing or increasing carbon in soils and in vegetation, which together contain four times as much carbon as the atmosphere.[224] Bioenergy cannot supply energy except at the expense of these other valuable uses of plants, unless bioenergy is derived from or results in some additional source of biomass.

Large estimates of bioenergy's GHG reduction potential have overlooked this need for additional biomass production and have relied on biomass and land already in use:[225]

- Much of the interest in bioenergy originated in the 2001 integrated assessment of the Intergovernmental Panel on Climate Change, which estimated that low-carbon bioenergy could potentially replace all global energy consumption at the time.[226] This analysis assumed that bioenergy crops could grow on the roughly 1.4 billion hectares of "potential croplands" estimated by FAO that were neither in food production today nor likely to be needed in the future. But the analysis failed to note that unused "potential croplands" consist of forests, woody savannas, and wetter, more productive grazing lands. Clearing them for bioenergy would release vast quantities of carbon and, in the case of grazing land, sacrifice food production. The IPCC analysis implicitly and incorrectly assumed that these lands were "empty" or free to use without sacrificing alternative uses.

- More recent analyses prepared by other researchers and sometimes cited by the IPCC have excluded denser forests from these estimates but otherwise have continued to assume that both potential cropland and most grazing lands are available for bioenergy.[227] These papers ignore the food production on grazing land and have incorrectly assumed that those tropical woody savannas wet enough to produce crops are "carbon free." Yet they too store abundant carbon and provide abundant biodiversity and other ecosystem services.[228]
- Some analyses assume that people can harvest trees as "carbon-free" sources of energy so long as they harvest only the annual growth of that forest.[229] The rationale is that if the forest's carbon stock remains stable, the harvest for bioenergy has not added carbon dioxide to the atmosphere. But this calculation ignores the fact that the annual growth of a forest would have added to the existing sum of biomass and stored additional carbon if it had not been harvested for bioenergy. The loss of one ton of such a carbon dioxide "sink" has the same effect on the atmosphere as a one-ton increase in carbon dioxide emissions to the atmosphere. Overall, despite the loss of forests in the tropics, the world's forests are accumulating carbon and providing a large carbon sink, which slows climate change and is critical to future strategies to reduce climate change impacts. In general, harvesting forests for energy reduces the quantity of carbon that forests store more than it displaces emissions of carbon from fossil fuel combustion (at least for decades).[230]

All these estimates are a form of "double counting" because they rely on biomass, or the land to grow biomass, that is already being used for some other purpose. Because bioenergy analyses assume that these other purposes continue to be met, they are in effect counting the biomass and land twice.[231]

Assumed greenhouse gas reductions result from the same double-counting error

The double counting of biomass and land is equivalent to treating them as "carbon free" in the sense that no global carbon consequences are assigned to their diversion for bioenergy use.

This approach also double-counts carbon, and the best way to understand how is by tracing the flow of carbon to and from the atmosphere when bioenergy is produced and comparing that to how carbon is counted in analyses that claim bioenergy use reduces GHGs in the atmosphere.

The starting point is that burning biomass, whether wood or ethanol, emits carbon in the form of carbon dioxide just like burning fossil fuels. In fact, because of the nature of biomass' chemical bonds and its water content, bioenergy emits a little more carbon dioxide than fossil fuels to produce the same amount of energy.[232] Why then do some analyses claim that bioenergy reduces GHG emissions?

The usual explanation is that this carbon dioxide is automatically *offset*, that is, canceled out, by the carbon dioxide absorbed by plants when they grow.[233] Because of this plant growth offset, the theory is that bioenergy does not add more carbon to the atmosphere, whereas burning fossil fuels adds new carbon to the air that would otherwise stay underground. Based on this theory, nearly all analyses estimating the climate benefits of bioenergy do not count the carbon dioxide released when biomass is burned.[234] Although such analyses may count the emissions from burning oil or gas in the course of bioenergy production—growing plants and converting them to biofuels—they treat the biomass itself as an inherently "carbon-neutral fuel," that is, a carbon-free source of energy just like solar or wind. For coal use, this would be the equivalent of counting the emissions from using coal mining machinery but not counting the emissions from burning the coal itself.

This assumption is erroneous because the first requirement for any offset is that it be additional. For example, if an employer wishes to "offset" a worker's overtime by providing vacation time, the employer must offer the worker more vacation time and not merely allow the worker to take vacation time already earned. For this reason, if bare land—that would otherwise remain bare—is brought into production to grow biomass for energy, the additional carbon absorbed by these plants offsets the carbon released by burning them. Similarly, if crop residues were going to be burned in the field, the carbon released by collecting and burning them for bioenergy is offset by the emissions avoided by not burning the residues in the field. But if maize is grown for ethanol by clearing forest, there is a large release of carbon, so that the net effect of growing maize for ethanol production is to release far more carbon than the maize plants will absorb and turn into ethanol for decades. (That point is now broadly accepted.)

Equally—but less well appreciated—there is no direct, additional carbon uptake when maize used for ethanol is grown on land that was already producing maize. That is typically what happens when an ethanol plant obtains its ethanol from the local silo, and that is the typical assumption by a model that assumes maize for ethanol is grown with no "direct" land-use change. Although the growing maize does absorb carbon, that maize growth and carbon absorption were going to occur anyway, and simply diverting the maize to ethanol does not absorb any more. By itself, stopping the analysis here, this maize production cannot provide a valid offset. (In our discussion of modeling below, we discuss whether the market responses to this diversion can lead to valid offsets and whether that would be desirable.)

Overall, only additional biomass, which means either additional plant growth or reduced waste, provides a valid offset. Figure 7-4 illustrates scenarios where bioenergy can directly lead to net GHG emission reductions and where it does not.[235]

What about replacing crops or pasture in one location with faster growing grasses or trees? For example, corn could replace soybeans, producing more biomass and absorbing more carbon. Alternatively, energy crops may generate more biomass per hectare than pasture lands. But if these crops for bioenergy replace the other food sources, land somewhere else still needs to be devoted to growing the forgone soybeans and forage if the world wants to continue to eat. Replacing these food and forage crops elsewhere displaces the vegetation and the carbon that other land would store and sequester. For bioenergy to reduce GHG emissions without displacing food or forest products, it must not only lead to more carbon removal from the air on the hectares where bioenergy is grown but also lead to an increase in total world carbon removal by land.

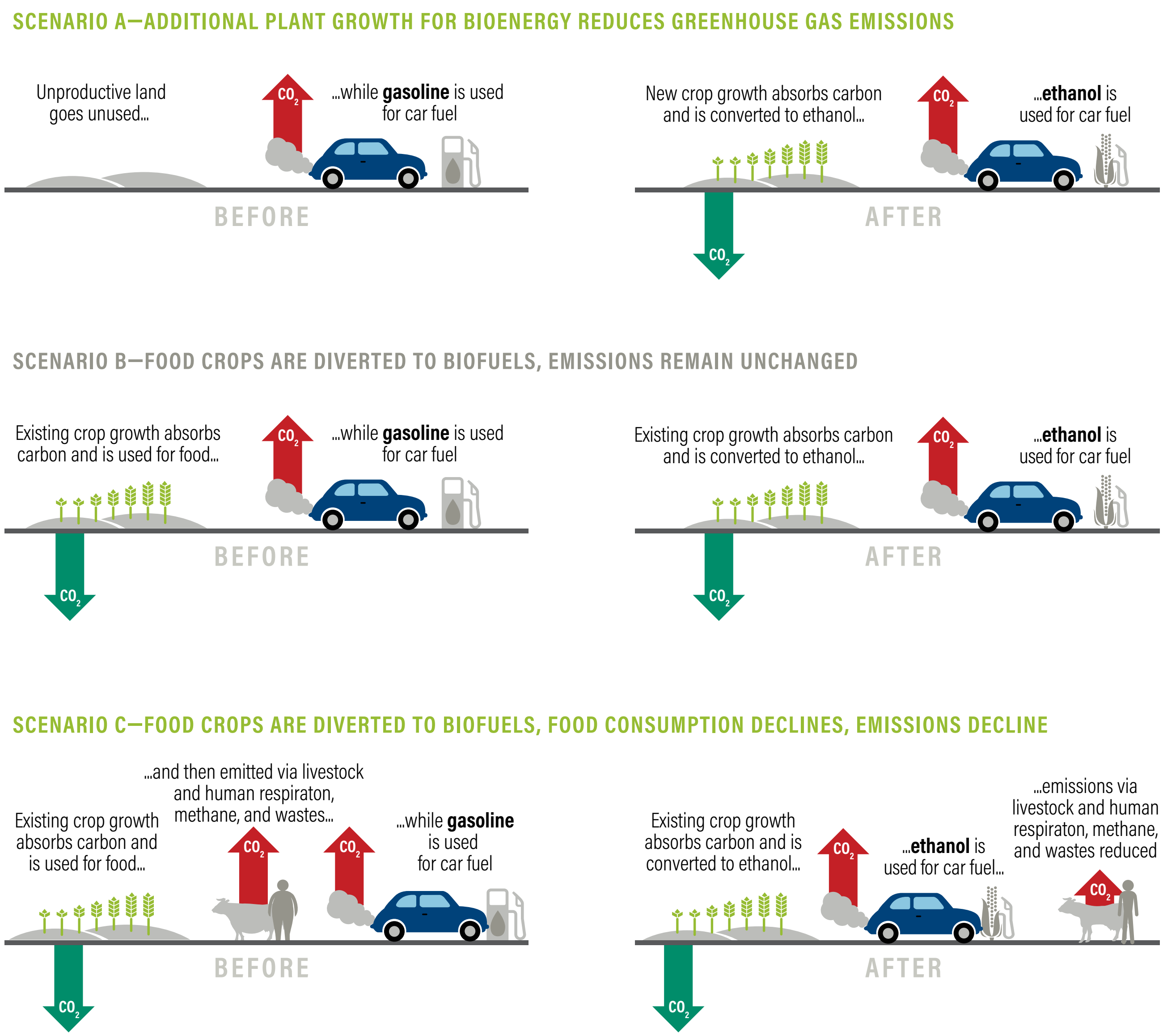
"Renewable" and "sustainable" does not make biomass carbon-neutral

What explains the belief that all bioenergy is carbon-neutral? One explanation is the common but incorrect intuition that anything renewable is carbon-free. That idea is based on thinking like the following: "If the world uses plant growth for energy and the plants grow again, it cannot cost the world any carbon." This intuition also explains the view that "sustainable" production makes plants carbon-free because sustainability is what ensures that the same level of plant growth is fully renewable over the long-term.

The analogy of a monthly paycheck illustrates the error in this thinking. Like annual plant growth, a paycheck is renewable in that a new check should come every month. But just because the money is "renewable" does not mean it is free for the taking for alternative uses. People cannot spend their paycheck on something new like more leisure travel or energy without sacrificing something they are already buying, like food and rent, or without adding less of that money to their savings. To afford more leisure travel or energy without sacrificing other benefits, people need a bigger paycheck or they must cut some source of wasteful spending.

Analogously, people use annual plant growth and the carbon it absorbs for food and forest products, and they leave some of the carbon to be stored in vegetation and soils—thereby limiting climate change. That annual plant growth and carbon is not free for the taking by bioenergy. The cost of using the carbon in plants to replace the carbon in fossil fuels is not using that carbon to eat, to build a house, or to replenish or increase the carbon in vegetation and soils. To be richer in carbon, one cannot merely divert plants from one use to another; one needs more plant growth or elimination of some plant waste. In other words, one needs "additional biomass."

Figure 7-4 | Why greenhouse gas reductions from bioenergy require additional biomass



Note: In scenario A, shifting from gasoline to ethanol use reduces emissions through additional uptake of carbon on land that previously did not grow plants. In scenario B, which is the typical bioenergy scenario, the shift from gasoline to ethanol does not reduce emissions, as the demand for bioenergy merely diverts plant growth (e.g., maize) that would have occurred anyway. In scenario C, higher demand for crops for ethanol drives up food and feed prices, and GHG emissions from human and livestock consumption decline, but at the expense of shrinking the food supply.
Source: Searchinger and Heimlich (2015).

Modeling studies can be misleading

Nearly all studies of the potential scale of bioenergy accept that demand for cropland to produce food is likely to grow, at least until 2050. They therefore exclude existing cropland from the category of potential land for bioenergy. Yet present biofuel policies not only allow but even encourage biofuels to use crops from existing croplands. These policies find some support from a few economic modeling studies of producing biofuels on cropland today (as opposed to modeling studies of land-use needs in the future). In fact, many such modeling studies analyzing the GHG implications of using crops for biofuels find little or no GHG savings if they take account of the conversion to agriculture of forests and grasslands necessary to replace the forgone food production.[236] However, some studies find that potential GHG savings of 50 percent or more can be gained from biofuels from some crops. Given the broad consensus among studies of bioenergy potential that existing cropland is unavailable to divert to bioenergy, what explains these other modeling studies that find that diverting cropland to bioenergy would reduce GHGs?

Economic models all estimate the "indirect" or "market-mediated" results of biofuels policies. When crops from existing cropland are diverted to bioenergy, crop prices rise and these models attempt to estimate the responses on land and consumption elsewhere. Those economic models favorable to bioenergy estimate one or more of three responses that could produce GHG benefits. Although each response is debatable, the more important point is that none of the outcomes predicted by the models would be ultimately socially or environmentally desirable, even assuming that the model prediction was accurate.

Food reduction

First, some models estimate that many of the food crops diverted to biofuels are not replaced. When food prices rise because of the additional demand for biofuels, the market responses are not only that other farmers produce more food but also that some consumers consume less. The reduction in consumption reduces GHGs in two ways. First, if people eat less food, farmers do not have to clear as much additional land to replace the forgone food crops. More directly, when people eat crops, they release that carbon, mostly through respiration (and a little through their wastes). If crops are not replaced, then people or livestock eat fewer crops and physically breathe out less carbon dioxide. Economic models used by the European Commission and the state of California have estimated that this effect is large—that between one-quarter and one-half of the food calories (and therefore roughly that much carbon) diverted to biofuels is not replaced.[237]

It is true that if biofuel production reduces food consumption, the effect could contribute toward GHG savings. And these models do ultimately estimate that biofuels generate small GHG savings. Yet, in such models, the reduction in emissions results from the reduction in food consumption, and few people would likely volunteer to reduce emissions in this way.

In fact, any food reduction effect of such biofuels is likely to be particularly undesirable because it is likely to fall disproportionately on the poor. Unlike taxes that could, in theory, be imposed on high-carbon foods such as beef, biofuels increase wholesale crop prices for basic commodities and for the rich and the poor alike. The effect on consumption by the poor is likely to be much greater than on consumption by the rich because poor people have less capacity to absorb the higher costs.[238] Even if these models are correct, such a strategy to reduce GHG emissions by reducing food consumption by the poor does not meet the poverty alleviation criterion of a sustainable food future.

Yield gains

Second, some models estimate that farmers replace crops or cropland diverted to biofuels largely or primarily by increasing their crop or pasture yields on existing agricultural land.[239] These yield gains avoid clearing more land to replace the food production area lost to biofuels. The theory is that because these diversions increase crop prices, farmers have more incentive to add fertilizer or otherwise improve management on existing agricultural land.

Yet the evidence for yield responses due to higher prices is weak and limited at best.[240] Global yield growth has shown remarkably consistent trends that fluctuate little or not at all in response to annual changes in price.[241] Unless yield gains rather than expansions of cropland replace nearly all the crops diverted to biofuels, the GHG reductions from biofuels relative to gasoline and diesel would at best be modest because the emissions from clearing more land would negate them.[242]

A more basic objection is that farmers already need to increase crop or pasture yields on existing agricultural land just to meet rapidly rising food demands. If biofuels grown on cropland or pasture are to make even a modest contribution to energy supplies by 2050 without sacrificing food production or clearing more land, farmers would have to raise their crop and pasture yields still more. As discussed in more detail in Chapter 1, meeting FAO's projections for food demand in 2050 without expanding harvested crop area already requires that global average crop yields grow at faster rates than in recent decades. Relying on even greater yield gains is a leap of faith; there is no convincing economic evidence to demonstrate that farmers will in fact achieve such levels of yield gains over the next several decades.

"Marginal" or "degraded" land

Third, some models can find GHG reductions because they claim that much of the land that will ultimately be pressed into production is "degraded" in the sense that it has little carbon cost. Some models, for example, assume that farmers will expand food production primarily by using idle land or by reclaiming abandoned agricultural land, which the modelers assume would not otherwise substantially regrow vegetation and sequester carbon.[243] Neither assumption has direct supporting evidence.[244]

For example, it has been claimed that oil palm for biofuels in Indonesia expands primarily onto already deforested land, which the modelers assume will neither reforest nor be used to meet expanding agricultural demands.[245] Although there is evidence that much oil palm expansion does follow deforestation, the scenario relies heavily on unsupported assumptions that all cutover forest would never reforest or produce food or other benefits. Regardless, to the extent that potentially productive yet currently low-carbon degraded lands do exist, they are already needed to meet expanding food demands (including oil palm for food products) without clearing other lands.

Double counting biomass when it plays a role in "bioenergy with carbon storage"

One reason some researchers continue to promote bioenergy is that current strategies for limiting emissions enough to hold global warming to 2 degrees Celsius no longer seem plausible and "carbon-negative bioenergy" seems like a way out. Carbon-negative bioenergy could result only if the bioenergy is made from a source of biomass that truly did not lead to GHG emissions because the biomass feedstock was additional. To become carbon negative, the biomass must then be burned in power plants and manufacturing facilities equipped with systems that capture the carbon dioxide emitted before it leaves the smokestack and store it underground. This is a form of "carbon capture and storage" (CCS). Viewed from a life-cycle perspective, the aspiration is that bioenergy feedstock plants would absorb carbon dioxide from the atmosphere, the plants would be combusted to generate energy, and the associated carbon dioxide emissions would be intercepted and stored underground, in a combination of bioenergy with carbon capture and storage (BECCS). The net result would be a gradual reduction in carbon dioxide concentrations in the atmosphere.

Some researchers interpret this aspiration as a rationale for supporting bioenergy today. In reality, the logic works the other way.

First, despite this vision, carbon capture does not transform nonadditional biomass that cannot generate carbon savings into additional biomass that can. The only way to generate carbon-negative energy is to start with additional biomass. Although carbon capture and storage can reduce carbon emissions, it can do the same for coal and natural gas, so there is no more benefit in applying carbon capture and storage to nonadditional biomass than in applying it to fossil fuels. Our earlier analysis explains why there is only limited opportunity for additional biomass. Modelers who estimate large potential benefits from BECCS rely on the same estimates of biomass potential that are based on double counting (see above).[246]

Second, there is no benefit to applying carbon capture and storage even to additional biomass to achieve "negative emissions" unless and until that is cheaper than reducing positive emissions, for example, from the continued use of fossil fuels. Generating one kilowatt hour of low-carbon energy through additional biomass in one location and applying carbon capture and storage to the burning of coal in another location generates precisely the same amount of GHG benefit as applying that CCS to the bioenergy itself, creating BECCS. The only reason to use BECCS would therefore be if it were cheaper, but even in favorable assessments, BECCS costs are estimated in the hundreds of dollars per ton of carbon dioxide mitigation, which is far more expensive than typical costs of mitigating emissions from power plants.[247] As some people have pointed out, if ethanol plants are going to continue to use crops, it would be beneficial to capture the carbon released from the fermentation of those crops to energy—just as it would be preferable to apply CCS to any source of carbon dioxide—but doing so only captures one-third of the carbon released by the whole process and therefore does not make the production of ethanol beneficial.[248] Only once cost-effective options for eliminating coal and other fossil emissions have been exhausted does the prospect of low-carbon biomass combined with carbon capture and storage perhaps provide an added cost-effective opportunity to mitigate climate change through negative emissions.

Third, even if there were a special benefit from BECCS, this is not a reason to use biomass today without carbon capture and storage. It would instead be a reason to hold on to biomass and use it only later, once carbon capture and storage technologies have presumably become feasible and cost-effective and would be used with additional biomass.

"Additional biomass" alternatives

One option is to produce bioenergy from a feedstock generated by additional biomass. Such sources include biomass that would have been wasted and decomposed or burned anyway or biomass that would not have grown without the demand for bioenergy. Such feedstocks would reduce GHG emissions without reducing the production of crops, timber, and grasses that people already use and without triggering conversion of natural ecosystems. Table 7-2 segregates biomass feedstocks that require the dedicated use of land (and thus are not advisable) from feedstocks that are potentially beneficial to climate.

Estimates of the technical potential to produce energy from these wastes vary. Some are as high as 125 EJ per year, which would be enough to generate almost 25 percent of global primary energy demand today and 14 percent in 2050.[249] More appropriate estimates must start by recognizing that most of these residues are already put to valuable use.[250]

Crop residues

After accounting for residues that are already harvested for animal feed, bedding, or other purposes, the best estimate is that harvesting half of the remainder could generate roughly 14 percent of present world transportation fuel, or almost 3 percent of today's delivered energy.[251] But even that estimate does not take into account the fact that most crop residues that are not harvested are important for replenishing soils. This fact is particularly critical in parts of the world such as Africa where soil fertility is low.[252] Even in high-yielding locations that produce huge quantities of residues, such as maize production in Nebraska, one paper estimated that the loss of soil carbon from harvesting residues for ethanol cancels out the benefit from replacing fossil fuels for at least a decade.[253]

This "technical potential" also unrealistically assumes that biofuel producers would harvest half of the crop residues from every crop and every field in the world. But the economics of harvesting and hauling such a bulky, non-energy-dense source of biomass would probably restrict the harvest to limited areas with highly concentrated, highly productive crops that have large quantities of residues. Therefore, crop residues overall are likely to be only a limited source of sustainable "low carbon" biomass for modern bioenergy.

Wood residues

Turning to wood residues, we estimate global forest residues of roughly 10 EJ per year, assuming that all residues could be collected.[254] At least some of these residues should be left to maintain soil fertility. In addition, although forest residues would mostly decompose, the process would still take many years, so burning them still accelerates the emissions of carbon. Harvesting and turning even residues into pellets also requires energy and generates emissions, and pelletizing is necessary to use residues more than a short distance from the forest source. Combining the accelerated loss of carbon

Table 7-2 | Advisable and inadvisable sources of biomass for energy use

INADVISABLE: FEEDSTOCKS THAT REQUIRE DEDICATED USE OF LAND	ADVISABLE: FEEDSTOCKS THAT DO NOT MAKE DEDICATED USE OF LAND
✗ Food crops	✓ Some forest slash left behind after harvest
✗ Fast-growing trees or grasses purposely grown on land dedicated to bioenergy	✓ Black liquor from papermaking
✗ Harvests of standing wood from existing forests	✓ Unused sawdust
	✓ Municipal organic waste
	✓ Landfill methane
	✓ Urban wood waste
	✓ Crop residues that are otherwise not used, are not needed to replenish soil fertility, and do not add substantial carbon to the soil or the soil functions of which are replaced by additional cover crops
	✓ Cover crops that would not otherwise be grown
	✓ Unused manure
	✓ Wood from agroforestry systems that also boost crop or pasture production
	✓ Intercropped grasses or shrubs for bioenergy between trees in timber plantations in ways that maintain timber yields
	✓ Tree growth or bioenergy crop production that has higher yields and is more efficiently burned than traditional fuelwood and charcoal and that replaces these traditional fuels in societies that continue to rely on them

from the forest and all these other emissions, one paper calculated that even after 25 years, using U.S. residues for wood pellets in Europe instead of coal would reduce emissions by only about one-half.[255]

Studies sometimes group with forest residues other wood wastes including sawdust, wood processing waste, and postconsumer waste wood. Adding these sources brings wood residues and wastes to a total of 19–35 EJ per year, according to one review.[256] However, sawdust and wood processing waste are, for the most part, already used.[257] Municipal solid waste might add roughly another 10 EJ per year.[258] These are technical potentials, however. In the real world, only some of this material could realistically and economically be collected.

Cover crops

Opportunities for biomass that could be additional because they result from additional plant growth might include cover crops that are planted after harvest of the main crop in order to reduce soil erosion and help replenish soil fertility. In the United States, for example, some farmers plant rye or a legume to plow into the soil to add nitrogen, while others use cover crops to reduce weeds, minimize erosion, or break up compacted soil layers. These practices are rare, however.[259] The potential to harvest cover crops for bioenergy, instead of adding them to their soils, might encourage more cover cropping, but their economic viability has yet to be proved.

Algae

Algae are sometimes viewed as a bioenergy feedstock that does not compete with fertile land and is therefore "additional" and "sustainable." Algae are potentially capable of far faster growth rates than land-based plants, and some algae have higher oil production, too. Algae fall into two categories: microalgae, which float loosely in the water and have high protein content, and macroalgae, which are essentially seaweeds. Seaweeds currently must be grown in nearshore waters, which are increasingly supporting other uses such as fish farming. Although some papers have urged greater focus on seaweeds, even if all the world's cultivated seaweeds were presently used for energy, they would supply at most 0.6 percent of just the United Kingdom's energy needs.[260] There is a lot of ocean, however, and if there is some way to tap the broader ocean, seaweeds might become an energy source that does not compete with land, although their uses for food and animal feed would be valuable alternatives.

Microalgae, although a focus of much interest, face even larger limitations in providing a natural resource advantage. As a U.S. National Research Council report concluded, using microalgae to meet just 5 percent of U.S. transportation fuel demand "would place unsustainable demands on energy, water, and nutrients with current technologies and knowledge."[261] In addition to the many technological obstacles that need to be overcome to bring costs down, water requirements are likely to be large. One estimate found that twice the present use of U.S. irrigation water would be needed to produce enough biofuel from microalgae to supply 28 percent of present U.S. oil consumption for transportation.[262] Even if other problems were resolved, land requirements for algae ponds are likely to remain formidable. One recent optimistic estimate concluded that "only" 49 percent of total U.S. nonarable land would be needed to replace 30 percent of U.S. oil demand with algae, even assuming no water, nutrient, or carbon dioxide constraints.[263] This is not an encouraging figure.

Although microalgae would use too much water and land to be viable, substantial energy sources, they might provide efficient alternatives for foods, which would take advantage of their high protein content and the special properties of their fats.[264]

Replacing traditional fuelwood

An entirely different category of modern bioenergy would be fast-growing trees, agroforestry products, or possibly some oil-bearing crops to supply or replace traditional fuelwood. Global studies nearly all claim that traditional uses of wood and crop residues for cooking and charcoal provide about 10 percent of global energy use (although this figure is a very rough estimate).[265] The harvest of trees for firewood or charcoal is a major source of forest degradation in some parts of the world,[266] and traditional use of firewood and charcoal is highly inefficient. Although shifting to a nonbiomass source would be preferable, in some parts of the world shifting to more efficient biomass feedstocks might be the only feasible alternative.

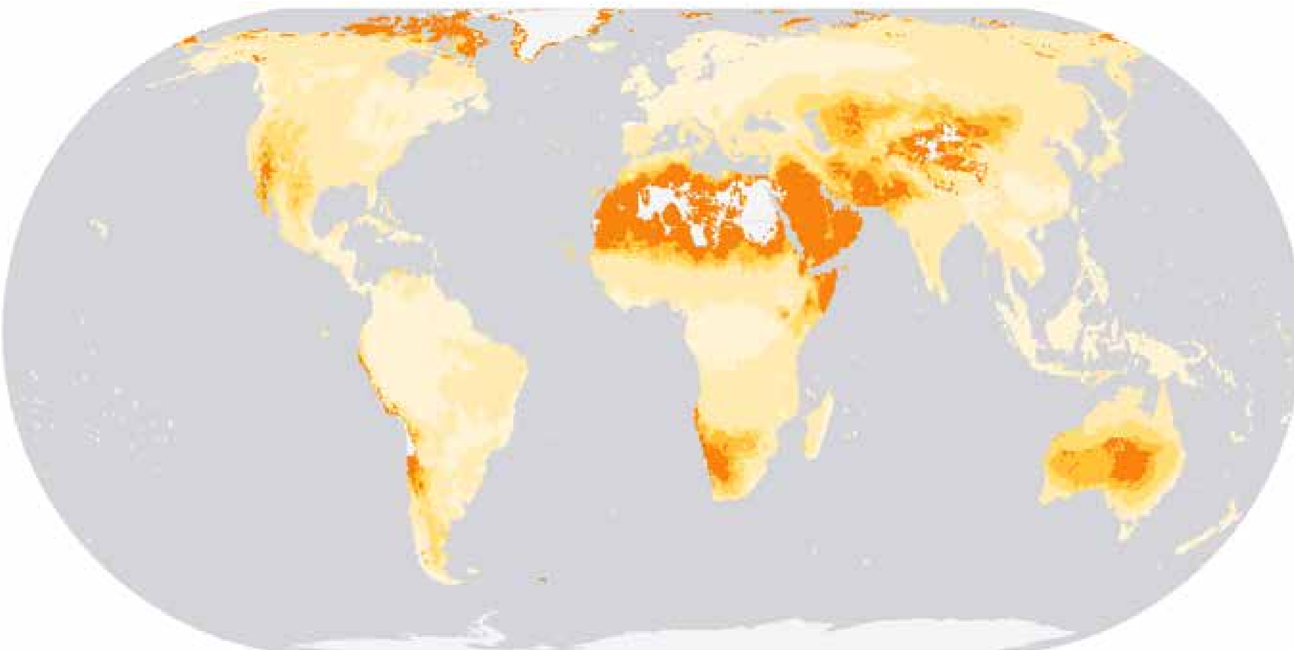
Solar alternatives to bioenergy

The more promising energy alternative to the use of land for bioenergy is to use a solar energy technology, such as photovoltaics (PV). Like bioenergy, PV converts sunlight into energy useable by people, and its land-use needs are often not trivial.[267] But PV's solar radiation conversion efficiency is far greater than that of biomass, and solar arrays do not require land with good rainfall and soils.

Bioenergy requires so much land because growing plants for energy is a highly inefficient way of converting the energy in the sun's rays into a form of nonfood energy useable by people. Even sugarcane, the world's highest yielding crop, grown on highly fertile land in the tropics converts only around 0.5 percent of solar radiation into sugar and only around 0.2 percent ultimately into ethanol.[268] Maize ethanol is even less efficient at making this conversion, and even if energy crops and conversion efficiencies for cellulosic ethanol can match some of the most optimistic estimates, this efficiency might grow to just 0.35 percent.[269]

Even in 2014, standard new PV cells available to homeowners in the United States would convert 16 percent of solar radiation into electricity, and on a net operating basis for a home, we estimate an efficiency of 11 percent.[270] For installations on land area, the efficiency depends on the spacing and tilt of solar cells but will still typically be around 10 percent.[271]

Figure 7-5 | On 73 percent of the world's land, the useable energy output of solar PV would exceed that of bioenergy by more than 100:1



Source: Searchinger et al. (2017).

As shown in Figure 7-5, we calculate that PV today would produce, at a minimum, 40 times more useable energy than even cellulosic ethanol is likely to produce in the future.[272] (Comparing solar energy to biomass used for electricity or heating rather than transportation biofuels shows even larger benefits for solar energy.[273]) One result is that producing bioenergy on 100 hectares of good farmland (assuming it were available, notwithstanding the challenges discussed in this report) would produce only the same amount of energy and 100 times more GHG emissions than using one hectare for PV and reforesting 99 hectares.[274] In addition, when solar energy is used to support electric cars, the added efficiencies of electric engines bring the ratio of solar to bioenergy to at least 150 to 1 (which would increase further if batteries were also produced using solar power).[275]

Even this comparison underestimates the advantages of solar energy because solar installations can use drylands and rooftops, while bioenergy requires productive land that could produce food or store carbon if not used for bioenergy.[276] For example, as shown in Figure 7-5, some of the "best" land for bioenergy is the world's dense, tropical forests, but clearing this land to plant bioenergy crops obviously would come with high carbon costs. According to this analysis, on one-quarter of the world's land, which is less productive but excluding desert and ice-covered areas, the ratio is a minimum of 5,000 to 1 in favor of solar.

Biomass is more easily stored than solar energy. But because electric vehicles provide their own storage and could, if required or given incentives, mostly be powered during the day, the storage advantage for bioenergy as a vehicle fuel is less significant. Phasing in solar-electric cars will take time, so biofuels might be a legitimate short-term alternative if they could reduce emissions today and do so cost-effectively but, for the reasons given in this chapter, we believe they cannot. Fortunately, with solar power providing less than 2 percent of global energy supply and the potential to supply solar without storage likely in the range of at least 20 percent,[277] there is abundant room to expand solar to displace use of fossil fuels. Unless and until that reasonable potential is exhausted, there is no need to direct climate change effort toward shifting transportation fuels. And by the time solar energy has saturated the capacity of both transportation and other end uses to use it without storage, the large research and development investments in storage may have made continued displacement of fossil fuels by solar both practical and economic.

Model Results

Using the GlobAgri-WRR model, we estimate the potential contribution to closing the three gaps that would result from phasing out the world's use of biofuels grown on dedicated areas of land.

A complete phase-out would reduce agricultural land demand in 2050 by 28 Mha, and reduce agricultural GHG emissions from both production and land-use change by 330 million tons CO_2e per year, closing the GHG mitigation gap by 3 percent (Table 7-3).

More significant than phasing out existing biofuels is avoiding the mistake of increasing biofuel's share in transportation fuels to 10 percent. Meeting the 10 percent target would increase land demand by an additional 106 Mha (18 percent) and annual GHG emissions by 1.3 gigatons (Gt), a 12 percent hike in the GHG mitigation gap for agriculture.

Recommended Strategies

Because bioenergy from the dedicated use of land presents multiple barriers to a sustainable food future and does not reduce GHG emissions for decades, we recommend the phase-out of policies to promote this kind of bioenergy. Changing the world's approach to bioenergy gains urgency because many recommendations and targets already adopted by some governments involve far greater use of bioenergy than we model in our 10 percent biofuel target scenario. These more ambitious bioenergy targets would make a sustainable food future far less achievable. Government efforts to use land to produce energy should focus on solar pathways, and any support for bioenergy should be limited to the "advisable" feedstocks identified in Table 7-2. This alternative approach to bioenergy would require changes in several types of policies:

Table 7-3 | Global effects of 2050 bioenergy scenarios on the food gap, agricultural land use, and greenhouse gas emissions

SCENARIO	FOOD GAP, 2010–50 (%)	CHANGE IN AGRICULTURAL AREA, 2010–50 (MHA)			ANNUAL GHG EMISSIONS, 2050 ($GT\ CO_2E$)			GHG MITIGATION GAP ($GT\ CO_2E$)
		Pasture land	Cropland	Total	Agricultural production	Land-use change	total	
2050 BASELINE	**56**	**401**	**192**	**593**	**9.0**	**6.0**	**15.1**	**11.1**
Phase out use of crops for biofuels (compared to maintaining 2.5% transportation fuel in baseline) *(Coordinated Effort, Highly Ambitious, Breakthrough Technologies)*	49	401 (0)	164 (-28)	566 (-28)	9.0	5.8	14.7	10.7 (-0.3)
Meet a 10% transportation fuel target from crop-based biofuels	78	401 (0)	298 (106)	699 (106)	9.3	7.1	16.4	12.4 (1.3)

Notes: "Cropland" includes cropland plus aquaculture ponds. Numbers not summed correctly are due to rounding. Numbers shown in parentheses are changes relative to 2050 baseline.
Source: GlobAgri-WRR model.

Phase out mandates and subsidies

Biofuels have expanded in part due to mandates that a nation's or region's transportation fuel supply incorporate a target share of biofuels.[278] Governments have supported these mandates or targets with a range of tax credits and other financial support for biofuels and the construction of biofuel production facilities.[279] Countries and regions that already have such policies in place should phase out these mandated targets and financial support packages for biofuels made from food crops and other feedstocks that make dedicated use of land. Countries and regions that are contemplating such policies should refrain from establishing them.

Eliminate bioenergy produced on dedicated land from low-carbon fuel standards

Countries should not allow biofuels made from food crops or from land dedicated to biofuel production to qualify for low-carbon fuel standards. These laws—in California, British Columbia, and the European Union—require that the carbon-intensity of all the transportation fuels sold by a company decline by a small percentage relative to gasoline and diesel, typically by 10 percent.[280] Proponents originally hoped that these laws would provide incentives to incorporate environmentally preferable biofuels, particularly those from cellulose. The policy reflects a time when thinking about the GHG consequences of biofuels ignored the land-use implications. California regulators later recognized the importance of land use and made efforts to incorporate emissions from land-use change into their analyses of crop-based biofuels. But we believe that, as with similar efforts, California's analysis incorporated forms of double counting discussed earlier in this chapter. For example, the state credited biofuels for the GHG reductions that its model estimated would result from reduced food consumption.[281]

Exclude bioenergy produced on dedicated land from renewable energy standards

As adopted by the European Union and many U.S. states, renewable energy standards require or encourage electric utilities and—in the case of Europe—whole energy sectors to obtain a minimum share of their annual power from renewable resources.[282] Such laws could be a good strategy for encouraging solar and wind power generation, but most standards also treat the burning of wood as a qualifying source of renewable energy. The result has been rising harvests of trees for electricity and the construction of large plants in the United

States and Canada for manufacturing and shipping wood pellets to Europe.[283] As many papers have now shown, burning whole trees or wood pellets increases GHG emissions for decades.[284] These standards also threaten to create a significant increase in the global harvest and degradation of forests for relatively little energy impact: Doubling the world's commercial timber harvest and using that additional harvest for energy would supply at most an additional 2 percent of global electricity supply by 2035.[285]

One solution would be to exclude wood from whole trees or sections of trees from the list of eligible resources, leaving residues as eligible. Another solution would be to qualify the eligibility of wood with proper GHG accounting. Massachusetts, for example, requires proper accounting of the GHG consequences of harvesting whole trees and, based on that, requires biomass to result in a minimum level of GHG emissions reductions compared to the use of fossil fuels. As a result, the Massachusetts renewable energy standard, as it applies to wood-based feedstocks, provides incentives only for forest residues.[286] This approach leaves electric power plants free to use forest residues—although the potential amount of such residues is relatively small.

Reform accounting of bioenergy

A variety of general climate laws and treaties incorporate the assumption that biomass is carbon neutral.[287] As mandates increase to reduce carbon emissions, or as governments move to charge more money for carbon emissions, the result will be to make bioenergy more and more attractive. The Kyoto Protocol is one example. It sets limits on GHG emissions for the countries that have agreed to it, but it incorporates the accounting error of ignoring all carbon dioxide emitted by burning biomass. The implications of this error are large. Taking an extreme example to illustrate, Europe could fell all of its forests, use the felled wood to replace coal, and count these actions as a 100 percent reduction in GHG emissions compared to burning that coal. Europe incorporated the same erroneous accounting into its emissions-trading system for power plants and large industries. This accounting error should be fixed wherever it occurs.

Maintain blend wall limitations

All of these recommended changes would go a long way, but they may not go far enough. When gasoline prices are extremely high, as they were in 2008, a number of studies have found that maize ethanol becomes a cost-effective replacement until maize prices rise to very high levels.[288] This relationship means, in effect, that high oil prices could lead to a continuous expansion of maize-based ethanol at the rate at which farmers can expand maize production and still keep maize below these "breakeven" prices with oil. Because the expansion of maize will displace other crops, this expansion of maize ethanol would also increase the prices of other crops. The result could be continuing and large pressures to expand agricultural area globally and consistently high crop prices.

If oil prices are high enough, other limitations will be necessary to hold down ethanol expansion. The most significant of these is the so-called blend wall. In the United States, because few cars can use more than a 10 percent blend of ethanol for technical reasons, the limited market has discouraged wholesalers from installing equipment to sell blends with higher quantities of ethanol. The U.S. Environmental Protection Agency has approved the use of 15 percent blends for new cars, but in recent years it has refused to impose expanded ethanol requirements for existing vehicles that might force gasoline wholesalers to install new equipment. In the past few years, the blend wall has effectively blocked expansion of ethanol in the United States.[289] It is important that this blend wall be maintained.

For more detail about this menu item, see "Avoiding Bioenergy Competition for Food Crops and Land," a working paper supporting this World Resources Report available at www.SustainableFoodFuture.org.

CHAPTER 8

MENU ITEM: ACHIEVE REPLACEMENT-LEVEL FERTILITY RATES

Population growth is driving much of the sustainable food future challenge, and some of this population growth is now inevitable because it is the consequence of high birth rates in the recent past. But some of this projected growth reflects continuing high birth rates in a limited number of countries. This menu item focuses on accelerating progress in education and public health that would likely move fertility rates more rapidly toward replacement levels—ideally achieving such rates everywhere on the planet by 2050.

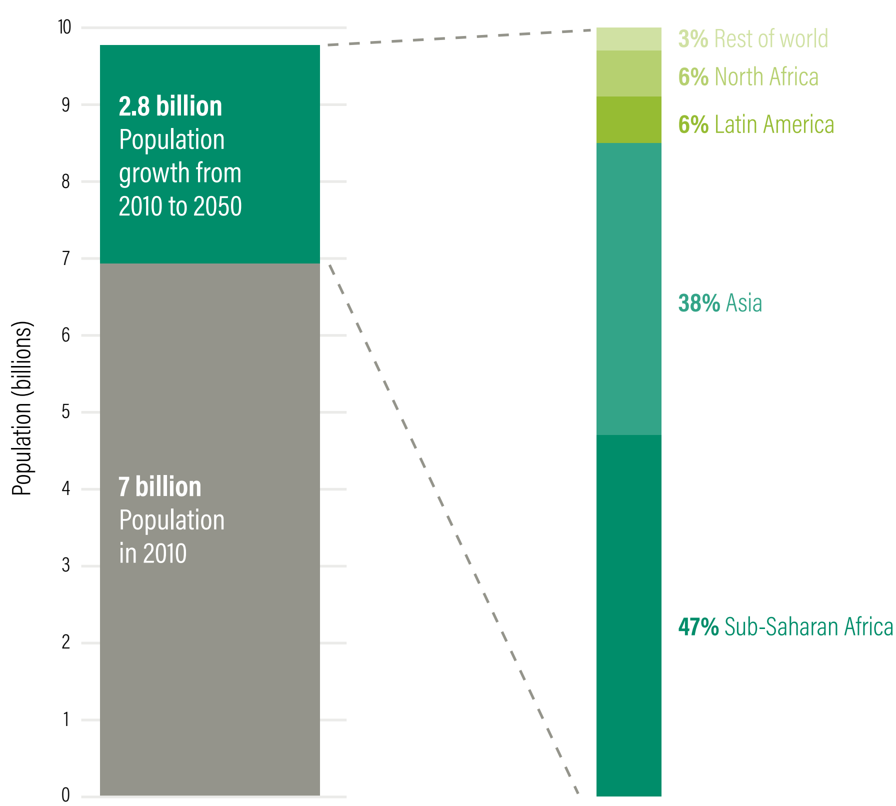
Achieving replacement fertility levels worldwide would bring enormous social benefits and could make a meaningful contribution to the food, land, and GHG mitigation gaps. But such an achievement would bring the greatest benefits to sub-Saharan Africa, whose population is facing the most formidable challenges to a sustainable food future.

The Challenge

According to the medium-fertility scenario in the UN population growth projections, global population will rise from 7 billion in 2010 to 9.8 billion by 2050.[290] Roughly half of this 2.8 billion increase will occur in Africa, and one-third will occur in Asia (Figure 8-1). The reasons for population growth differ by region. Asia's growth will come from a demographic bulge of people of childbearing age that results from high fertility rates in the past, while Africa's growth will result in large part from continuing high birth rates.

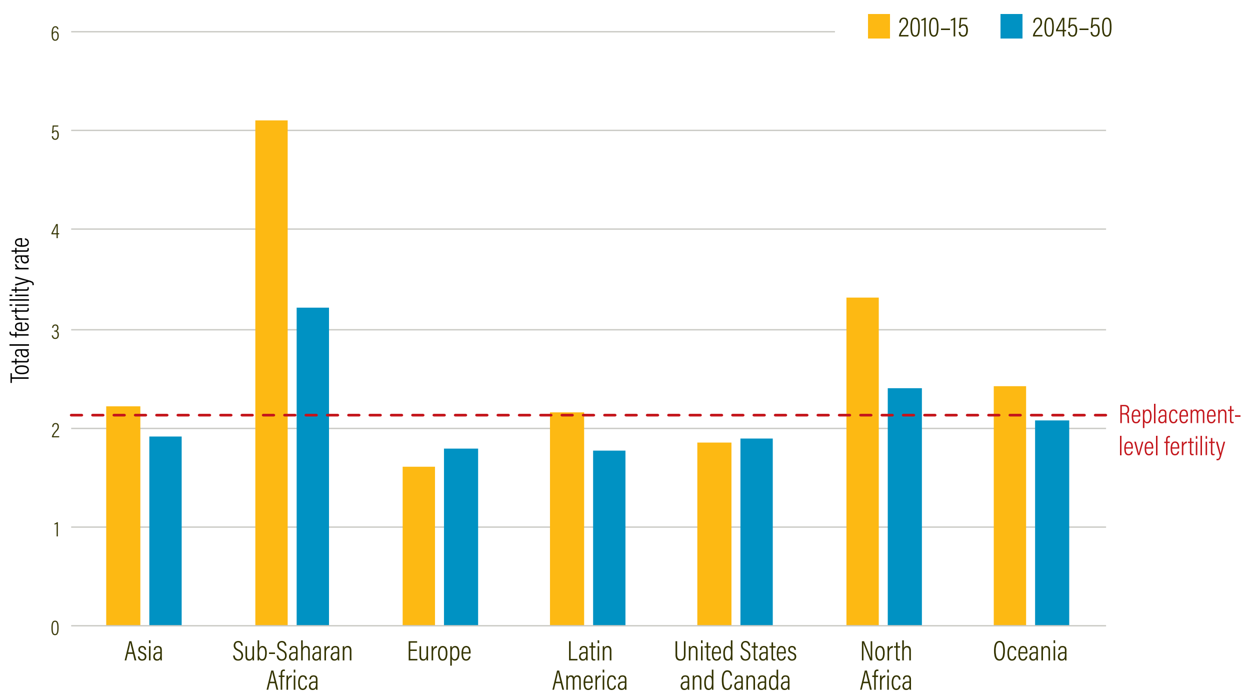
Overall, most of the world's regions are close to achieving replacement-level fertility rates and will achieve or even dip below replacement level by 2050 (Figure 8-2). The "replacement-level" rate is the total fertility rate[291] at which a population exactly replaces itself from one generation to the next (excluding migration) and is typically around 2.1 children per woman.[292] North America and Europe are already below replacement level and are projected to remain there through 2050. Asia, Latin America, and Oceania had fertility rates just above replacement level in 2010–15, and these rates are likely to fall below replacement levels by 2050. North Africa's average total fertility rate is projected to decline from 3.3 in 2010–15 to 2.4 in 2050, which is close to the replacement level.

Figure 8-1 | The world's population is projected to grow from 7 billion people in 2010 to 9.8 billion in 2050, with roughly half the growth in Africa



Source: UNDESA (2017). Medium-fertility variant.

Figure 8-2 | All regions except sub-Saharan Africa are projected to approach or reach replacement-level fertility by 2050



Source: UNDESA (2017). Medium-fertility variant.

Sub-Saharan Africa is the notable exception. By 2010–15, it had a total fertility rate of 5.1. The United Nations projects that this rate will decline gradually over the coming four decades but will fall only to 3.2 by 2050—well above replacement rate. This trajectory will result in a population increase of 1.3 billion in the region between 2010 and 2050, more than doubling the population of sub-Saharan Africa from 0.9 billion in 2010 to 2.2 billion by mid-century. Such high fertility rates in the region will also result in a large group of young people entering their childbearing years over the coming decades. As a result, even with a decline in fertility rate after 2050, the region's population will continue to grow to 4 billion by 2100, more than a fourfold increase from 2010 levels.[293]

This projected increase in sub-Saharan Africa's population poses substantial economic, social, and food security challenges. The region must spend enormous resources on infrastructure just to maintain present transportation, housing, and living standards. As described in Chapter 2, Box 2-4 of this report, the region is already the planet's hungriest, has the lowest crop yields, and has low average income levels. In many parts of the region, soils are depleted of organic matter and nutrients, and rainfall levels can be quite variable. Climate change threatens to exacerbate the difficulty in growing crops, putting downward pressure on crop yields. As a result, the region is at the center of the sustainable food challenge.

The Opportunity

Sub-Saharan Africa could achieve large food security and economic benefits and contribute to meeting global and regional land-use and GHG emission targets if it were to lower its present total fertility rates to approach—and ideally reach—replacement level by 2050. Experience from other regions shows that fertility rates decline, often rapidly, wherever countries make progress in three key forms of social progress. Each form has its own inherent benefits for human well-being and human rights, independent of the impacts on population growth rates.[294]

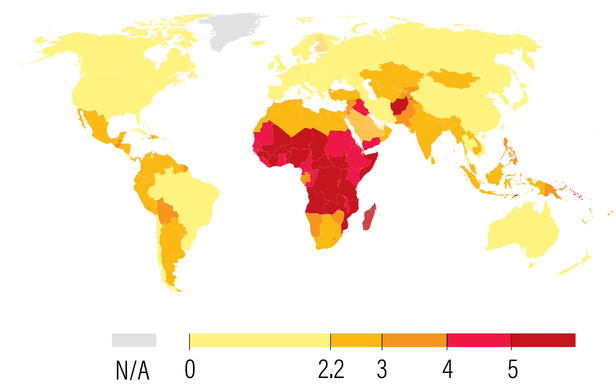
Female education

Increasing educational opportunities for girls provides one opportunity. In general, the longer girls stay in school, the later they start bearing children and the fewer children they ultimately have.[295] In most countries with total fertility rates of 2.1 children per woman or lower, 80 to 100 percent of girls attain at least a lower secondary education—that is, some high school in U.S. terms. As Figure 8-3 shows, sub-Saharan Africa illustrates this relationship in reverse: the region has the lowest proportion of girls attaining lower secondary education and the highest fertility rates in the world.

The link between education and fertility rates occurs within countries, too. Ethiopia's 2016 Demographic and Health Survey, for instance, found that women with no formal education have on average five children, while those with a secondary education have only two.[296] In addition to postponing the first child birth, which is a strong indicator of how many children a woman will ultimately have,[297] education helps women diversify and increase

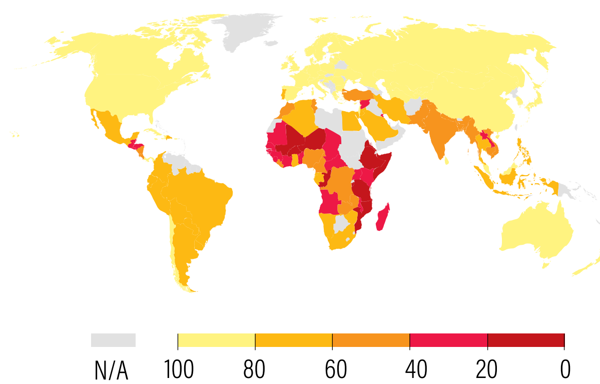
Figure 8-3 | Sub-Saharan Africa has the world's lowest performance in key indicators of total fertility rate, women's education, use of contraception, and child mortality

Total fertility rate (2010–15)



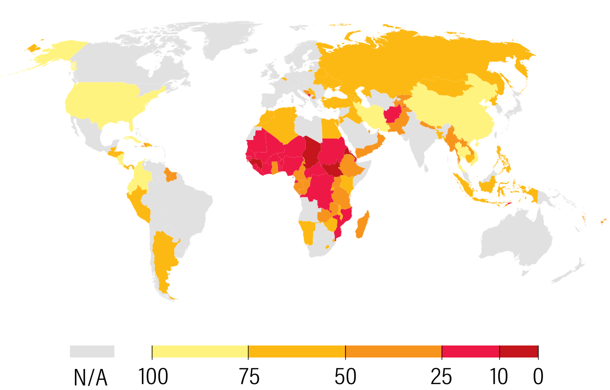
Source: UNDESA (2017).

Percent of women aged 20–39 with at least a lower secondary education (2005–10)



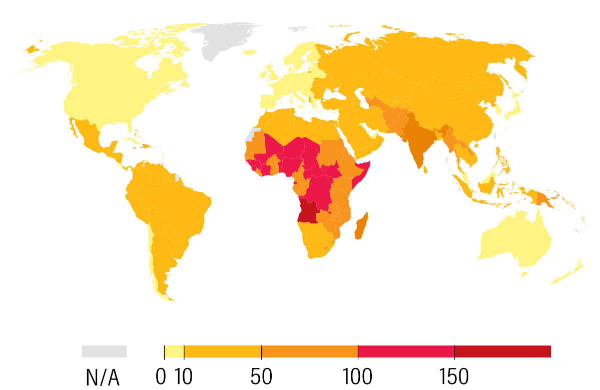
Source: Harper (2012).

Percent of women aged 15–49 using contraception (2010–15)



Source: World Bank (2016b).

Mortality of children under age 5 per 1,000 live births (2010–15)



Source: World Bank (2016c).

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.

income, which in addition to other benefits, typically strengthens a woman's role in deciding how many children to have.[298]

Reproductive health services

The second form of social progress involves increasing access to reproductive health services, including family planning. Access to family planning counseling and technology ensures that women and men can make informed choices about reproduction and act on those decisions. Access to reproductive health services can also lower maternal mortality and rates of HIV/AIDS and other diseases.[299] Millions of women, educated and uneducated, want to space and limit their births but do not have the means to do so. The United Nations found that 24 percent of women in sub-Saharan Africa who wish to control their fertility lack access to birth control, compared with 10–11 percent in Asia and Latin America.[300] Studies by WHO and UNICEF also show that sub-Saharan Africa has the lowest share of women of childbearing age using contraception (Figure 8-3).[301]

Infant and child mortality

Reducing infant and child mortality assures parents that they do not need to conceive a high number of children to assure survival of a desired number.[302] On average, countries with low fertility rates have low infant and child mortality rates.[303] Once again, sub-Saharan Africa illustrates this relationship in reverse (Figure 8-3).

Every country that has educated girls, provided access to reproductive health, and reduced infant and child mortality has also greatly reduced its fertility rates, regardless of national religion or culture. This progress has occurred even in many countries that were either extremely poor at the time or had large areas of extreme poverty, including Bangladesh, Bolivia, and Peru. As shown in Box 8-1 and Figure 8-4, this progress can occur with surprising speed.

In addition to the inherent benefits of each form of social progress, achieving replacement fertility rates would also likely lead to economic benefits through a "demographic dividend."[304] During and for several years after a rapid decline in fertility, a country simultaneously has fewer children to care for—freeing up resources—and a greater share of

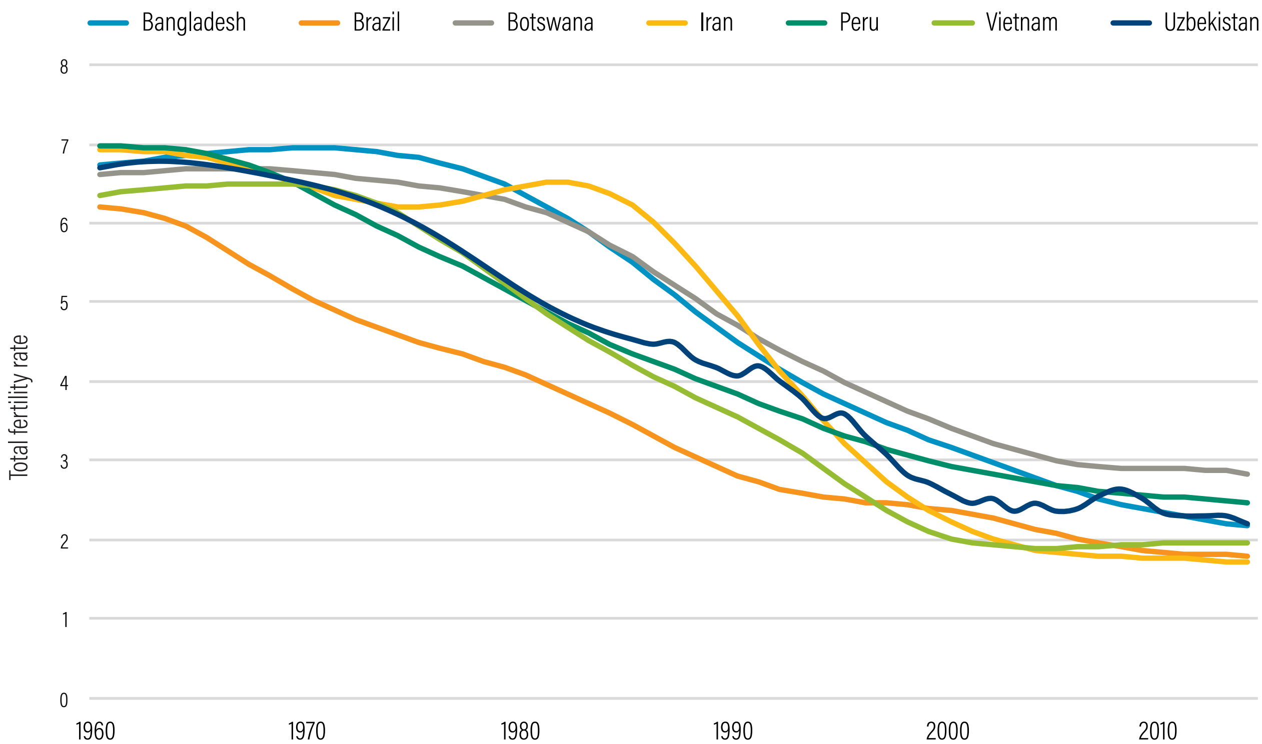
BOX 8-1 | Is it possible to reduce fertility rates quickly?

Could sub-Saharan Africa achieve replacement-level fertility by 2050? History from other regions suggests it could. Although some researchers once believed that only developed countries could dramatically lower their birth rates,[a] a number of less-developed countries have done so as well. For example, Peru, Uzbekistan, and Bangladesh all went from fertility rates of just under 7 in 1960 to below 2.5 by 2014.[b] Yet these countries were still relatively poor in 2015, ranking 81st, 122nd, and 139th out of more than 170 countries in per capita income.[c] Being "economically developed" does not seem to be a precondition for lowering total fertility rates.

Moreover, reductions in fertility rates can occur rapidly. In Vietnam, the fertility rate dropped from 7.4 to 2.0 in 30 years, partly in response to government penalties for larger families. Brazil went from a fertility rate of 6.2 to around 2.8 in an equivalent number of years without government mandates. And Iran's fertility rate declined from 5.2 to 2.2 in the 11 years between 1989 and 2000, also without mandates. These experiences show that rates can drop rapidly in a variety of cultures and without coercion.

Sources:
a. Coale (1973).
b. World Bank (2016a).
c. World Bank (2016b).

Figure 8-4 | Total fertility rates can decline rapidly



Source: World Bank (2017c).

its population in the most economically productive age bracket. Researchers have estimated that this demographic dividend was responsible for up to one-third of the economic growth of the East Asian "Tigers" between 1965 and 1990.[305] With good governance, sub-Saharan African countries should also be able to reap a demographic dividend if fertility levels fall.[306]

Model Results

Using the GlobAgri-WRR model, we examined two scenarios for sub-Saharan Africa only, in which sub-Saharan Africa reduces its fertility rate by 2050 relative to the baseline (the UN medium-fertility scenario). We then analyze the consequences for the food, land, and GHG mitigation gaps both globally and in sub-Saharan Africa.

UN low-fertility scenario. In its low-fertility scenario, the UN analyzes reductions in total fertility rates that are 0.5 children per woman lower in each country in each year than in the medium-fertility scenario. The low-fertility scenario has the effect of reducing sub-Saharan Africa's fertility rate in 2050 from 3.2 to 2.7. According to our analysis, this fertility path reduces the region's population by 216 million compared to the baseline medium-fertility scenario.[307]

Replacement-level fertility scenario. This more ambitious scenario has the effect of further reducing sub-Saharan Africa's fertility rate from 2.7 to the replacement level of 2.16.[308] According to our analysis, the region's population is then reduced by 446 million compared to the medium-fertility scenario.[309]

At the global level, achieving replacement-level fertility would close 5 percent of the crop calorie gap, but it would reduce sub-Saharan Africa's crop calorie gap by nearly one-third.[310] Even the UN low-fertility scenario would reduce this regional food gap by one-seventh, and we consider either reduction level significant for reducing the risk of food insecurity (Table 8-1).

The environmental benefits would also be significant. The UN low-fertility and our replacement fertility scenarios would cut global land-use change by roughly 100 and 200 million hectares, respectively, and would close the global GHG mitigation gap by 9 and 17 percent, respectively. Assuming that FAO's yield and diet projections for the region are correct, achieving replacement-level fertility would avoid more than 60 percent of the projected net land-use change in the region.

Although beyond the time horizon of this report, the effects going forward to 2100 would be even more significant because the regional population is now expected to be more than four times 2010 levels. But the population could be held to a dramatically lower level if the region reaches replacement-level fertility by 2050.

Recommended Strategies

Most African countries have adopted a goal of reducing population growth.[311] Fertility rates have been declining in most sub-Saharan African countries, albeit at varying rates.[312] Countries in the region that have been improving women's education, access to reproductive health care, and infant mortality rates have experienced rapid declines in fertility rates (Box 8-2). The challenge is that the current rate of improvement in the region has proved slower than previously estimated and is not fast enough to avoid a doubling of the continent's population by 2050. As a result, between 2010 and 2015 the United Nations raised its projected 2050 world population from 9.3 billion to 9.8 billion.[313]

The priority must be to accelerate the three forms of social progress: increased educational opportunities for girls; improved access to reproductive health services, including family planning; and reduced rates of infant and child mortality. Because each of these three is deserving of its own book, we will not elaborate further except to note that they are mostly within the authority of national governments. Governments control most of the funds and set policies for the public education and health care

Table 8-1 | Effects of 2050 fertility rate reduction scenarios on the food gap, agricultural land use, and greenhouse gas emissions

SCENARIO	FOOD GAP, 2010–50 (%)	CHANGE IN AGRICULTURAL AREA, 2010–50 (MHA)			ANNUAL GHG EMISSIONS, 2050 ($GT\ CO_2E$)			GHG MITIGATION GAP ($GT\ CO_2E$)
		Pastureland	Cropland	Total	Agricultural production	Land-use change	Total	
GLOBAL EFFECTS								
2050 BASELINE	**56**	**401**	**192**	**593**	**9.0**	**6.0**	**15.1**	**11.1**
UN low-fertility scenario (216M fewer people) *(Coordinated Effort)*	54	335 (-66)	148 (-44)	483 (-111)	8.9	5.2	14.0	10.0 (-1.0)
Replacement-level fertility scenario (446M fewer people) *(Highly Ambitious, Breakthrough Technologies)*	51	277 (-125)	113 (-78)	390 (-203)	8.7	4.4	13.2	9.2 (-1.9)
EFFECTS IN SUB-SAHARAN AFRICA								
2050 BASELINE	**192**	**158**	**104**	**262**	**1.1**	**2.1**	**3.1**	**N/A**
UN low-fertility scenario (216M fewer people) *(Coordinated Effort)*	164	110 (-48)	72 (-32)	182 (-80)	1.0	1.4	2.4	N/A
Replacement-level fertility scenario (446M fewer people) *(Highly Ambitious, Breakthrough Technologies)*	135	59 (-99)	38 (-66)	97 (-164)	0.9	0.8	1.6	N/A

Notes: "Cropland" includes cropland plus aquaculture ponds. Numbers not summed correctly are due to rounding. Numbers shown in parentheses are changes relative to 2050 baseline. Although it is straightforward to define a "food gap" for sub-Saharan Africa (i.e., change in regional crop calorie production between 2010 and 2050 baseline), it is not straightforward to define a GHG mitigation gap for the region because the 4 Gt CO_2e target is global.
Source: GlobAgri-WRR model.

systems in most countries. Governments, therefore, need to devote more resources to improving educational opportunities for girls, family planning, and reducing infant and child mortality. Governments also need to strengthen the technical skills, human capacity, and institutional coordination of agencies responsible for delivering education and health reforms.

One further opportunity might also come with increased farm mechanization. Rural women in sub-Saharan Africa do much of the farming and also face heavy demands on their time for gathering wood and water, cooking, and caring for children.[314] The demand for labor can be an incentive for farming families to have many children. Improving yields per hectare and yields per unit of work should reduce the perceived need for many children.

Civil society organizations have an important role to play, too. They can raise awareness, deliver services, and monitor performance. In some countries, such as Thailand, civil society organizations have successfully generated resources to ensure effective design and delivery of maternal and reproductive health services.[315] Bilateral and multilateral development agencies can also contribute by supporting programs that advance gender equity in education, strengthen family planning programs, and improve health services for mothers and their young children.

For more detail about this menu item, see "Achieving Replacement-Level Fertility," a working paper supporting this World Resources Report available at www.SustainableFoodFuture.org.

BOX 8-2 | Progress in Botswana and Rwanda

Botswana's experience suggests that well-structured investments aimed at the three strategies can reduce fertility rates. In particular, a countrywide system of free health facilities that integrates maternal and child health care, family planning, and HIV/AIDS services has played an important role.[a] Mortality rates for children under five declined from 83 per 1,000 in 2000 to 44 per 1,000 in 2015.[b] Contraceptive use increased from 28 percent in 1984 to 53 percent in 2008.[c] For many years Botswana provided free education to all, and it still exempts the poorest from school fees, resulting in an 85 percent literacy rate and a rate of 88 percent of girls enrolled in lower secondary education. The result: Botswana's fertility rate declined from 6.1 in 1981 to 2.9 by 2015.[d]

Rwanda is at an earlier stage of making similar progress. All children are entitled to nine years of free education in state-run schools, with six years of primary education and three years of secondary education. In 2010, President Paul Kagame announced plans to extend free education for an additional three years of secondary education, and between 2011 and 2015 the number of students in upper secondary education increased by 12 percent.[e] Girls' education in Rwanda is more widespread than ever before, with a net primary enrollment rate of 97 percent in 2015, up from 91 percent in 2008.[f] An extensive system of free health care for the poorest has helped lower Rwanda's mortality rate for children under five from 184 per 1,000 in 2000 to 42 per 1,000 in 2015.[g] Support and education for family planning has increased the rate of contraceptive use from 17 percent to 52 percent, and cut unmet needs for family planning in half to 19 percent.[h] As a result, Rwanda's total fertility rate is in steep decline, from 8.0 as recently as 1985–90 to 4.8 in 2012.[i]

Sources and notes:
a. World Bank (2010b).
b. World Bank (2016c).
c. World Bank (2016b).
d. World Bank (2010b); UNDESA (2017).
e. Rwandan Ministry of Education (2016).
f. Rwandan Ministry of Education (2016).
g. World Bank (2016c).
h. Muhoza et al. (2013).
i. Total fertility rate for 1985–90 from UNDESA. Figure for 2012 from the U.S. Central Intelligence Agency at http://www.indexmundi.com/g/g.aspx?c=rw&v=31.


Flamingo
Flamingo
Flamingo

CHAPTER 9

POVERTY IMPLICATIONS OF RESTRICTING GROWTH IN FOOD DEMAND

This report makes the case for holding down growth in excess demand for certain agricultural products as a means both to meet food needs sustainably while reducing pressure on the environment, and to keep prices low enough that food can be more accessible to the poor.

Governments have often pursued policies to boost agricultural development by stimulating demand—in the past decade or so with a global push for biofuels. Hunger and development advocates have also sometimes pointed to the deleterious effects of low global food prices on small farmers, particularly when focusing on the consequences of agricultural subsidies in wealthier countries.[316] Are policies to reduce food loss and waste and to reduce demand for bioenergy and meat therefore antipoor?

Like producers of any product, all farmers find farming more profitable, and investments more justifiable, when prices are higher. Moreover, some biofuel supporters in particular have argued that increasing demand for biofuel crops should create new market opportunities for poor farmers.[317] But when crop prices rose dramatically in 2007 and mostly stayed high through 2012 (at least in part because of the diversion of crops to biofuels),[318] organizations combating hunger complained.[319] Some commentators then wondered whether they were complaining about what they had wished for.[320] This conundrum raises several questions. Which is the problem: higher prices or lower prices? Should agricultural policies seek to boost prices or lower them? Or should policy seek to get prices to a "golden mean"?

By themselves, these are poor questions because they do not distinguish between the different kinds of forces that drive prices. For example, if crop prices rise because the prices of fertilizer or other inputs rise due to higher energy costs, then these increases in prices will be bad for farmers and consumers alike. If crop prices fall because of a reduction in demand due to a global recession, then poor people buy less food and the overall consequences are similarly bad for both small farmers and consumers. In contrast, if the productivity of small farmers increases (if they produce more food for each day of their labor), then their incomes will rise and food prices will tend to fall—to the benefit of farmers and consumers. These examples illustrate that both rising prices and decreasing prices are associated with good or bad outcomes depending on their cause.

The concern over the adverse impacts of low prices is mostly associated with the global consequences of subsidies in developed countries.[321] Those subsidies can to some extent benefit the poor around the world by lowering food prices, but they also harm farmers in the developing world who are not comparably subsidized.[322] If one group of farmers is subsidized and another is not, then the subsidized farmers will be able to sell at a lower price than the unsubsidized farmers, who will have to respond through some combination of producing less, paying lower wages, or making less profit. The case against these subsidies is not that low prices are bad per se but that, at whatever price level, discriminatory subsidies in the developed world unfairly suppress agricultural development in developing countries, denying economic opportunities and making poorer countries vulnerable to food shocks. (The issue of agricultural subsidies is discussed at greater length in the final section of this report, "Cross-Cutting Policies for a Sustainable Food Future.")

By contrast, the literature shows that when food prices fall as a result of gains in agricultural productivity, the lower food prices contribute to economic development.[323] There is little dispute that lowering food prices by increasing agricultural productivity is desirable.

The remaining question, then, is whether raising food prices by increasing demand is desirable. On the environmental side, the effects are clear. Rising food prices can encourage improvements in the efficiency of land and water use, but those same higher prices will also send signals to farmers to expand agricultural production on new land—or to use more water or chemicals—to reap more profits from increased production. Rising prices due to increasing demand therefore do not distinguish the sustainable from the unsustainable ways of increasing production. In contrast, falling food demand and production overall mean less demand for water, land, and chemicals.

What about the effects of rising food prices on the poor? There is general agreement that, in the short-term, higher food prices caused by increasing demand harm the poor and increase malnutrition, despite much variation in regional impacts and many complexities. Food consumes a large portion of the disposable incomes of the world's poor. The approximately 1 billion people who lived on $1.25 per day or less in 2011 typically devoted more than 50 percent of their income to food. The percentage is still high for the additional 1.2 billion people living on $2 per day or less.[324] Studies have consistently found that, even in rural areas, the majority of poor people are net food purchasers, either because they hold too little land or because they are landless.[325] If staple food prices rise, then the poor either eat less, cut back on more nutritious foods to maintain caloric intake, or cut back on purchasing other goods, such as health care or education.[326]

A few studies claim that, in the medium or longer term, higher food prices globally help the poor because they stimulate more agricultural activity and demand for labor, either directly on farms or through broader stimulation of rural economies.[327] However, the economics of these studies are challenging because they must employ a range of assumptions or engage in a range of uncertain estimates of the effects of agricultural demand on wages and on how wage gains in one sector translate into gains in others. These studies also appear to conflict with some fundamental economic reasons to believe that higher food prices spurred by demand competition for food are generally harmful to the world's poor and hungry:

- First, the hungriest regions in the world—namely, portions of sub-Saharan Africa and South Asia—import large quantities of food staples on a net basis.[328] Although results will vary by country, poor countries as a whole will therefore have to transfer more money to richer countries when global staple crop prices increase. This fact means they will be poorer. Any economic gains accruing to farmers in net food-importing poor countries can therefore only result from a transfer of wealth from other people in those countries. Some of those other people will be wealthy, but many will be poor or living just above the poverty line.

- Second, although Latin America is a large net food exporter, and will benefit at the gross economic level from higher prices, large farms dominate its production, particularly of staple crops. The benefits to the poor of higher farm prices will therefore be diffuse, while the harm will be direct.

- Third, the basic economic finding that demand for food falls when prices rise suggests that higher food prices harm the poor. When prices rise, demand decreases.[329] Although the effects of global price increases vary greatly from country to country and among groups of poor people, the evidence is strong that poorer consumers reduce their consumption more than richer consumers.[330] The reasons are obvious. Poorer consumers are less able to afford higher prices, so richer consumers outcompete them when supplies are limited. Moreover, poor consumers eat foods with less processing, and thus the food prices they pay more directly reflect the wholesale prices of crops.

More research may help to resolve these ambiguities, but even strategies designed to boost prices by boosting demand can only be sustained by continually boosting that demand even further. Demand increases spur price increases mainly by creating temporary shortages that allow producers to charge higher prices as long as the shortages persist. As farmers boost production, prices mostly come back down.[331] Unless policymakers are willing to continually drive higher and higher demand—with more and more environmental effects—policies to boost prices by spurring demand are not sustainable. The better way to address the challenges of poor farmers while striving for a sustainable food future is to target their specific needs while holding down the growth in food demand.