

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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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."

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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.

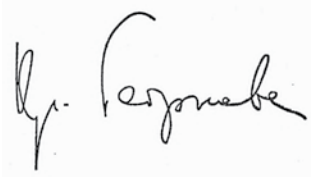
A common thread in many of the solutions is the urgent need to "produce, protect, and prosper." The world must act decisively to intensify production on agricultural land. The world must also act decisively to protect natural ecosystems that store carbon, support biodiversity, and provide the many ecosystem 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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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.

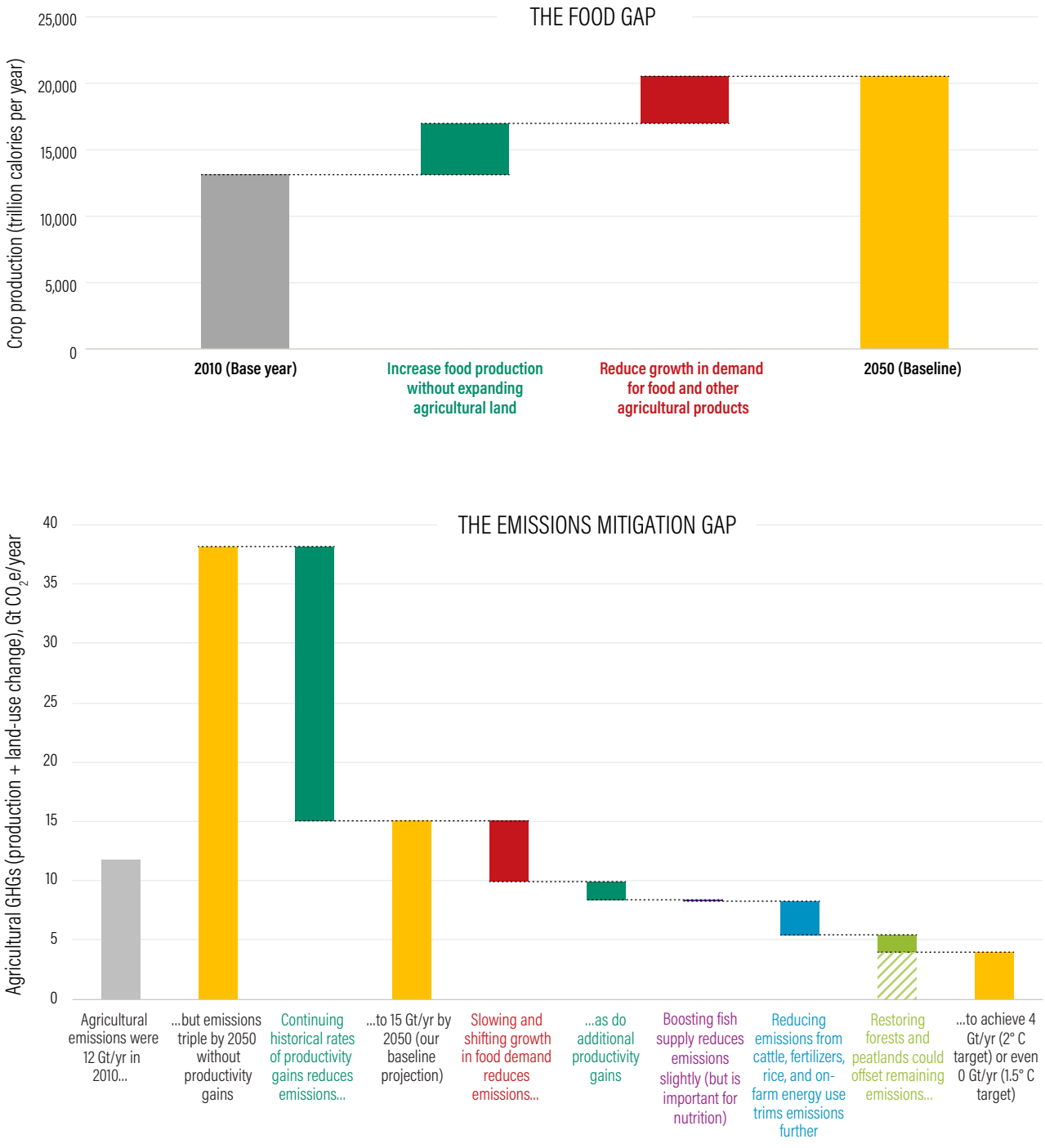
- **Require production-related climate mitigation.** Management measures exist to significantly reduce GHG emissions from agricultural production sources, particularly enteric fermentation by ruminants, and from manure, nitrogen fertilizers, and energy use. These measures require a variety of incentives 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.

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CHAPTER 1

A RECIPE FOR CHANGE

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

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

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

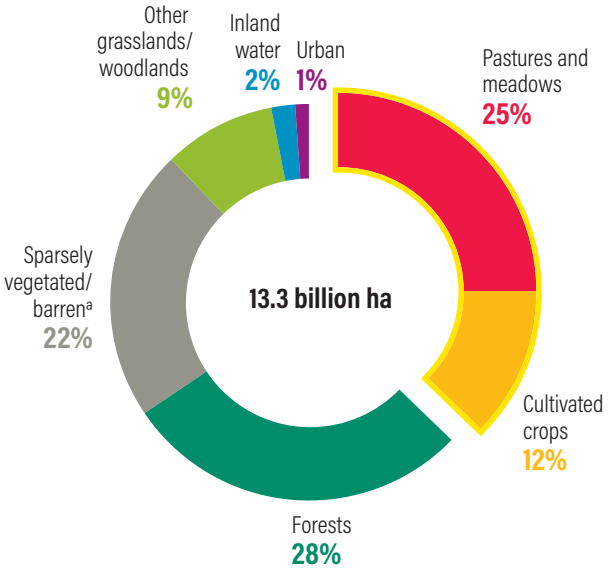
Second, the world needs agriculture to contribute to inclusive economic and social development to help reduce poverty. More than 70 percent of the world's poor live in rural areas, where most depend on agriculture for their principal livelihood.[7] Growth originating in the agricultural sector can often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

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

Land-based Ecosystems

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

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



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

Climate

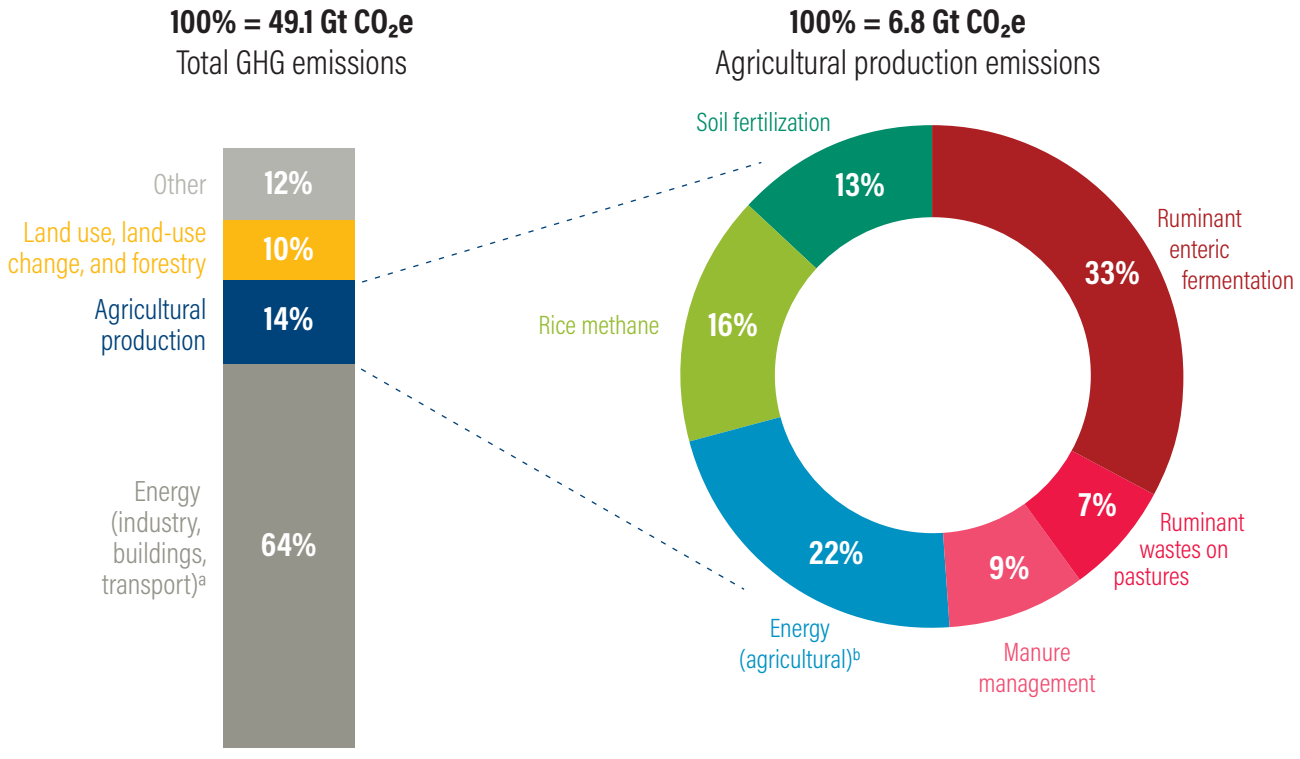
Agriculture and associated land-use change such as deforestation accounted for nearly one-quarter of global greenhouse gas (GHG) emissions in 2010 (Figure 1-2). Of these, agricultural production contributed more than one-half.[17]

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

Water

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

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



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

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

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

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

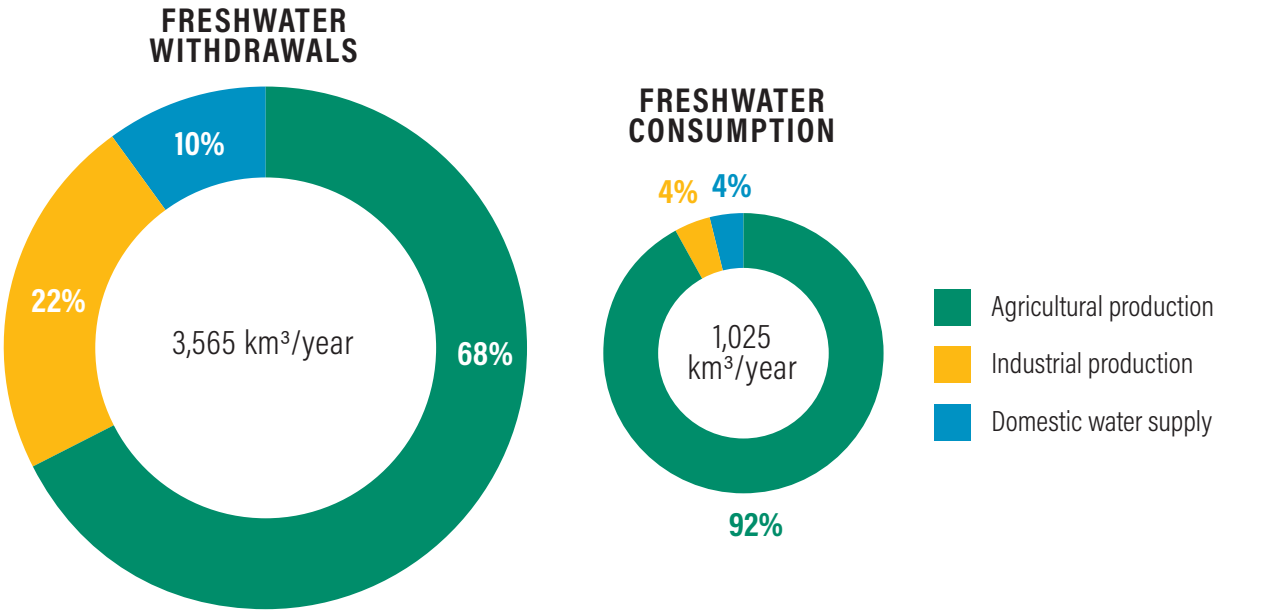
Addressing Food Supply, Development and Poverty Reduction, and Environmental Protection

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

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

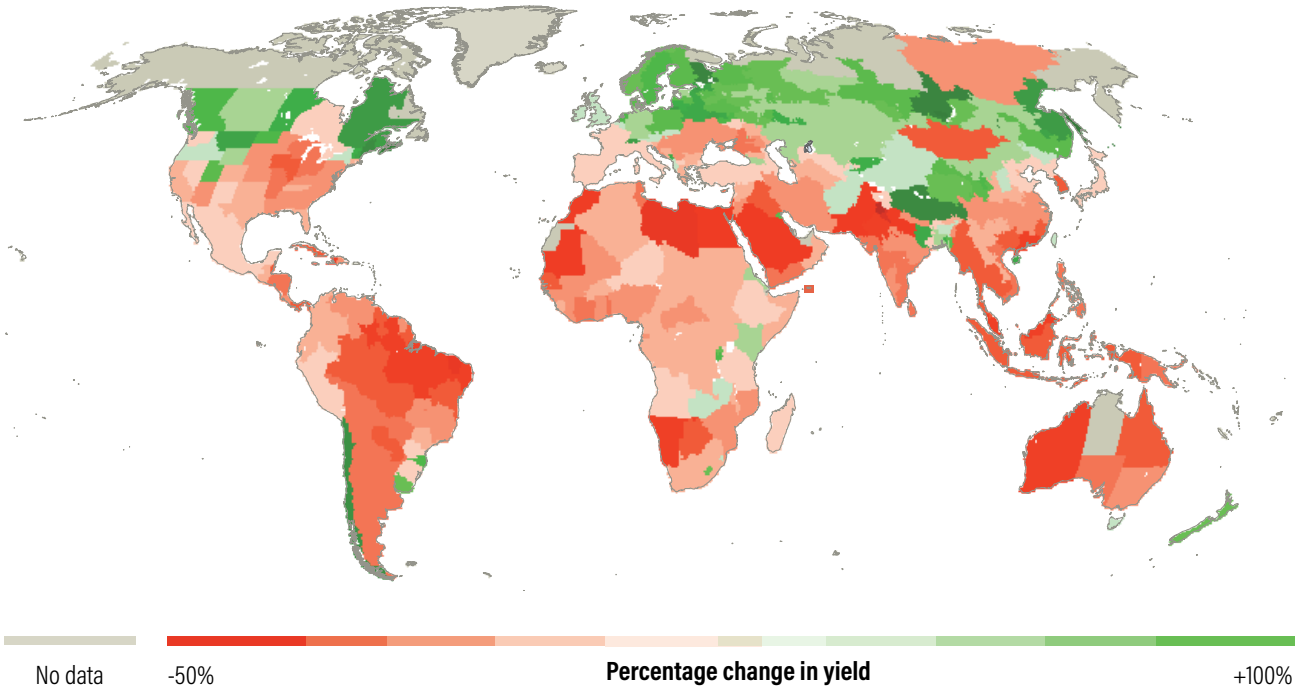
To balance by midcentury the three great needs—meeting food demand, supporting development, and protecting the earth's natural resources—the world's food system must exceed previous achievements in increasing food production while reducing poverty, avoiding land conversion, and mitigating agriculture-related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

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



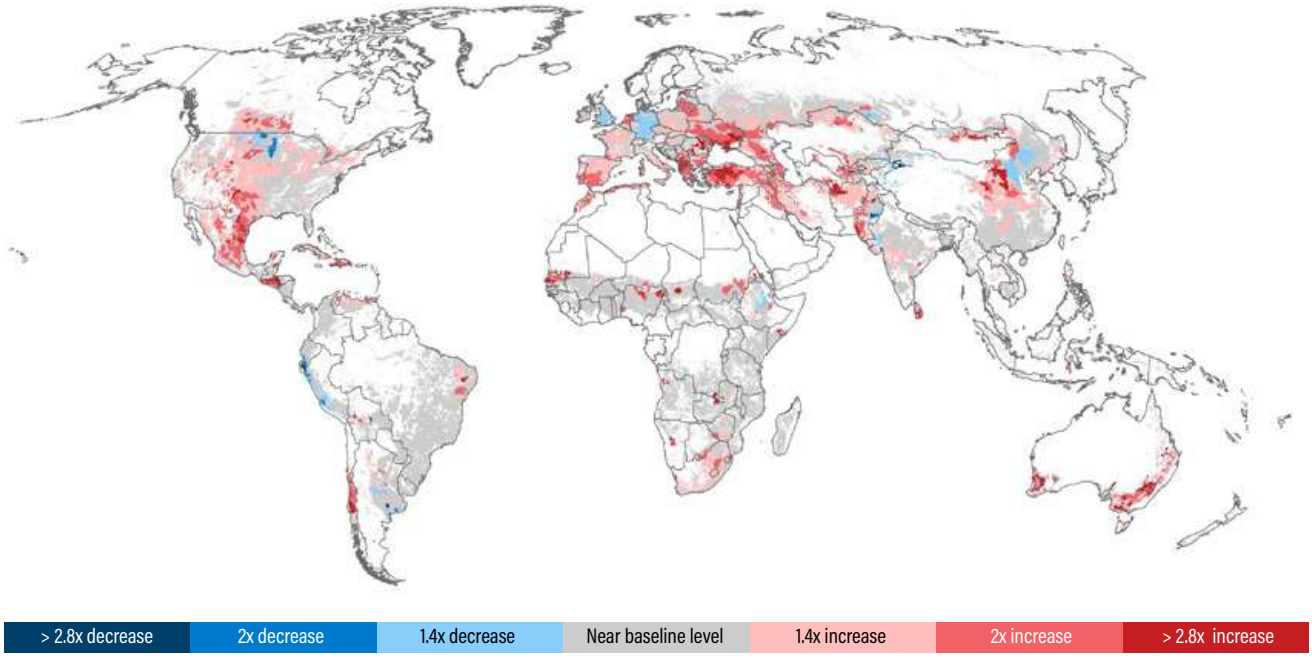
Note: Figures measure only "blue water" demand and do not consider rainfed agriculture ("green water"). Consumption figures are averaged for the years 1996–2005; withdrawal figures are for the year 2000.
Sources: Hoekstra and Mekonnen (2012) (consumption); OECD (2012) output from IMAGE model (withdrawals).

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



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?

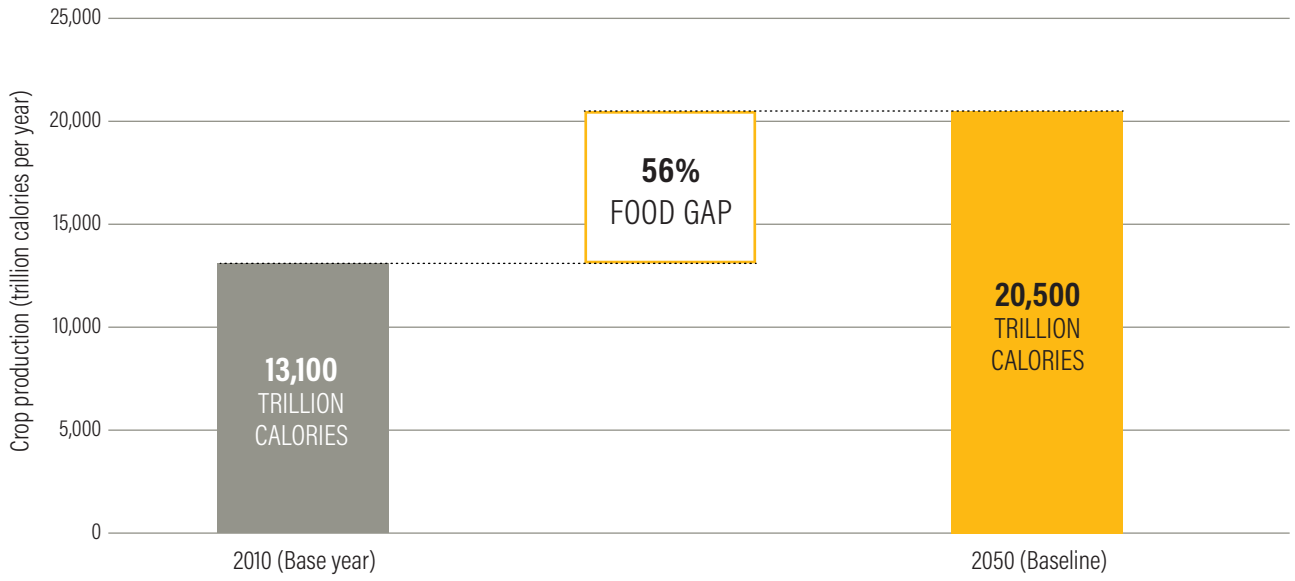
To project food demands in 2050, we start with a 2012 FAO projection of the diets that the average person in each country will consume in that year.[30] FAO based its projections on economic growth and income trends and culture in different countries. We adjust these projections per person moderately,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

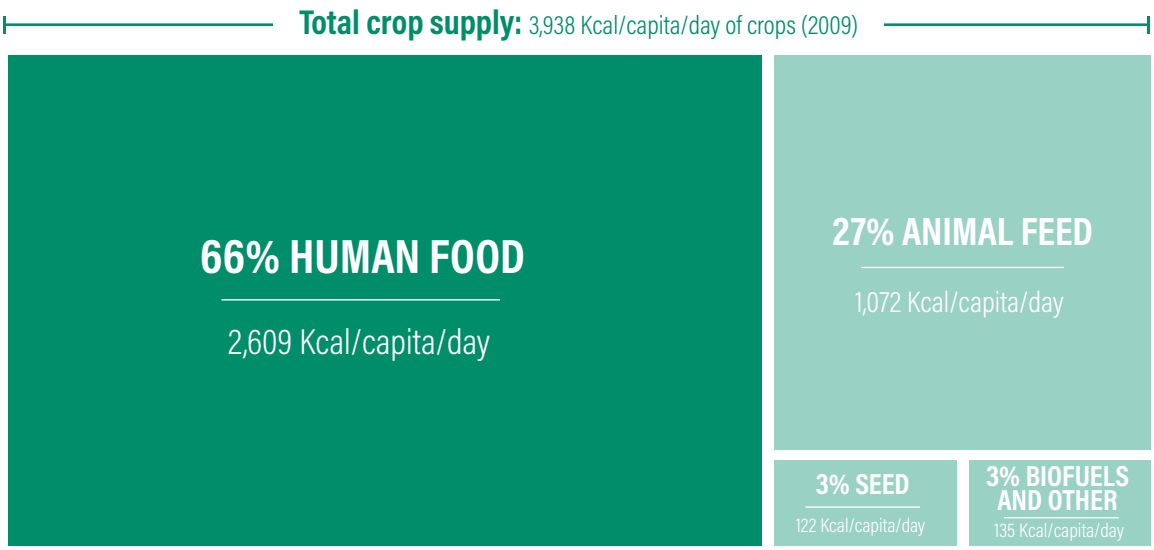
Is there really a "food gap"?

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]

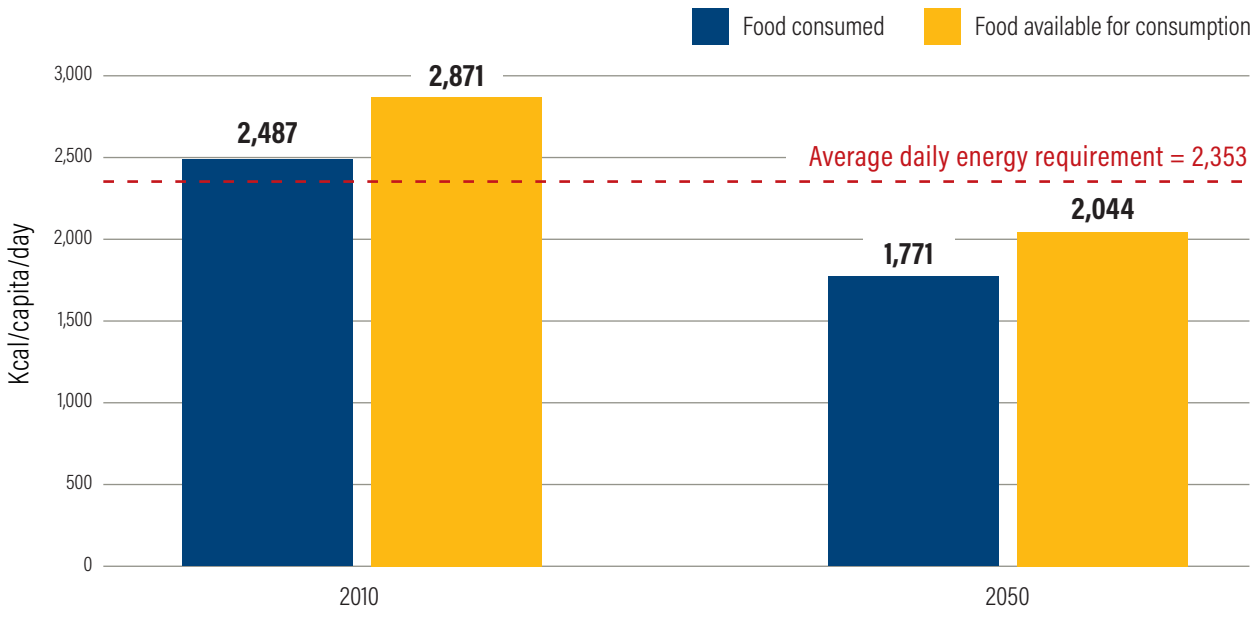
Realistically, we should focus on actual food consumption patterns, including meat and milk, and account for food losses and waste. Doing so yields a very different result. The amount of food consumed in 2010 (nearly 2,500 kcal per person per day), spread over the projected population in 2050, would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

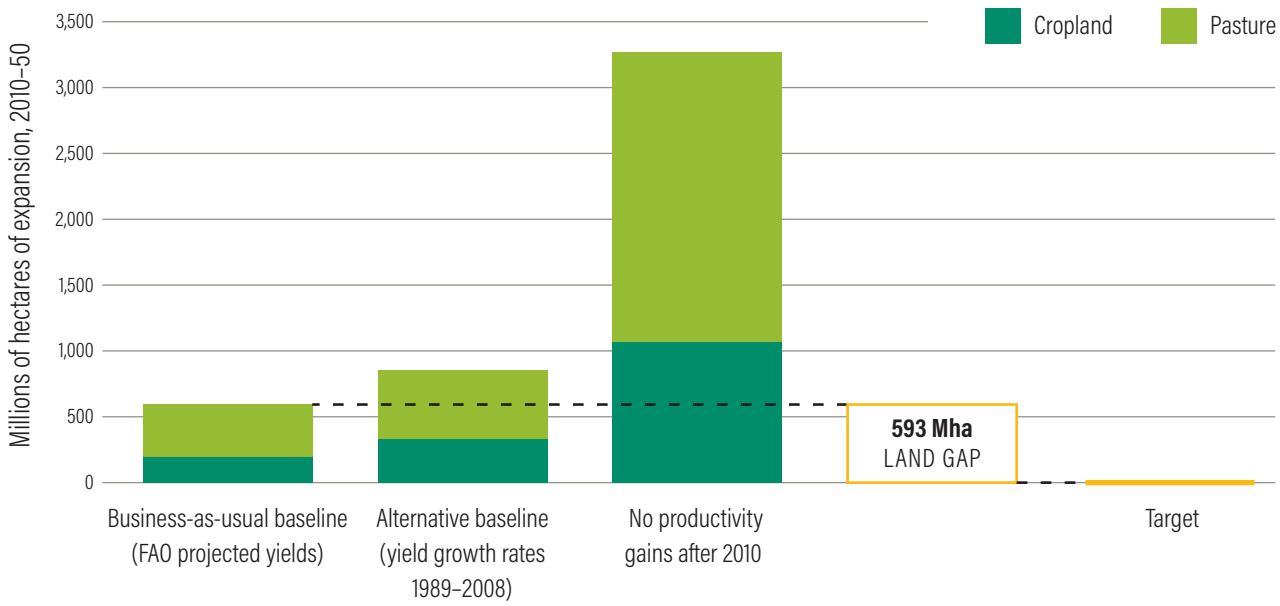
Using these FAO estimates of growth in yield and cropping intensity, GlobAgri-WRR projects a net increase in global cropland between 2010 and 2050 of 171 Mha. Using an analysis of aquaculture systems described more in Course 4, we also project an additional 20 Mha of aquaculture ponds, bringing the total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



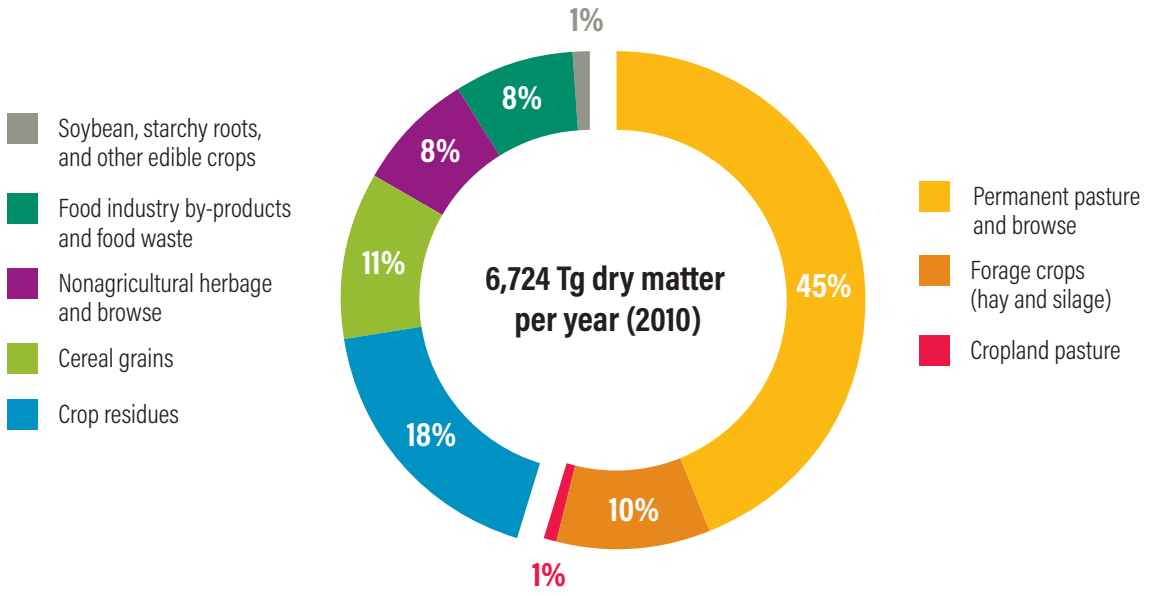
Note: "Cropland" increase includes a 20 Mha increase in aquaculture ponds under the two projected baselines and a 24 Mha increase in the "no productivity gains after 2010" projection.
Source: GlobAgri-WRR model.

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.

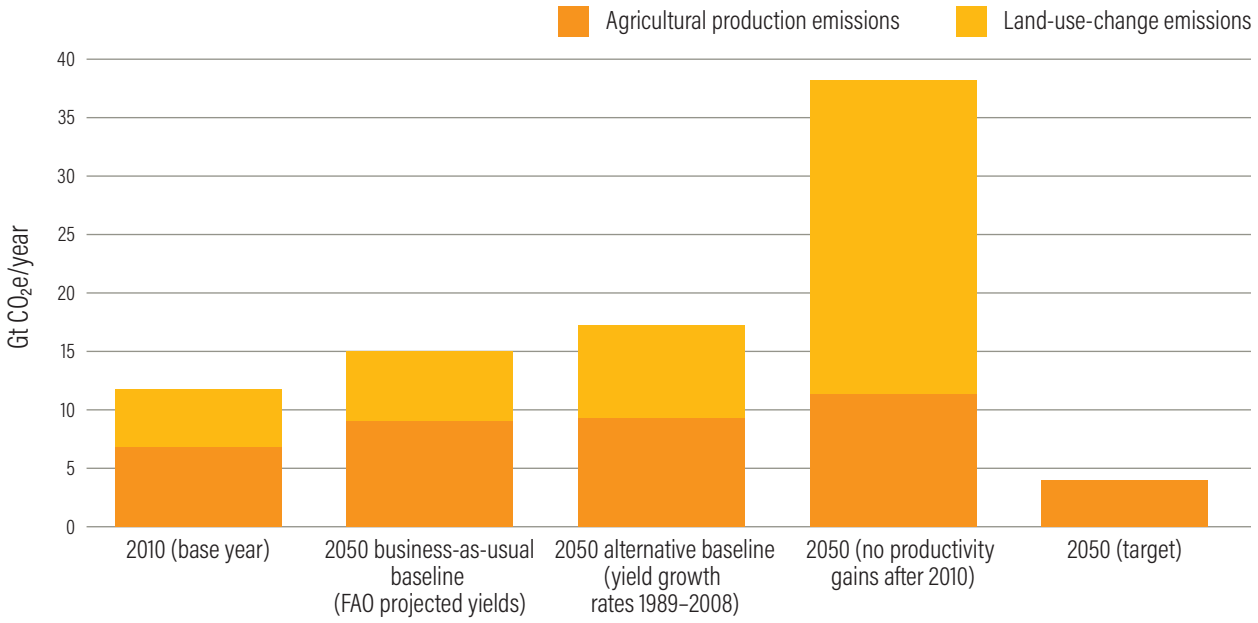
Fortunately, yields will probably continue to grow, and the use of chemicals, animals, and other inputs to the production process that lead to emissions will probably become more efficient as well. (We describe these assumptions in more detail in Course 5.)

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.

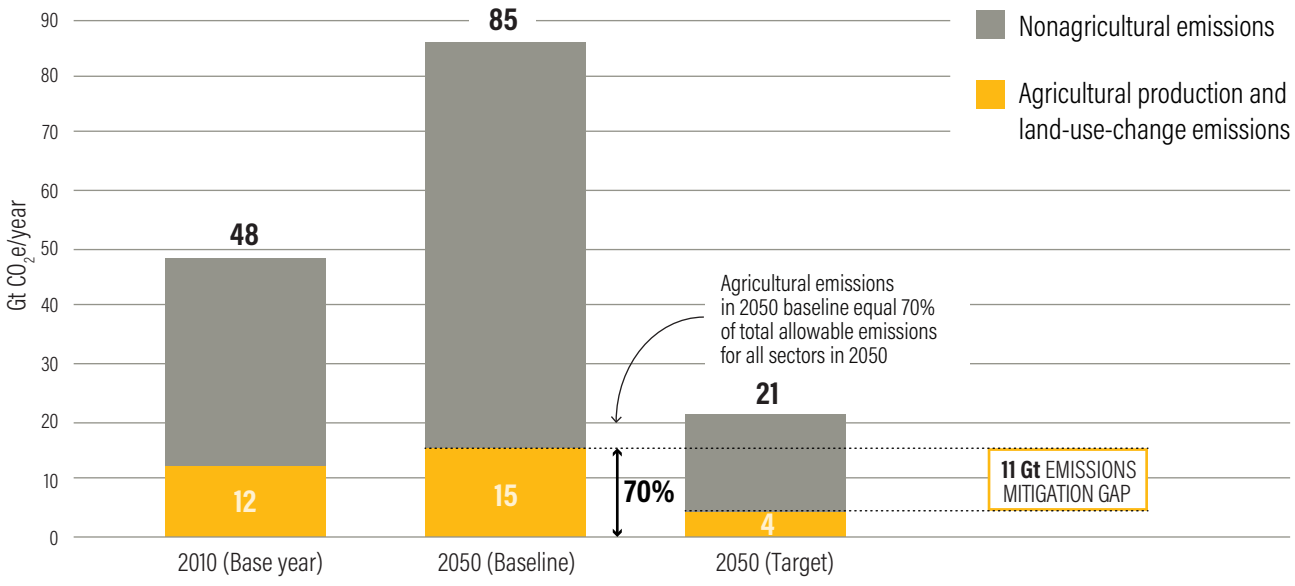
As with our land-use projections, we again develop a less optimistic alternative baseline using recent yield growth trends.[63] In this scenario, emissions from agricultural production would grow to 9.3 Gt CO_2e per year in 2050 and total emissions, including those from land-use change, would rise to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

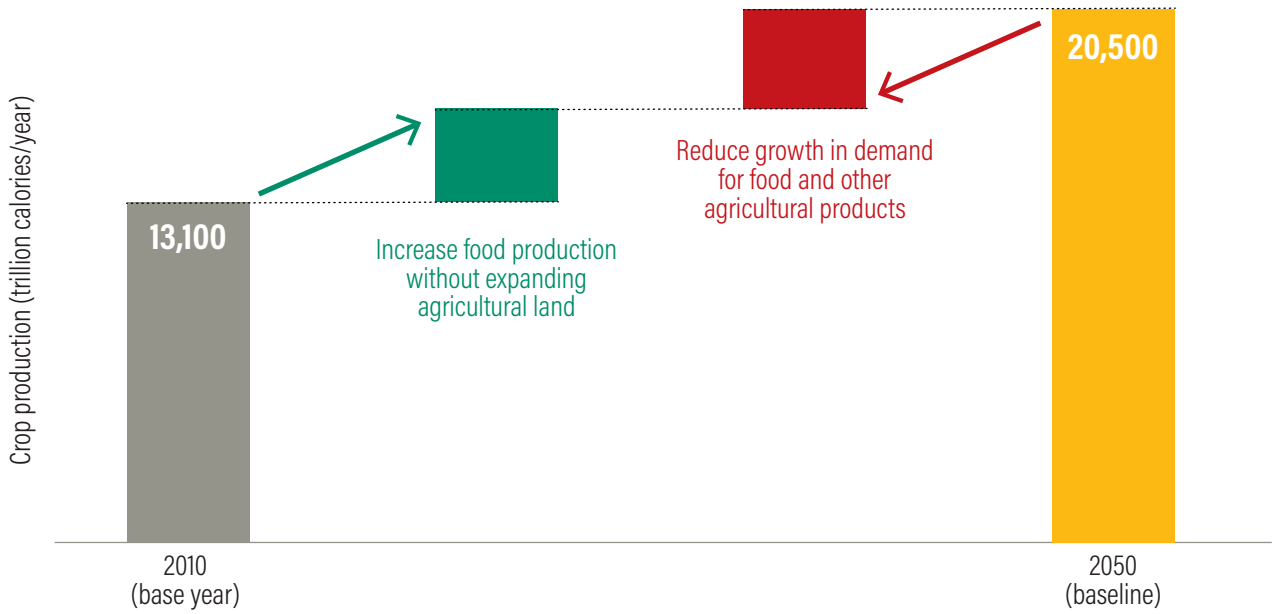
Notes:
a. FAO (2006a).
b. The following definitions are paraphrased from Gross et al. (2000).
c. Richardson (2010); Daily et al. (1998).
d. Millennium Ecosystem Assessment (2005).

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.

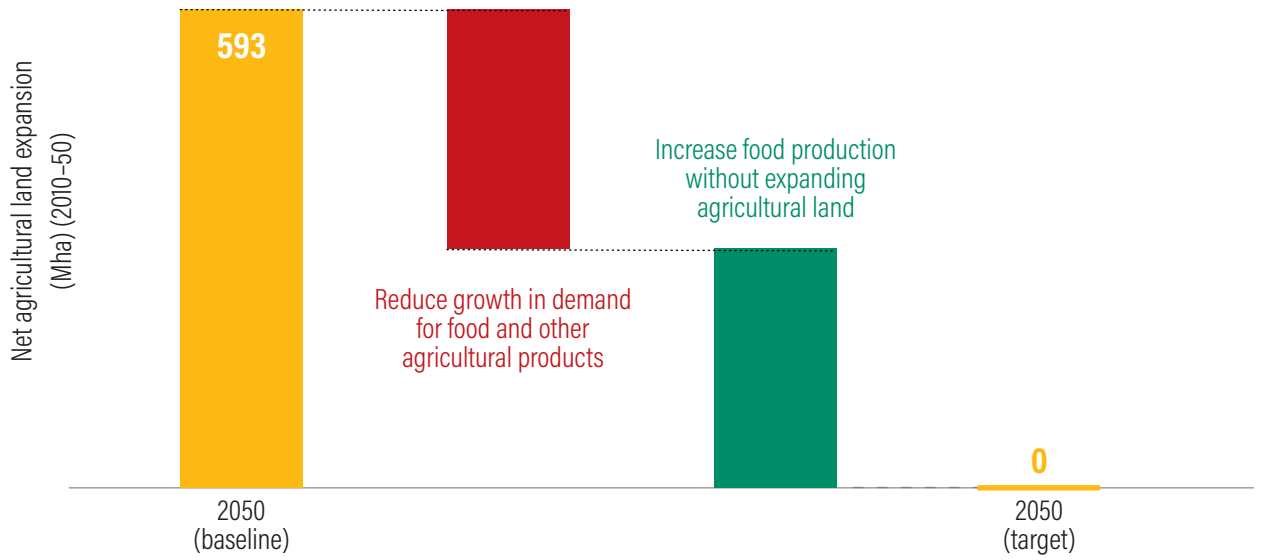
For each menu item, we also offer policy recommendations for moving forward. Policy recommendations can be broad or detailed. Our standard is one of "usefulness." Where issues remain controversial, even broad recommendations can be useful, but we try to make detailed recommendations wherever feasible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

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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.

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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

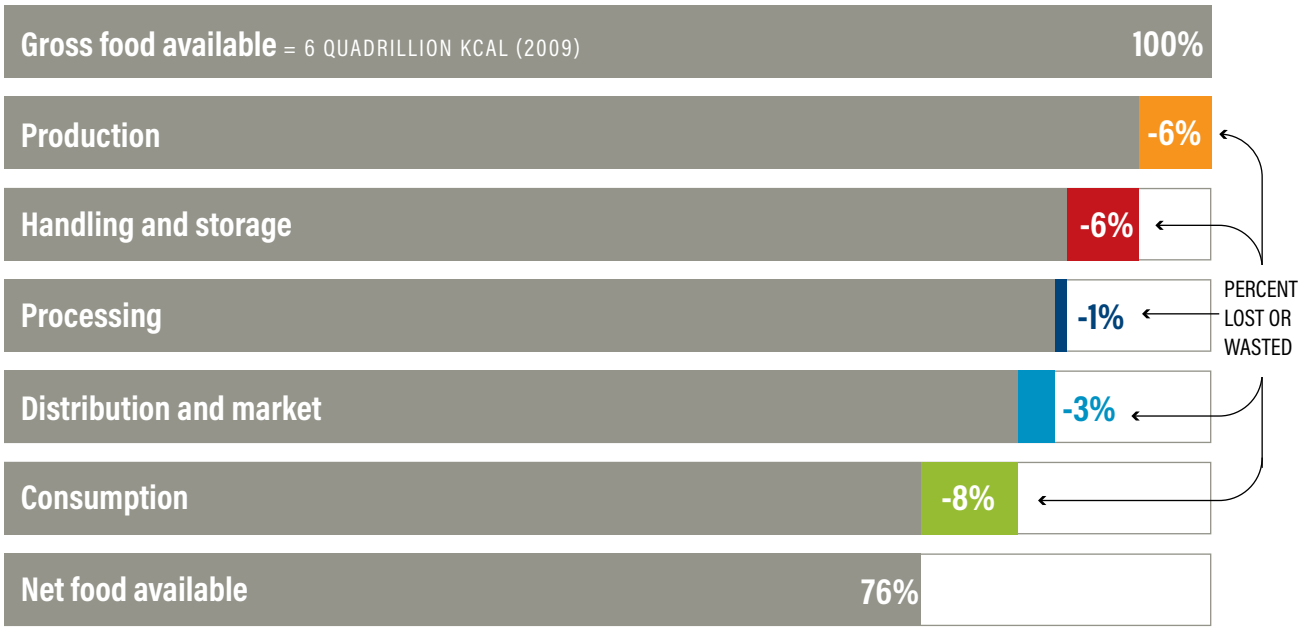
Efforts to reduce food loss and waste (FLW) must overcome the challenge posed by the fact that losses occur mostly in relatively small percentages at different stages as different handlers move food from farm to fork. To reduce these losses requires broadly shared commitments to strong quantitative goals,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

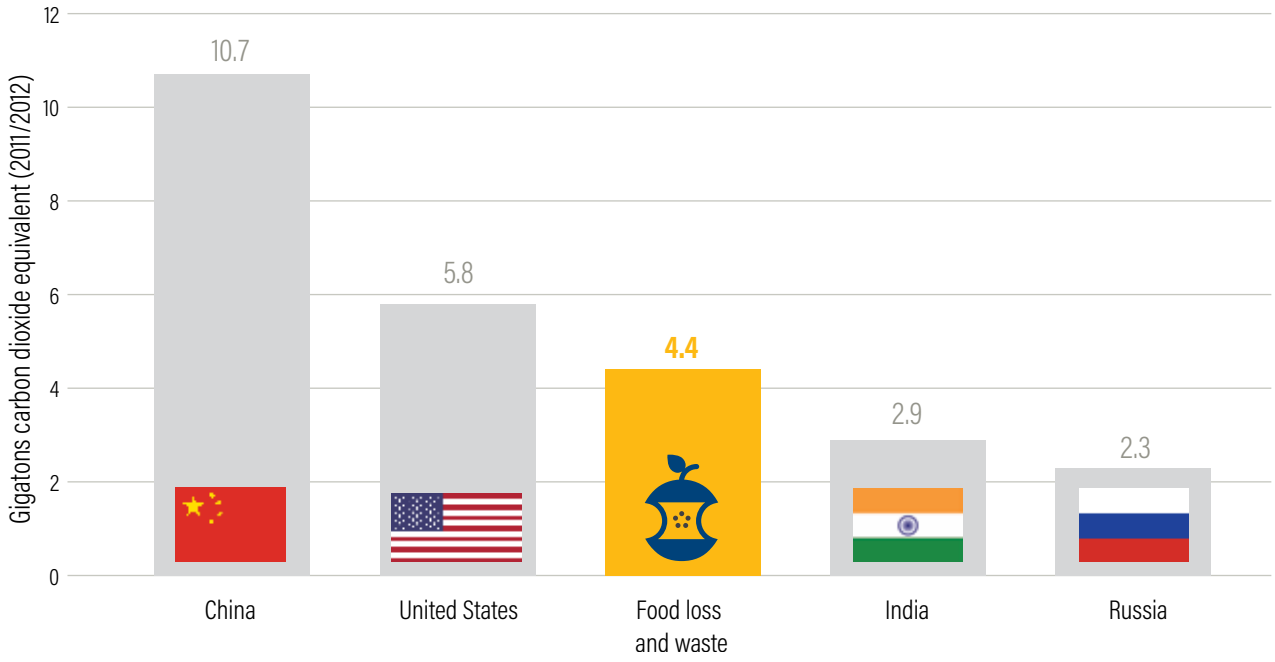
"Food" refers to any substance—whether processed, semiprocessed, or raw—that is intended for human consumption or, more specifically, ingestion. "Inedible parts" refers to components associated with a food that, in a particular food supply chain, are not intended to be consumed by people; inedible parts 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.

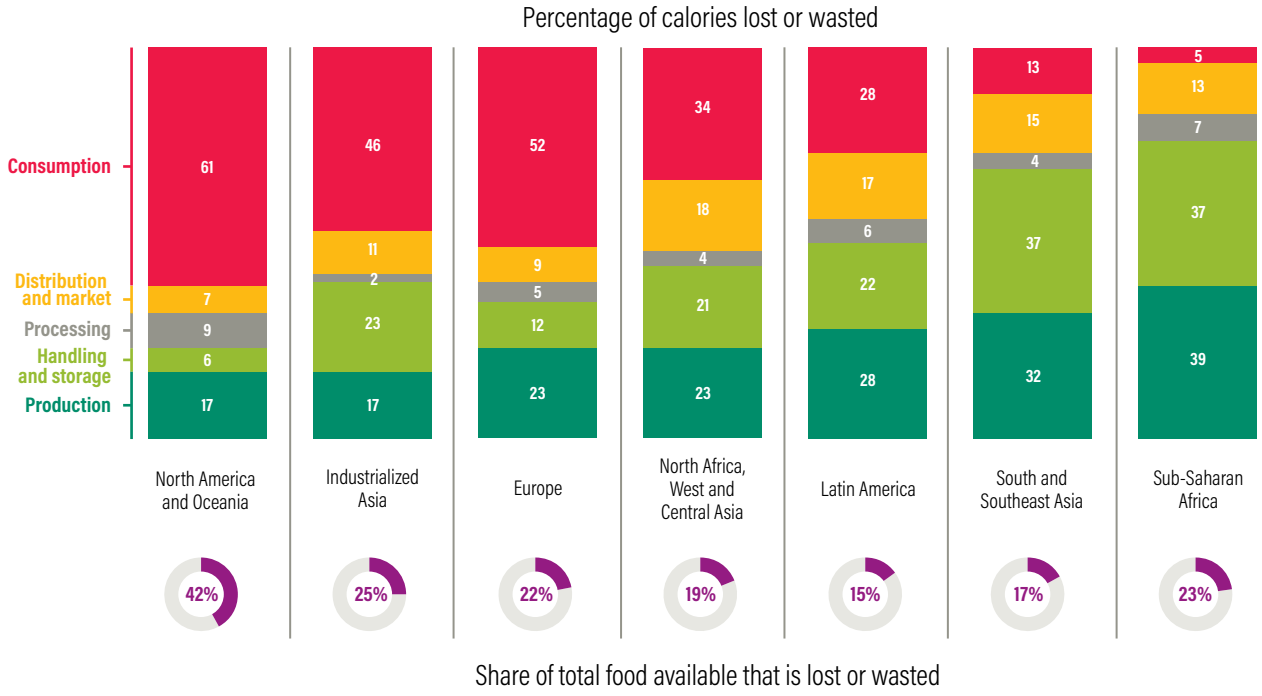
The total share of available food that becomes lost or wasted ranges from 15 percent to 25 percent across most regions. As Figure 5-3 indicates, the outlier is North America and Oceania, where loss and waste is approximately 42 percent of all available food.

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

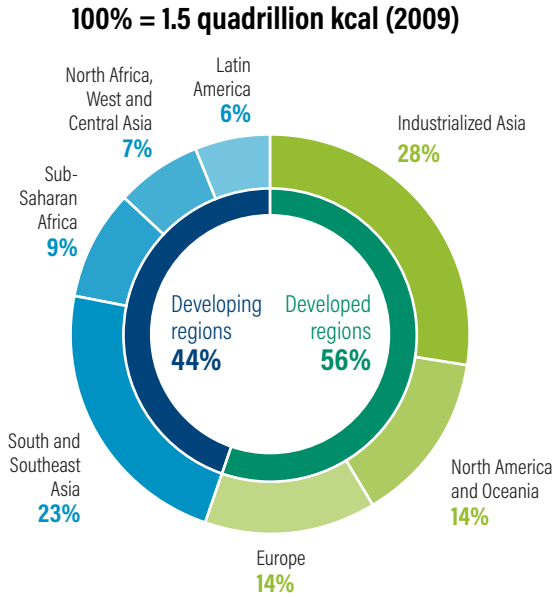


Note: Numbers may not sum to 100 due to rounding. Data are for the year 2009.
Source: WRI analysis based on FAO (2011c).

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



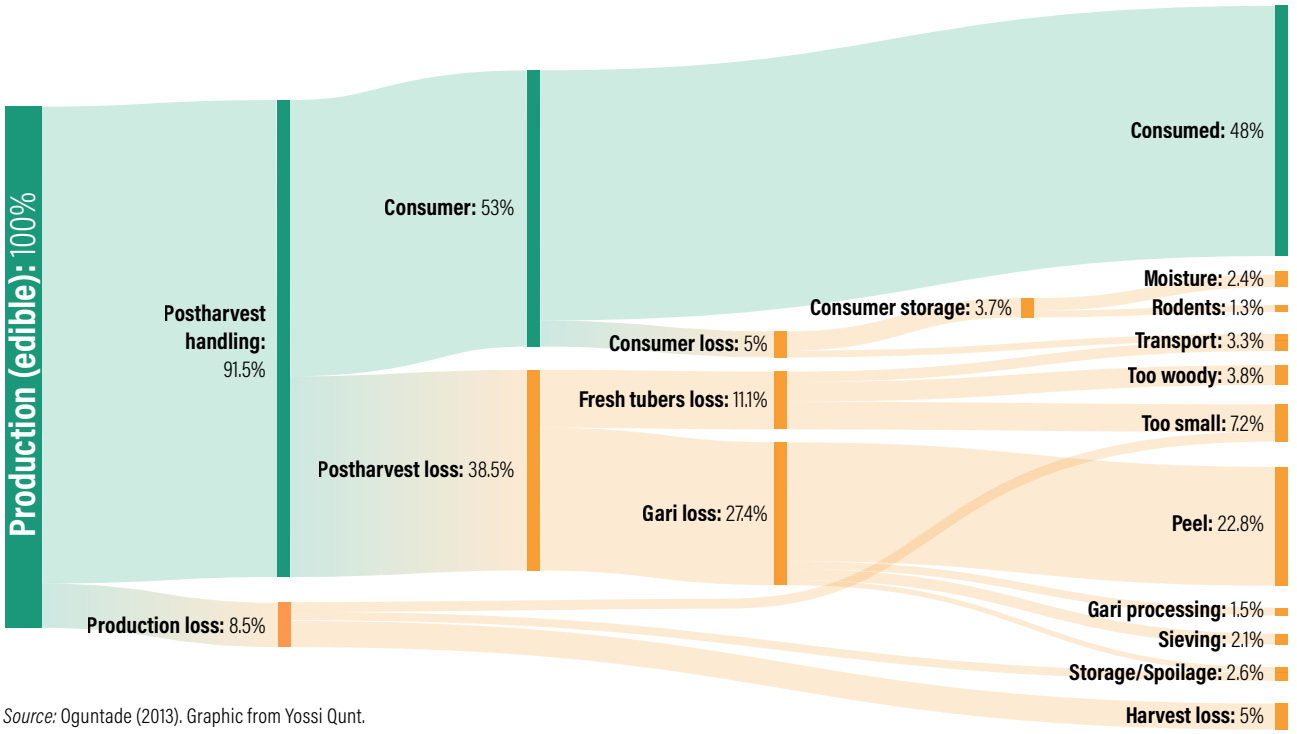
Source: WRI analysis based on FAO (2011c).

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

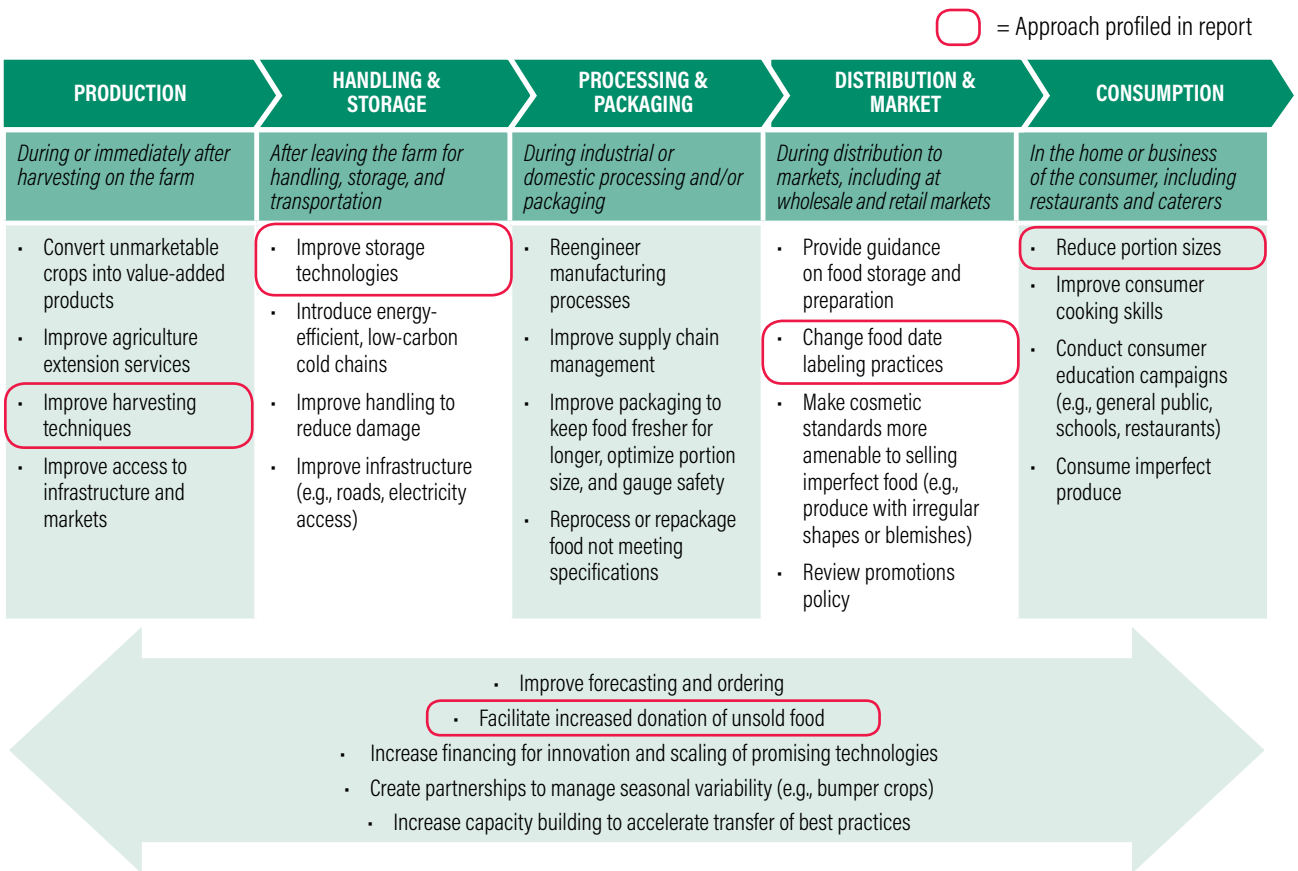
FLW in the production stage often occurs because of poor harvesting equipment, because of uneven ripening, or because bad weather prevents crops from being harvested in time. In Senegal in the early 1990s, hand threshing processes led to losses of 35 percent of harvested rice. Researchers worked with 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

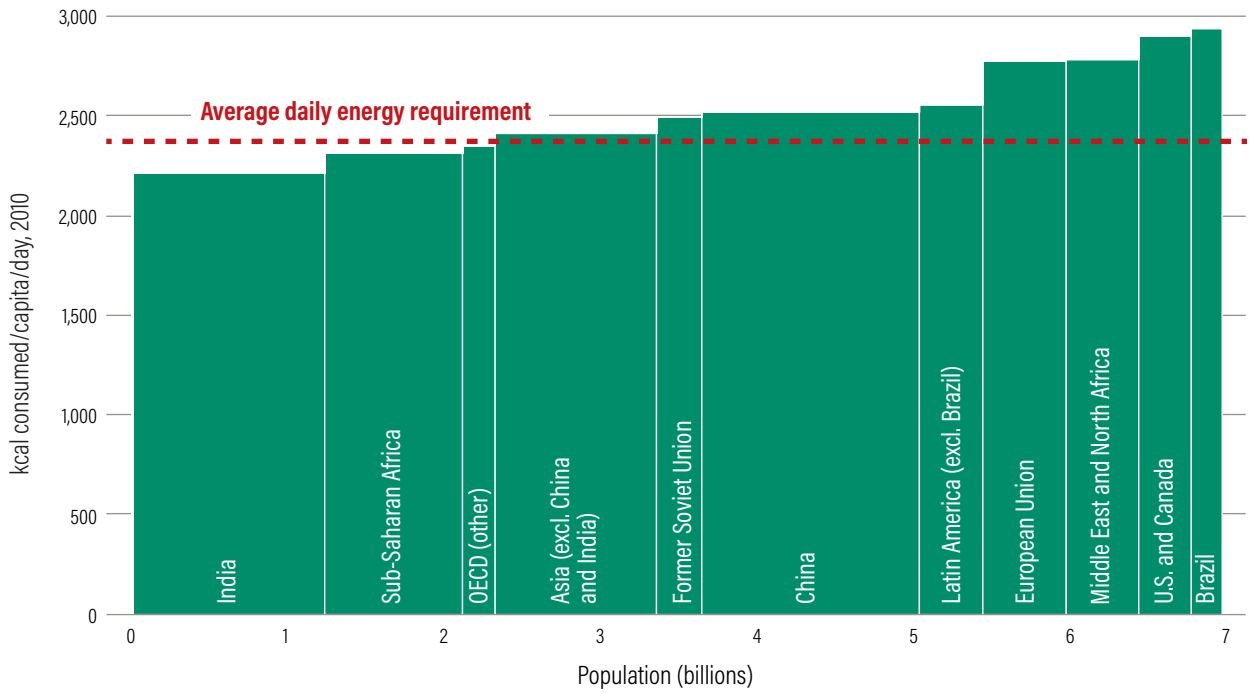
The global convergence toward Western-style diets will make it harder for the world to achieve several of the UN Sustainable Development Goals, including those related to hunger (SDG 2), good health and well-being (SDG 3), water management (SDG 6), climate change (SDG 13), and terrestrial ecosystems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

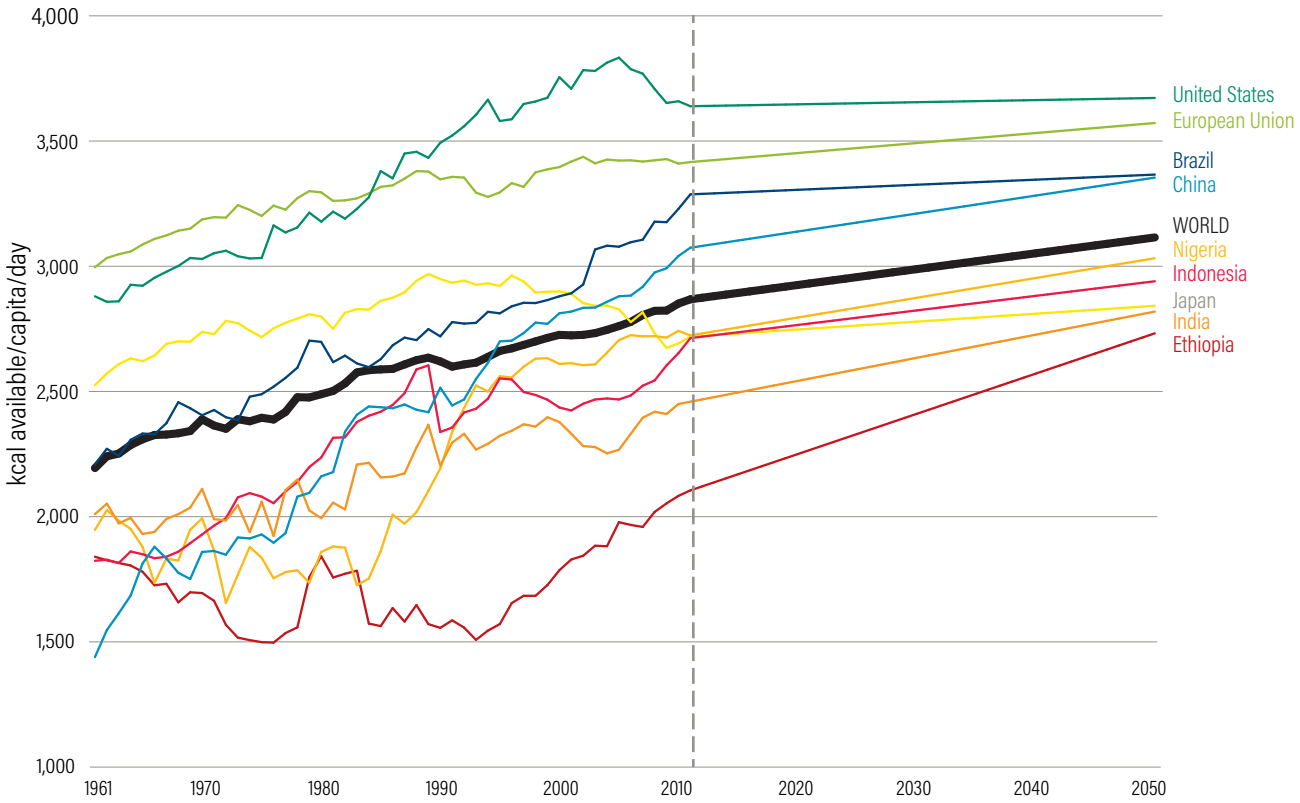
Even as chronic hunger remains widespread in poor countries, the average consumption of calories is already above daily energy requirements in most world regions (Figure 6-1).[62] These excesses are likely to grow (Figure 6-2).

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.

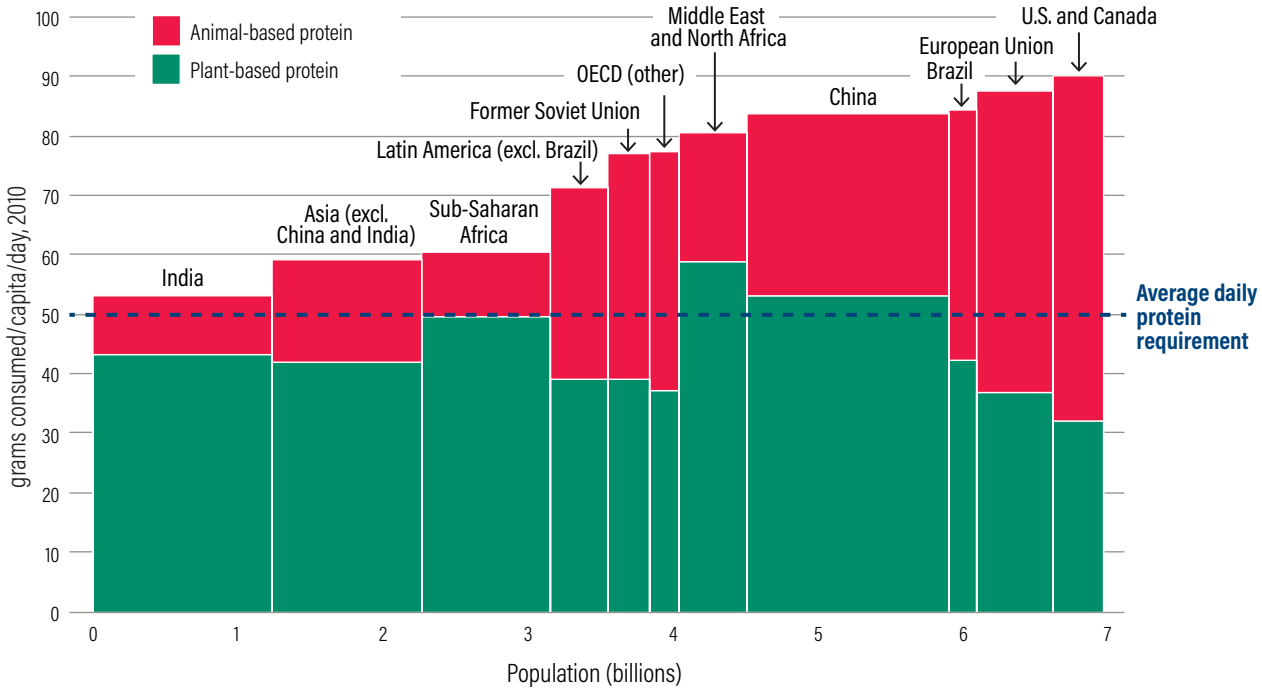
In fact, separate consumption of amino acids during different meals still ensures nutritional benefits[g] because the body breaks down proteins into separate amino acids, which it stores for later use.[h]

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]

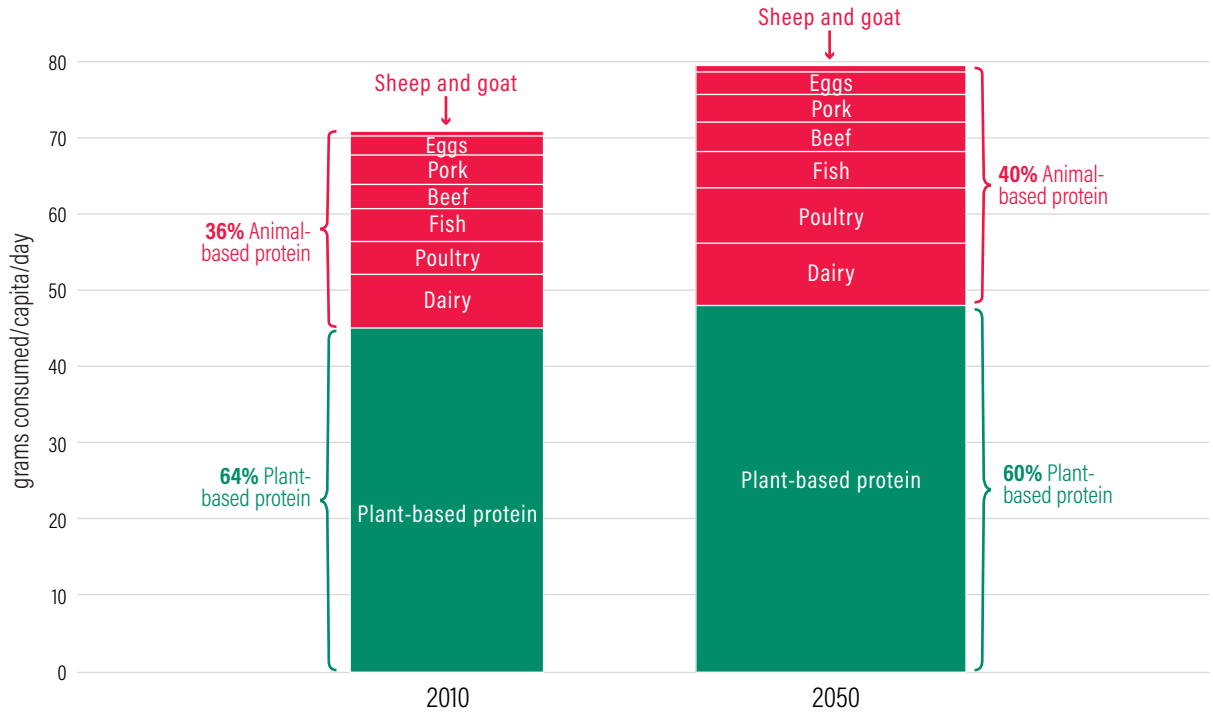
FAO's projection of a continued inequitable distribution of animal-based food consumption has important implications when developing options for a sustainable food future. It means that large *global* reductions in meat and dairy consumption by all would be highly inequitable. Instead, policy should 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.

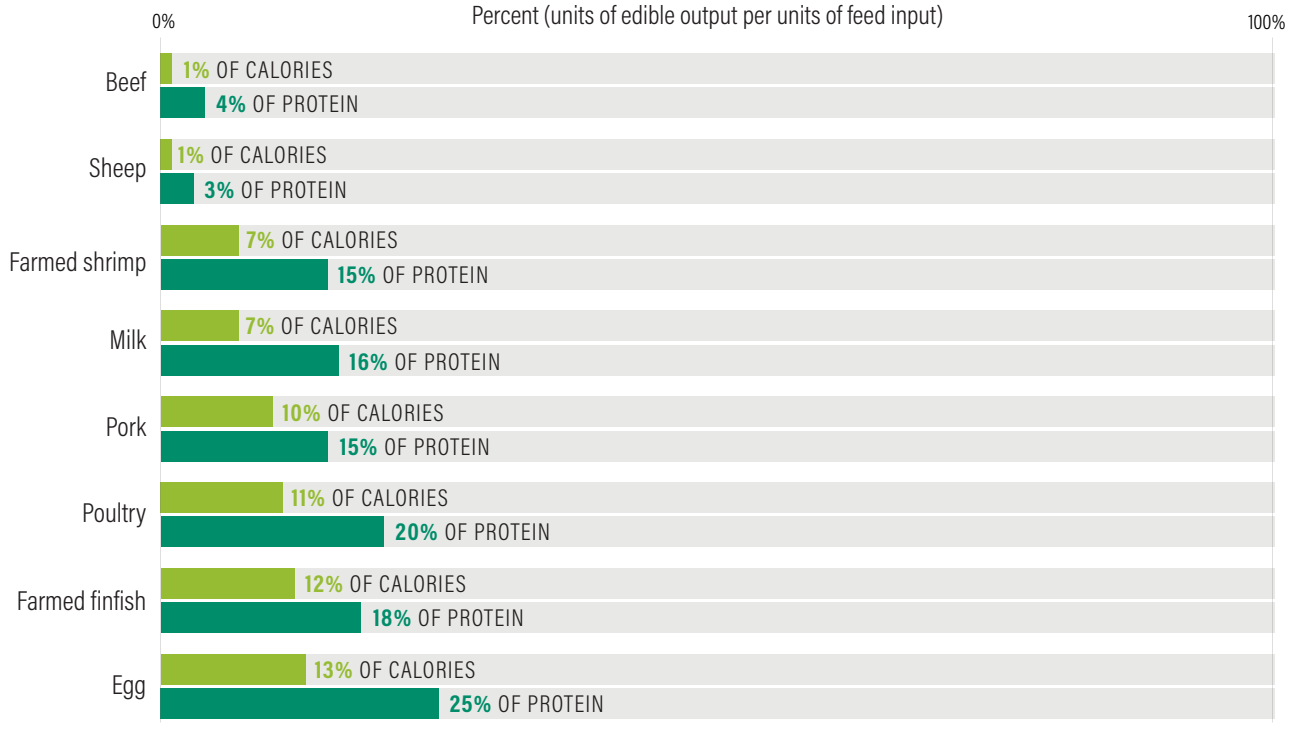


- **Underestimates: Failure to fully account for all animal feeds**. The most significant underestimate results from methods that count the environmental consequences of only "human-edible" animal feeds.[104] This approach excludes animal feed provided by crop residues and food processing wastes, which 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

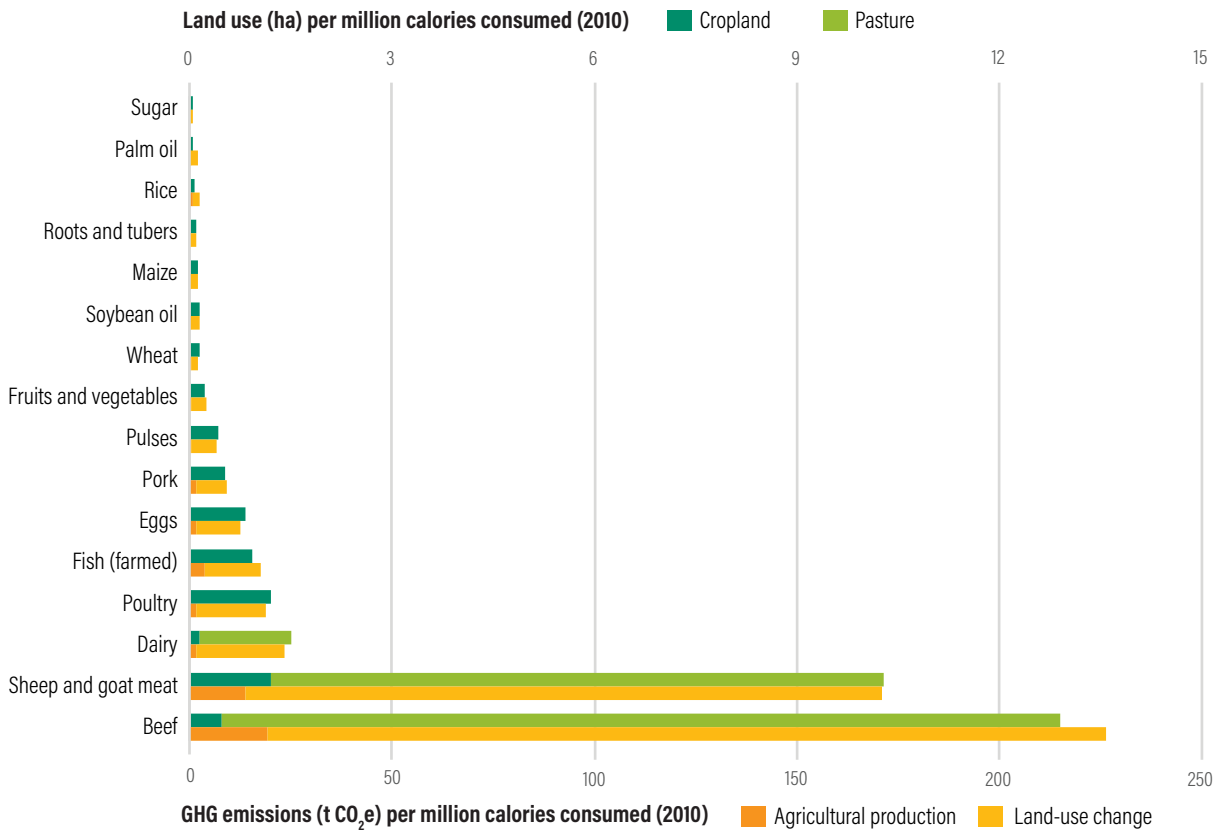


Figure 6-6b | Foods differ vastly in land-use and greenhouse gas impacts

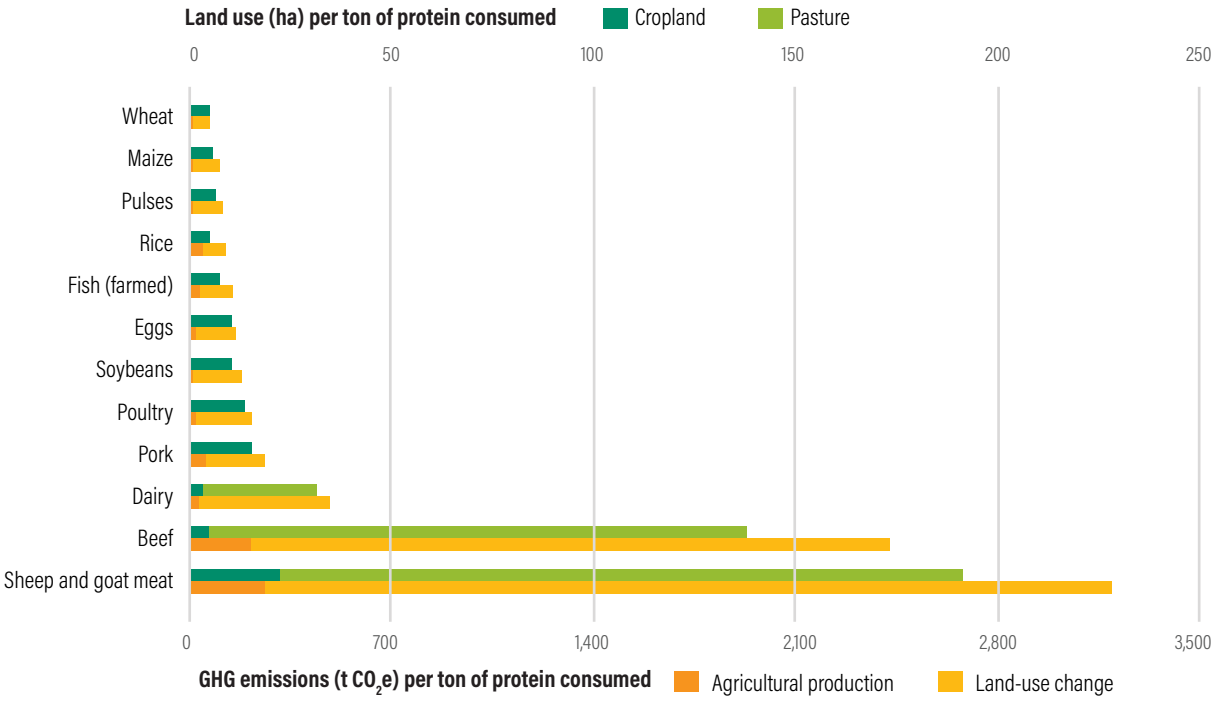


Figure 6-6c | Foods differ vastly in greenhouse gas impacts

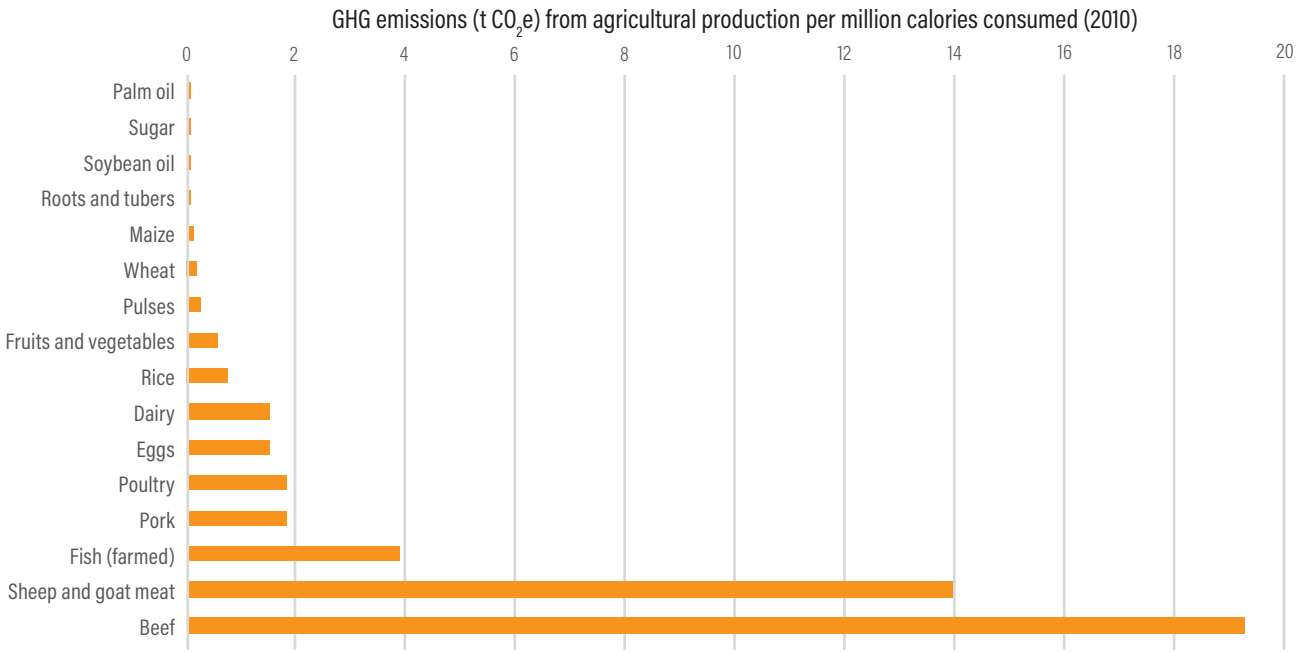
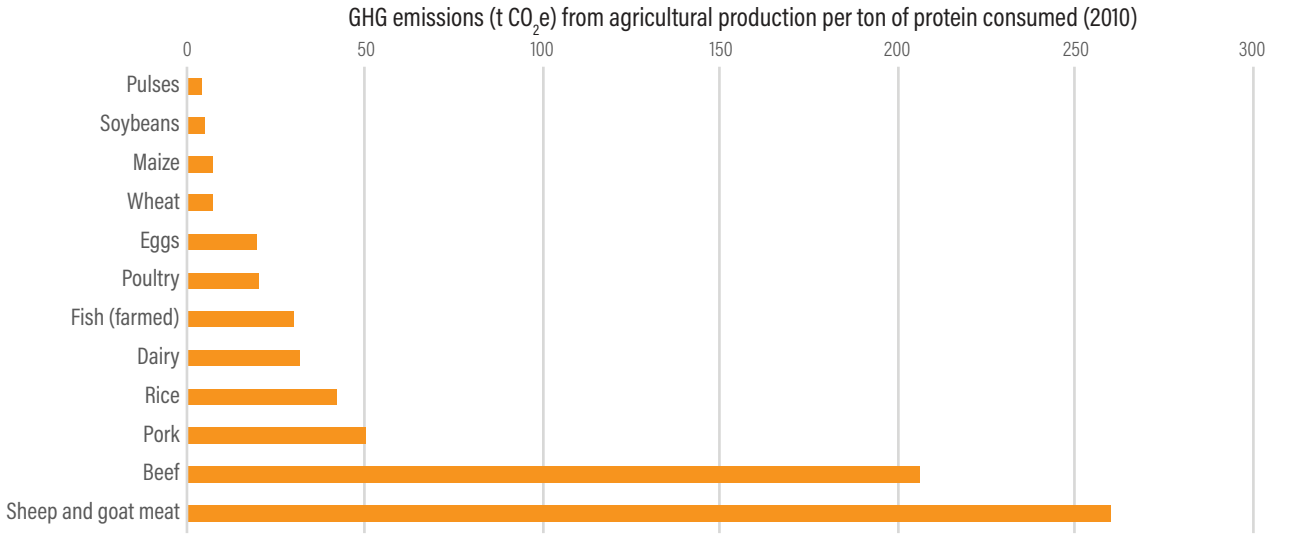


Figure 6-6d | Foods differ vastly in greenhouse gas impacts



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

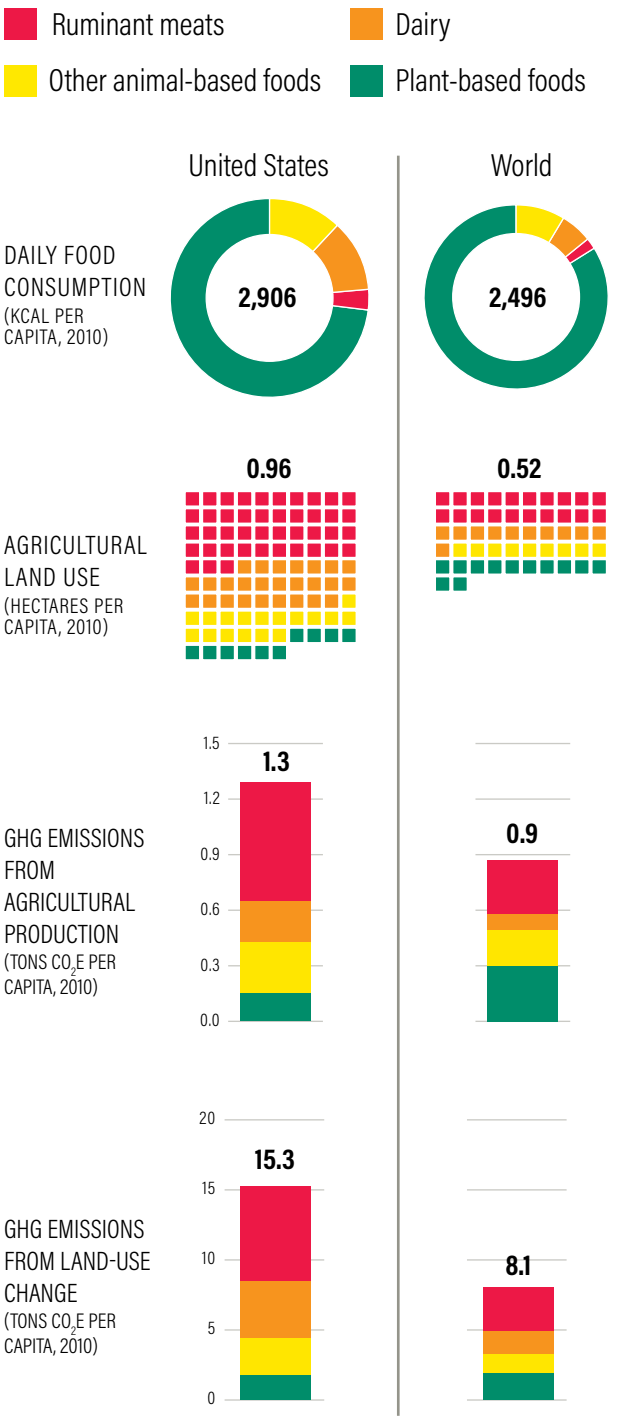
The large differences in land-use and GHG consequences of different foods explain why the global convergence toward Western-style diets has important implications for the resource needs and environmental impacts of agriculture. The average diet of the United States provides a good illustration because 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.

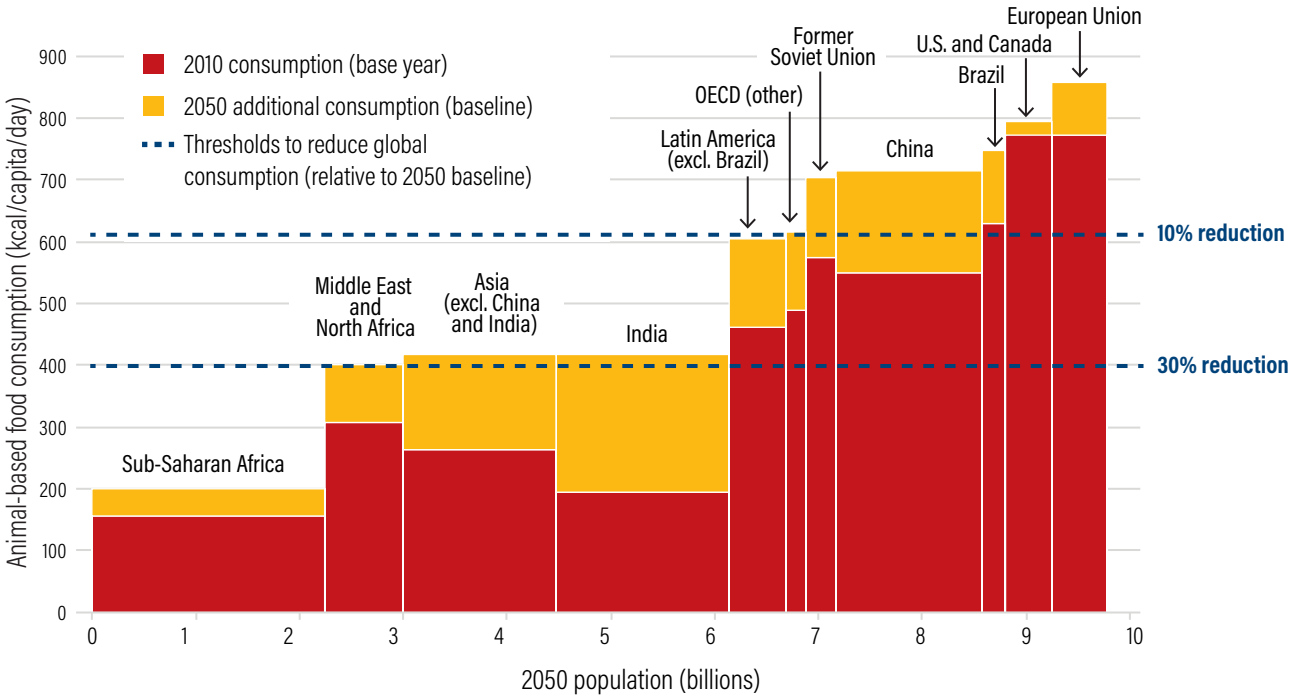
Less Meat Diet (Figure 6-9). We explore scenarios in which people cut back their consumption of all meats (but not other animal-based foods), by 10 or 30 percent (to a maximum of 372 or 238 kcal/person/day, respectively). In one variation for each level of cut, people substitute their meat with a 50/50 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.

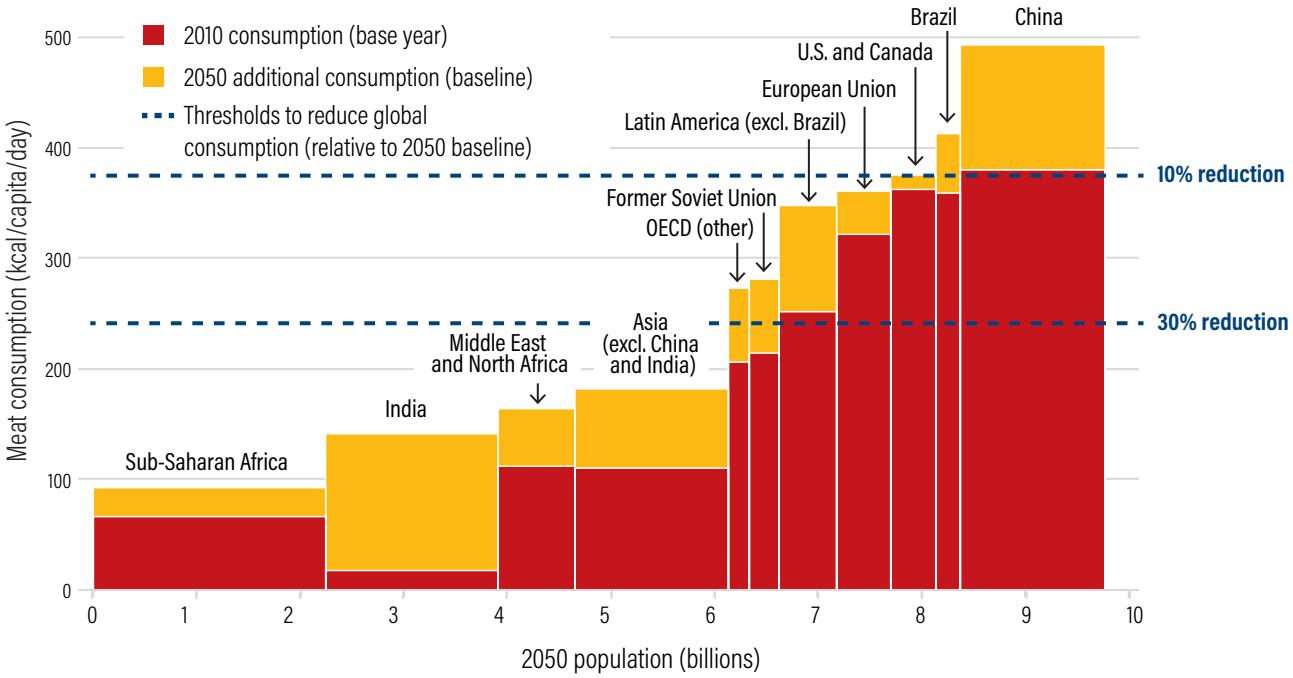
Less Ruminant Meat Diet (Figure 6-10). A fourth category of alternative diets focuses on reducing consumption of ruminant meats only (beef, sheep, and goat). These changes require large reductions in consumption but only by people in the United States, Canada, Europe, Latin America, and the former Soviet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

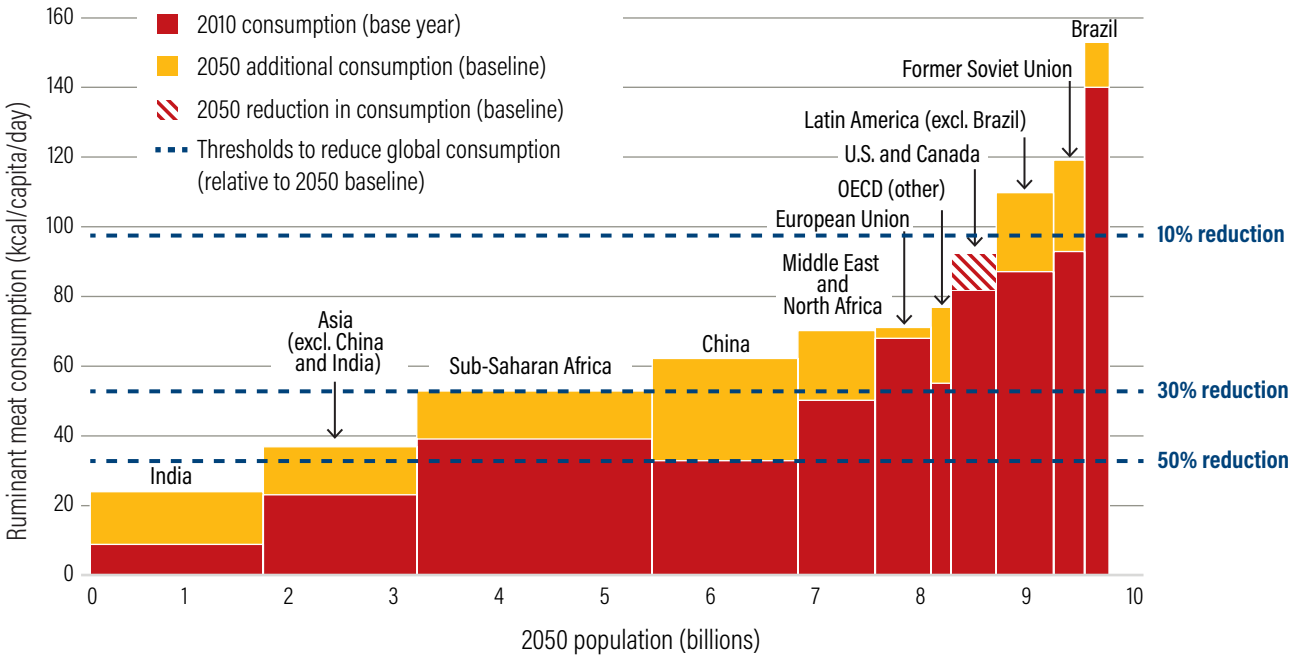
meat, although they comprised just one-quarter of the world's population.[128] Using our threshold approach, we explore three levels of cuts in global ruminant meat consumption relative to predicted 2050 levels:

- 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

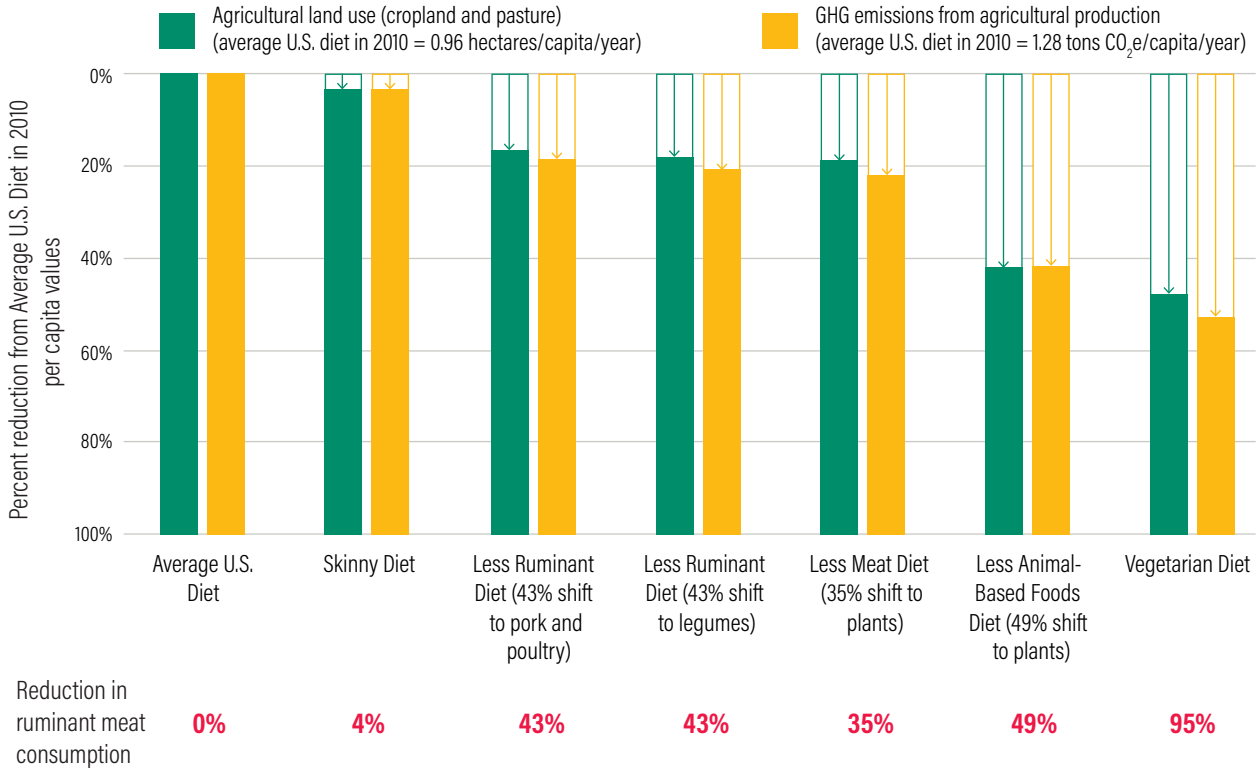
To better understand the feasibility and importance of the various global diet shifts we analyzed, Table 6-3 explains the dietary changes that would be required in the United States (a high meat-consuming country) in 2010, according to our principle of equity, and Figure 6-11 shows the per capita implications 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

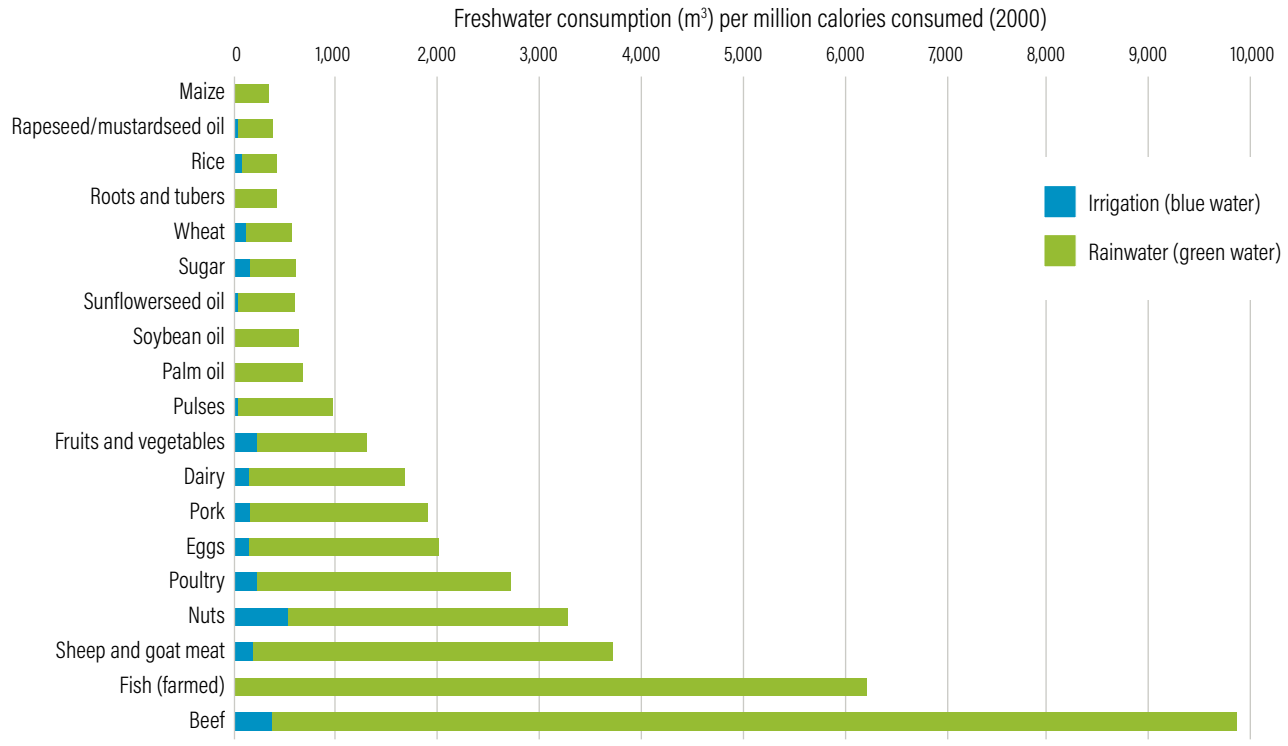
Just as with land use and GHG emissions, increasing demand for animal-based foods will likely increase pressure on the world's freshwater resources—and shifting to diets with a greater share of plant-based foods will likely reduce that pressure. Mekonnen and Hoekstra (2011, 2012) provide a comprehensive 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.

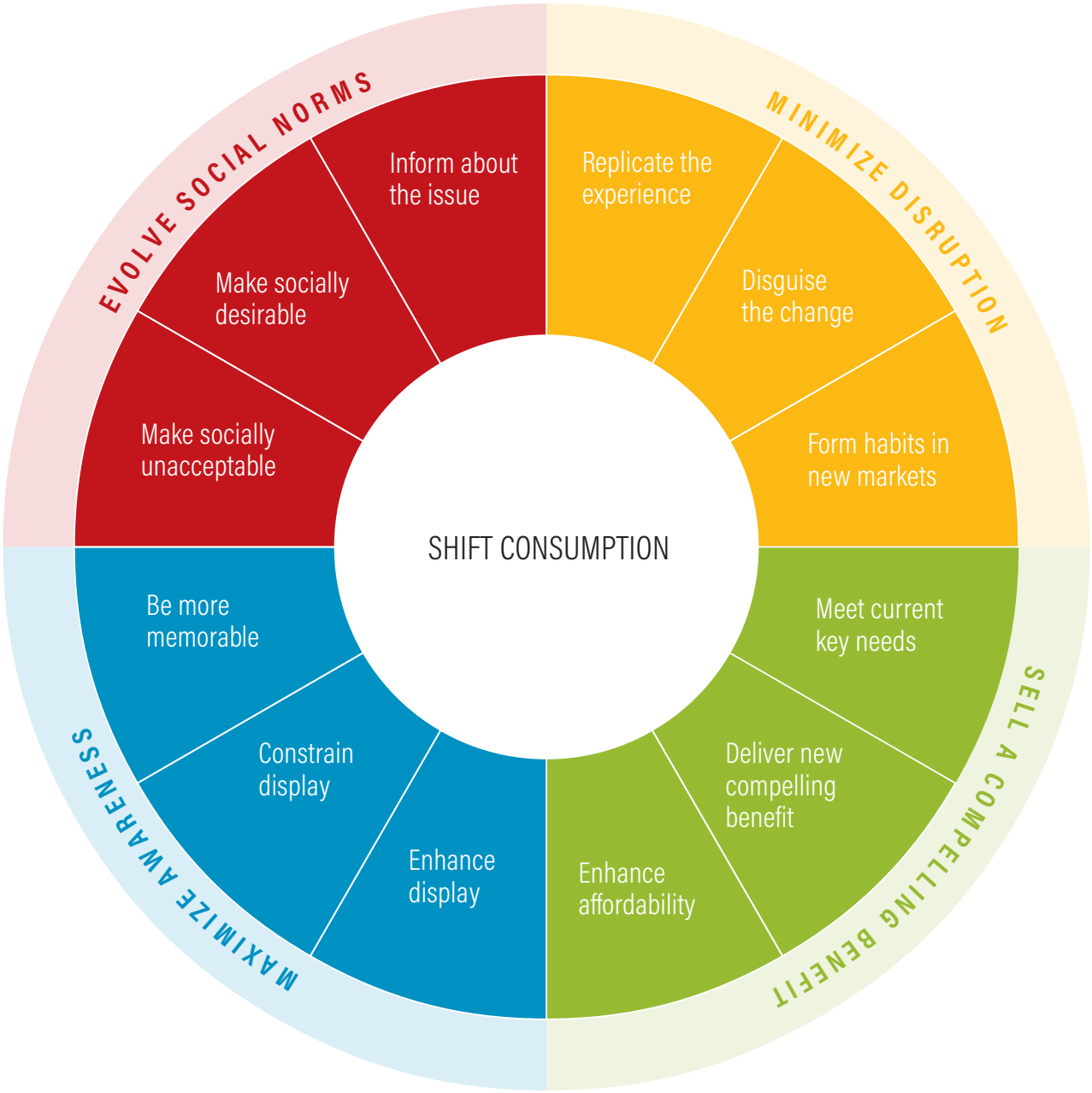
Minimize disruption

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.

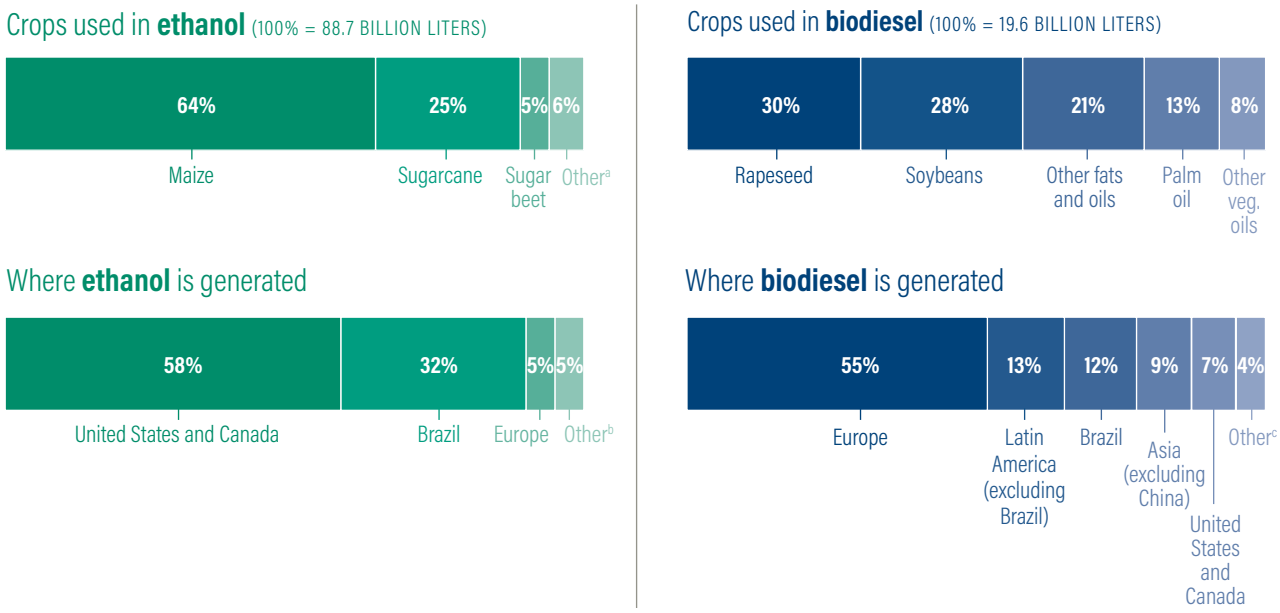
We call these forms of bioenergy "bioenergy from the dedicated use of land" because land must be dedicated to the purpose of producing bioenergy feedstocks. The productive potential of land is thus diverted from food and fiber production or carbon storage to bioenergy. This diversion still occurs, at 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]

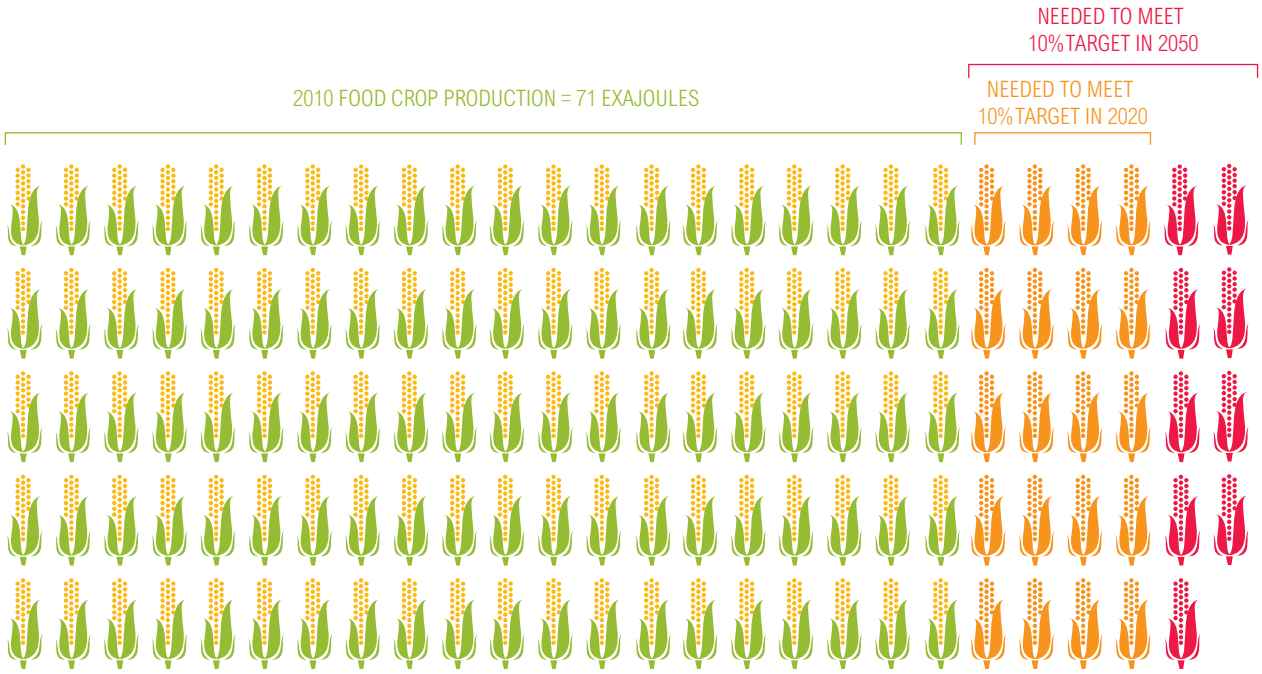
These numbers can be used to show the implications for the crop calorie gap of increasing biofuel production to 10 percent of transportation fuels from the 2.5 percent we already factor into our baseline. In that event, the crop calorie gap between 2010 and 2050 would widen from 56 to 78 percent (Table 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.

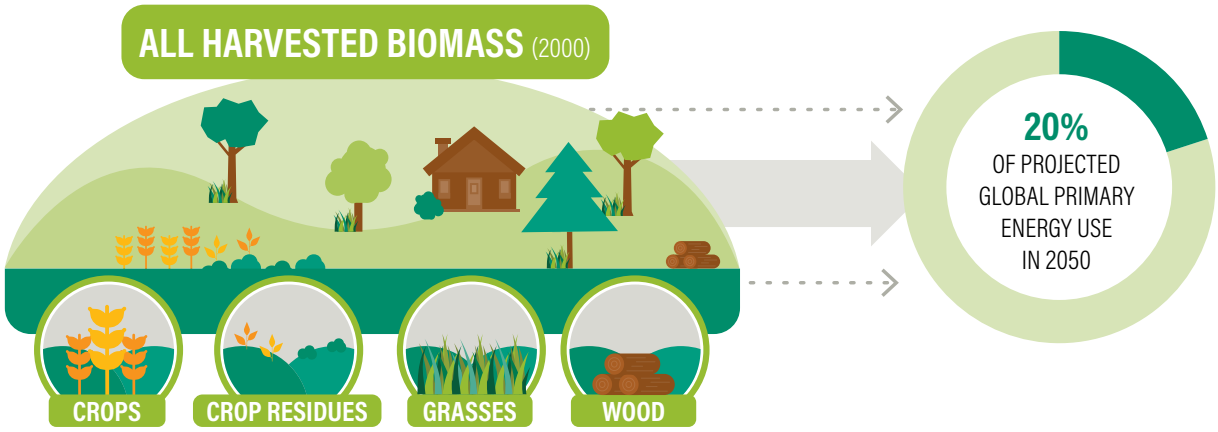
The Opportunity

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.

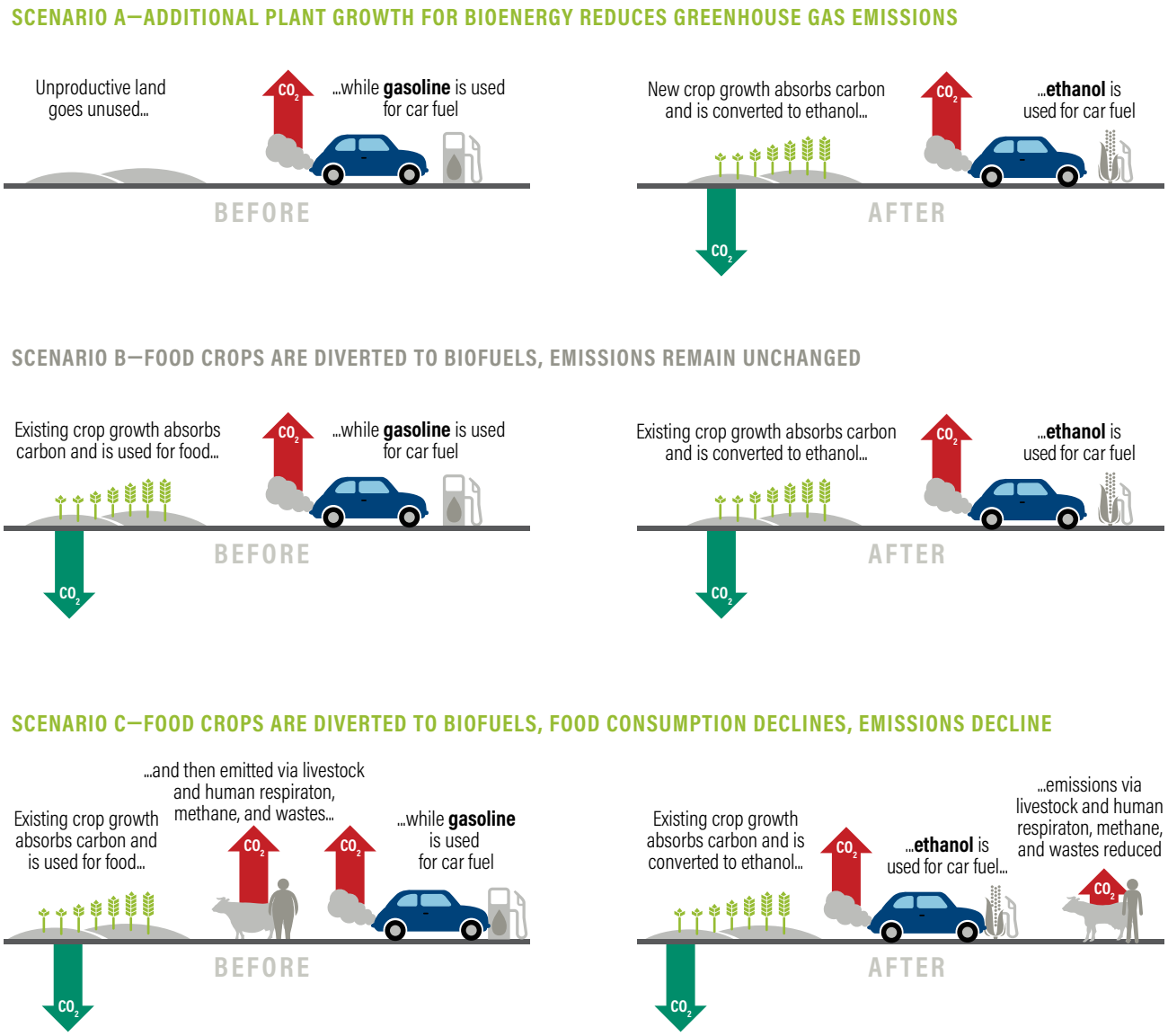
"Renewable" and "sustainable" does not make biomass carbon-neutral

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.

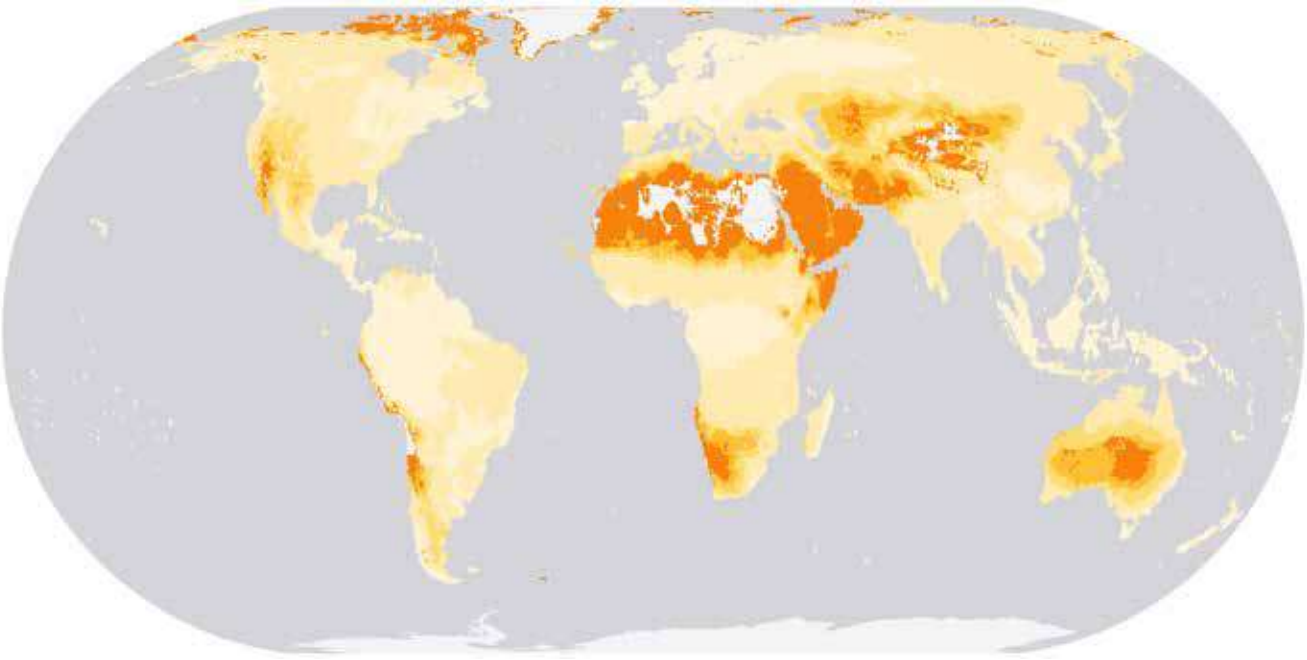
Solar alternatives to bioenergy

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. Massachussetts, 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 Massachussetts 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.

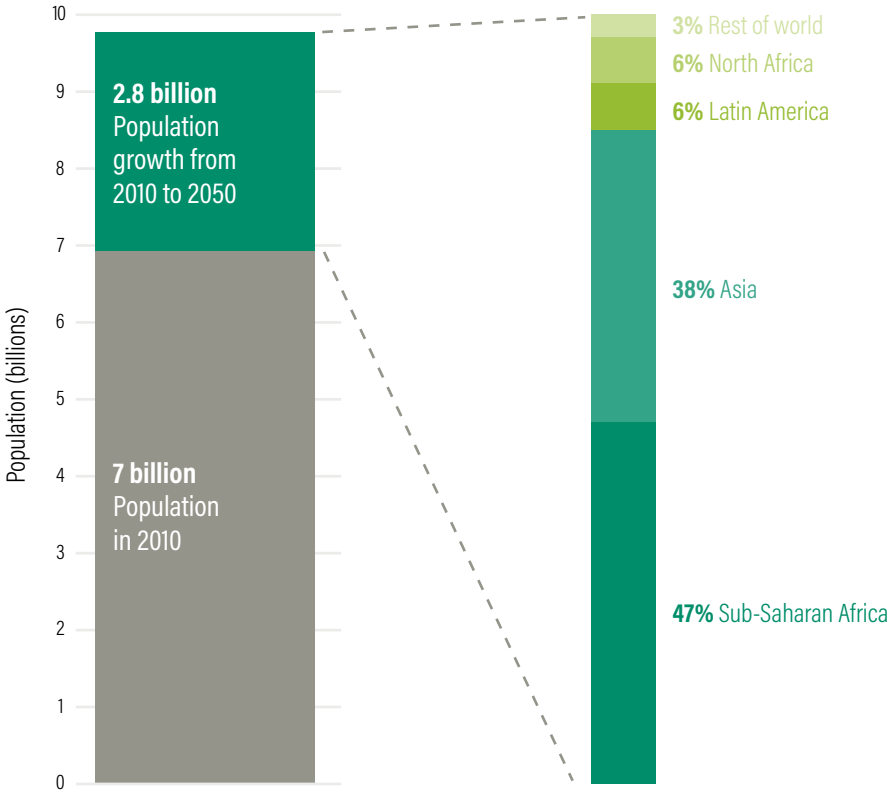
Achieving replacement fertility levels worldwide would bring enormous social benefits and could make a meaningful contribution to the food, land, and GHG mitigation gaps. But such an achievement would bring the greatest benefits to sub-Saharan Africa, whose population is facing the most formidable challenges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

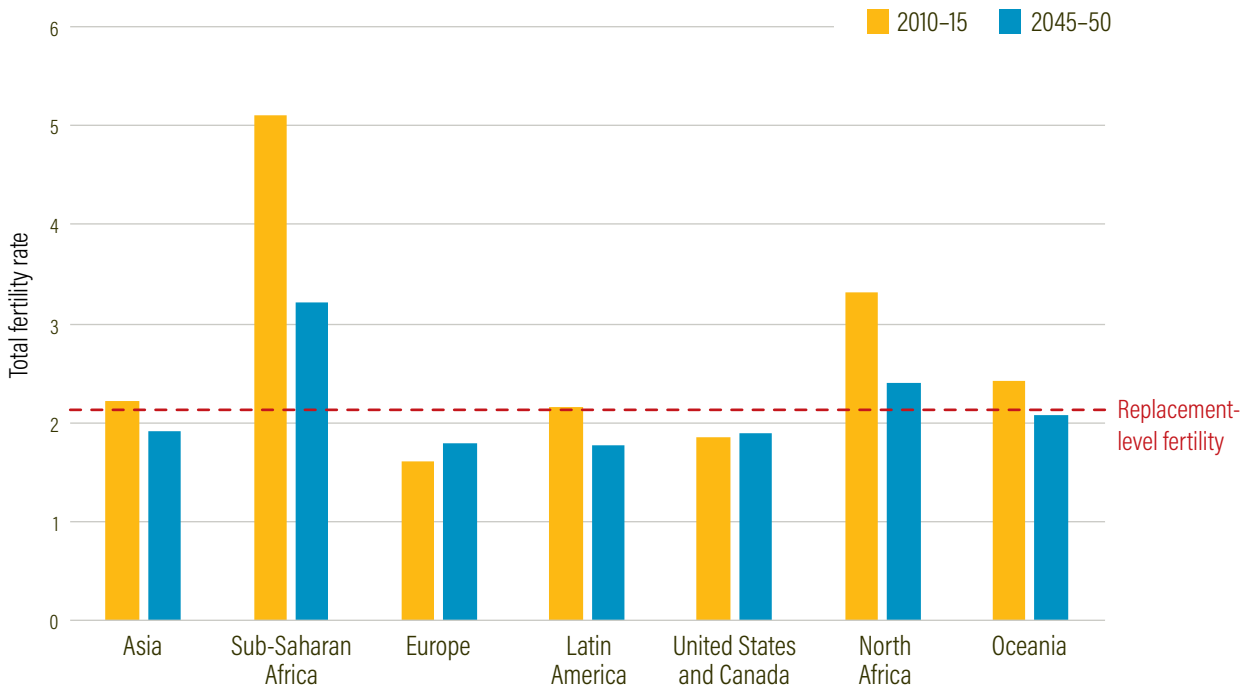
Overall, most of the world's regions are close to achieving replacement-level fertility rates and will achieve or even dip below replacement level by 2050 (Figure 8-2). The "replacement-level" rate is the total fertility rate[291] at which a population exactly replaces itself from one generation to the 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

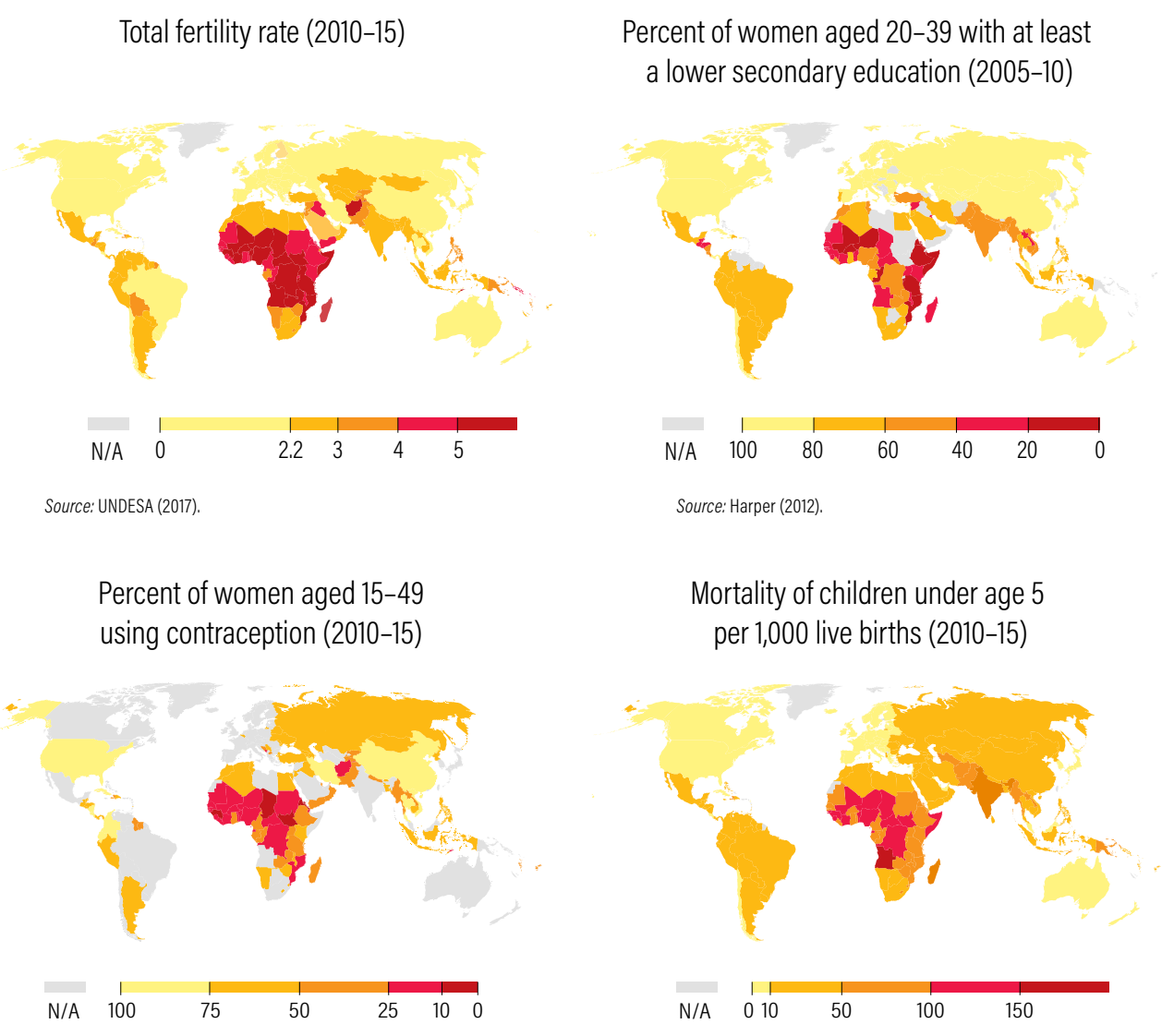
Sub-Saharan Africa could achieve large food security and economic benefits and contribute to meeting global and regional land-use and GHG emission targets if it were to lower its present total fertility rates to approach—and ideally reach—replacement level by 2050. Experience from other regions shows 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



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



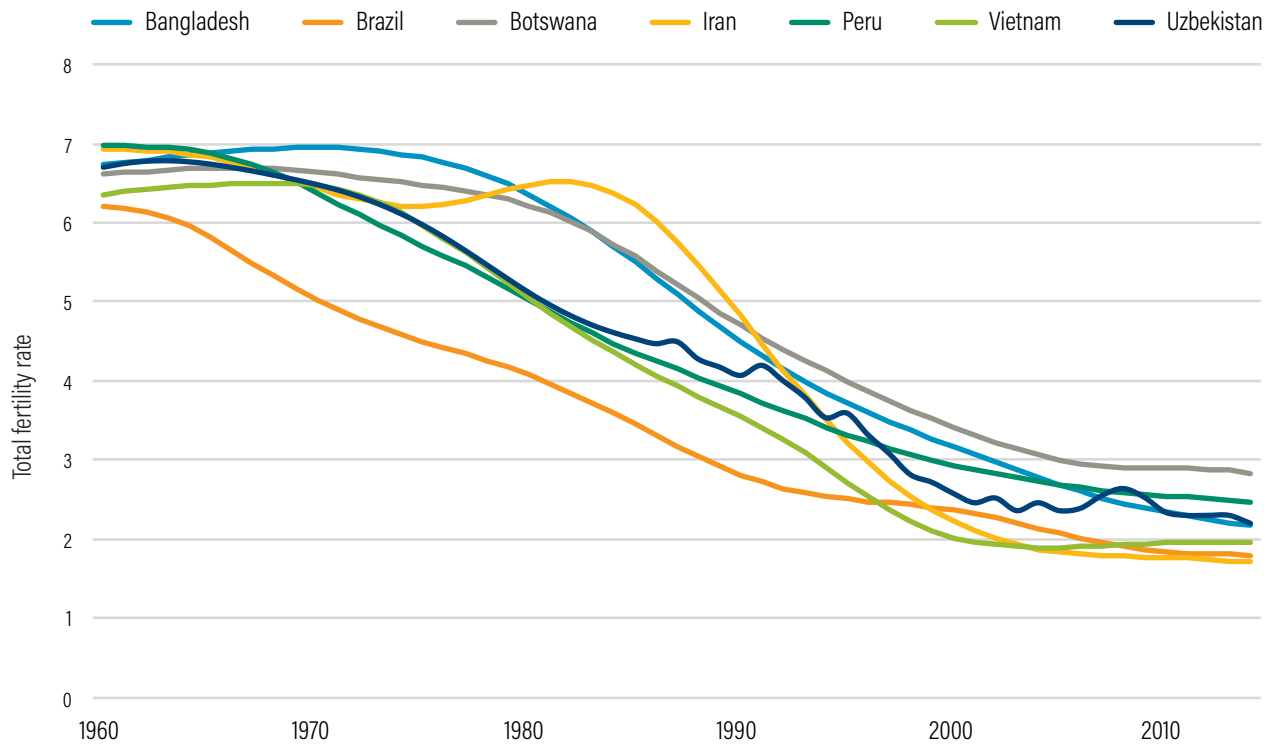
BOX 8-1 | Is it possible to reduce fertility rates quickly?

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.

ENDNOTES

1. FAO (2011c). This figure is one-third as measured by weight. This is a rough estimate given that it extrapolates from individual food loss and waste studies across countries and stages of the food supply chain. Subsequent research papers have found wide variations in food loss and waste estimates. For instance, as reported in Affognon et al. (2015), one study for maize in Benin found postharvested losses of 41% while another found losses of 12%, and one sweet potato study in Tanzania found losses of 67%, while another found losses of 6%. Yet FAO estimates are consistent in a broad way with estimates in the differences between how much food farmers produce and how much people consume. Although the food loss and waste estimates provided by FAO have uncertainties, they are the most comprehensive global numbers currently available.

2. Authors' calculations based on FAO Food Balance Sheets, which convert metric tons into calories per type of food. We convert tons into calories in order to estimate the impact of food loss and waste on the food gap (which we measure in calories) and in order to more closely reflect the nutritional value of food, since a lot of weight in food is water. Measuring by calories avoids the water embedded in food. Kummu et al. (2012) separately found loss and waste on a caloric basis to equal 24% of all food produced.

3. FAO (2015a). The precise FAO figure is $940 billion.

4. World Bank (2011b).

5. Buzby et al. (2014).

6. WRAP (2015).

7. Kummu et al. (2012).

8. FAO (2015a).

9. FAO (2015a).

10. FAO (2011c); Gunders (2012); Kummu et al. (2012).

11. In FAO (2011c), Oceania includes Australia and New Zealand. The FAO data combine North America and Oceania. One cannot split the data apart.

12. Authors' calculations based on FAO (2011c).

13. Gebhardt and Thomas (2002).

14. Oguntade (2013).

15. WRAP (2013).

16. Hanson and Mitchell (2017). Costs covered in the UK analysis are those associated with a wide range of actions including the "Love Food Hate Waste" campaign, date labeling changes, pack size and format changes, in-store messaging by food retailers, TV and digital media advertising that included "Love Food Hate Waste" messaging, and periodic quantification of food waste to monitor progress. The financial benefits were primarily the savings to households of the food waste that was prevented (measured by retail purchase value) complemented by municipal savings from avoided food waste disposal costs.

17. Hanson and Mitchell (2017). Costs included communication and outreach to resident households, practical tips on managing food, and other awareness-raising expenditures. The benefits reflect the boroughs' avoided waste management and disposal costs. The benefit to borough citizens reflect the avoided purchase value of food that otherwise would have been wasted.

18. Hanson and Mitchell (2017). Although specifics varied between sites, the financial costs incurred by company sites in this analysis included conducting food loss and waste quantification ("inventories") in order to identify how much and where food was being lost and wasted, prioritize hotspots, and monitor progress over time; purchasing or leasing on-site equipment to quantify food loss and waste; training staff on food loss and waste reduction practice; purchasing equipment as part of material flow process redesigns or improved storage; changing food storage, handling, and manufacturing processes; changing packaging to extend shelf-life; changing date labeling on packaging; and pursuing other staff and technology investments to reduce food loss and waste. The financial benefits realized by the company sites included avoiding the costs of buying food (as ingredients or directly for sale) that previously had been lost or wasted without being sold; increasing the share of food purchased or prepared that gets sold onward to customer; introducing new product lines made from food that otherwise would have been lost or wasted; reducing food waste management costs (including labor) and tipping fees; and realizing other modes of reducing input costs or increasing output sales.

19. It is important to note that many technical solutions can be effective only when other parts of the food supply chain are effective. For example, improved on-farm storage will not ultimately lead to reductions in food loss if farmers have no access to a market where they can sell their harvest surplus. Retailers using poor forecasting techniques may place food orders and later cancel them, negating per unit efficiency gains made by food processors. Therefore, progress in reducing food loss and waste will require an integrated supply chain approach. Personal communication, Robert van Otterdijk (team leader, Save Food, FAO), May 17, 2013.

20. Frid-Nielsen et al. (2013).

21. Practical Action (2010).

22. Practical Action (2003).

23. Nenguwo (2013); Kitinoja et al. (2011).

24. Baributsa et al. (2012).

25. Hell et al. (2010).

26. Coulibaly et al. (2012).

27. Moussa et al. (2012).

28. Moussa et al. (2012).

29. Parfitt et al. (2016).

30. Kowitt (2017); Garfield (2017). Short videos of its performance can be seen at http://www.businessinsider.com/coating-extends-produce-life-apeel-sciences-2017-10#the-coating-is-are-made-of-discarded-materials-from-organic-produce-anything-from-pear-stems-to-leftover-grape-skins-to-grass-clippings-we-dont-discriminate-rogers-said-7.

31. Parfitt et al. (2016).

32. Gunders (2012).

33. Lipinski et al. (2016).

34. One such example of this type of law is the Bill Emerson Good Samaritan Act in the United States, enacted in 1996. This law protects food donors from civil and criminal liability if the product they redistributed in good faith to a charitable organization later causes harm to the needy recipient. It also standardizes donor liability exposure: donors no longer have to accommodate 50 different liability laws in 50 different states.

35. Morenoff (2002).

36. Morenoff (2002).

37. Gunders (2012).

38. EPA (2013).

39. Young and Nestle (2002).

40. Bloom (2011), as cited in Gunders (2012).

41. Gunders (2012).

42. Aramark (2008).

43. WRAP (2011).

44. USDA (2011). The only product that is required in the United States to have a "use-by" date is infant formula. More than 20 states have laws regarding food date labeling, but these laws vary greatly.

45. USDA (2011); Gunders (2012).

46. In 2014, the 54 member states of the African Union issued the Malabo Declaration, a set of agriculture goals aimed at achieving shared prosperity and improved livelihoods. Part of the Malabo Declaration is a commitment "to halve the current levels of postharvest losses by the year 2025." Although this target does not match SDG Target 12.3 directly since the numeric target applies to food losses and not to food waste, it is "in the spirit" of SDG Target 12.3 in that it calls for a 50% reduction—and even five years earlier than the SDGs. Moreover, focusing on food loss is arguably justified since, as Figure 1 indicates, food losses during production and storage are currently a larger issue in Africa than food waste at the market or consumption stage.

47. See WRAP (n.d).

48. Lipinski et al. (2016). For information about 2030 Champions, see USDA (2017).

49. Republic of Rwanda (2015).

50. Lipinski et al. (2016).

51. The Food Loss & Waste Protocol (FLW Protocol) is a partnership that has developed the global *FLW Standard* for quantifying and reporting on food and/or associated inedible parts removed from the food supply chain. FLW Protocol partners are the Consumer Goods Forum, EU FUSIONS, FAO, UN Environment, World Business Council for Sustainable Development, and WRAP. WRI serves as the FLW Protocol's secretariat.

52. The FLW Protocol website, http://www.flwprotocol.org, provides access to the *FLW Standard*, supporting tools, case examples, and training material.

53. Recognizing the need for collaborative action, actors in the food service industry created the International Food Waste Coalition to reduce food loss and waste all along the value chain. Members include Sodexo, which is working to prevent and reduce food waste in schools, hospitals, and workplace restaurants.

54. For more on these examples, see Lipinski et al. (2016).

55. It is important to note that many technical solutions can be effective only when other parts of the food supply chain are effective. For example, improved on-farm storage will not ultimately lead to reductions in food loss if farmers have no access to a market where they can sell their harvest surplus. Retailers using poor forecasting techniques may place food orders and later cancel them, negating per unit efficiency gains made by food processors. Therefore, progress in reducing food loss and waste will require an integrated supply chain approach. Personal communication, Robert van Otterdijk (team leader, Save Food, FAO), May 17, 2013.

56. However, the environmental and economic implications of these solutions can vary greatly based on where the roads are built and the type of fuel used to generate the electricity.

57. Pulses are annual leguminous crops harvested for dry grain, including beans, peas, and lentils.

58. Keats and Wiggins (2014); Khoury et al. (2014); Tilman and Clark (2014); Popkin et al. (2012).

59. Strong correlations between per capita gross domestic product and consumption of both total calories and meat are demonstrated in Tilman and Clark (2014), (Figure 2); Khoury et al. (2014); and Pingali (2007).

60. Anand et al. (2015); Reardon et al. (2014).

61. Popkin et al. (2012); Delgado et al. (1999).

62. 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. Because historical rates of food loss and waste are unknown, graphs showing trends from 1961 display "availability" instead of "consumption."

    Although median levels of consumption would give the most accurate picture of an "average" person's consumption in a given country or region, data presented in this and similar figures in this chapter are means, because means are the only globally available averages. Of course, countries exceeding the 2,353 calorie threshold on an average basis will likely have a percentage of their populations below the threshold. For instance, although China, Nigeria, and Indonesia all lie above the threshold in Figure 6-1, in 2010–12, 12% of China's population was undernourished, as was 6% in Nigeria, and 11% in Indonesia, according to FAO, IFAD, and WFP (2015). This underscores the importance of properly targeting diet shifts at "overconsuming" segments of the population within a country or region.

63. Protein requirements differ by individual based on age, sex, height, weight, level of physical activity, pregnancy and lactation (FAO, WHO, and UNU 1985). Similar to other developed countries, the U.S. government (CDC 2015) lists the estimated daily requirement for protein as 56 grams per day for an adult man and 46 grams per day for an adult woman, or an average of 51 grams of protein per day. Paul (1989) estimates the average protein requirement at 0.8 g per kg of body weight per day. Since the average adult in the world weighed 62 kg in 2005 (Walpole et al. 2012), applying the rule of 0.8 g/kg/day would yield an estimated global average protein requirement of 49.6 grams per day. Other international estimates are lower still. For instance, FAO, WHO, and UNU (1985) estimate an average requirement of 0.75 g/kg/day. Furthermore, these estimates are conservative to ensure that they cover individual variations within a population group. For example, the estimated protein requirement of 0.8 g per kg of body weight per day given in Paul (1989) includes 0.35 g/kg/day as a safety margin.

64. GlobAgri-WRR model with source data from FAO (2019a) and FAO (2011c). Of course, countries exceeding the threshold of consumption of 50 grams of protein per capita per day will likely have a percentage of their populations below the threshold. See the discussion around Figure 6-1. A true comparison of protein intakes to dietary requirements would involve an analysis of the distribution of usual intakes across a population, rather than simply comparing to mean intakes. For example, the U.S. Department of Agriculture used the 2001–02 national dietary survey in the United States to find that protein consumption fell under the estimated dietary requirement in only 3% of the population (Moshfegh et al. 2005).

65. GlobAgri-WRR model, based on projections from Alexandratos and Bruinsma (2012).

66. FAO (2019a).

67. GlobAgri-WRR model.

68. As summarized in Valin et al. (2014), the average demand increase for calories among other models was actually 37% higher than the FAO projection, with the lowest other model projection 15% higher. Nearly all model projections of increases in ruminant meat are also higher than FAO projections, and most are higher for pig and poultry meat, eggs, and dairy products (Valin et al. 2014, Figure 2). Tilman et al. (2011) also projects much greater consumption of animal products due to historical relationships across societies between income and their consumption. Bijl et al. (2017) also developed a statistical model to project future consumption of animal products, which results in higher projections for consumption in 2050 under business-as-usual.

69. Authors' calculations using Alexandratos and Bruinsma (2012), updated population projections from UNDESA (2017), and postconsumer waste figures incorporated into GlobAgri-WRR.

70. Authors' calculations based on GlobAgri-WRR model.

71. A basic summary of the literature showing the reductions in stunting provided by improved total nutrition, some meat consumption among the poor, and general dietary diversity is provided in Godfray et al. (2010); Neumann, Demment, et al. (2010); and Dror and Allen (2011).

72 One survey of 13 low-income countries in Asia, Latin America, and Africa found that livestock provided 10–20% of the average income of rural households in each of the lowest three out of five income categories. Pica-Ciamarra et al. (2011).

73. Popkin and Gordon-Larsen (2004).

74. USDA and HHS (2015); WHO (2012); Popkin and Gordon-Larsen (2004); Micha et al. (2017).

75. USDA and HHS (2015); WHO (2012).

76. USDA and HHS (2015).

77. According to various studies, obesity accounted for 12% of the growth in health spending between 1987 and 2001 in the United States (American Diabetes Association 2008), accounted for 13% of health care costs in China in 2010 (*Economist* 2014), and caused $144 billion in excess health care spending in 2008 (Finkelstein et al. 2009). Another study found that obesity leads to 25% higher health care costs on average for an obese person than a person of normal weight across different countries (OECD 2010).

78. Fry and Finley (2005); Finkelstein et al. (2010).

79. Dobbs et al. (2014).

80. The World Health Organization 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 or her height in meters (kg/m^2) (WHO 2012a).

81. Ng, Fleming, et al. (2014).

82. Popkin et al. (2012).

83. Cecchini et al. (2010).

84. FAO, WFP, and IFAD (2012), Figure 16.

85. Grecu and Rotthoff (2015).

86. Within a population, the degree to which calorie availability has peaked varies based on a number of factors, such as socioeconomic status and race or ethnicity. See Ng, Slining, et al. (2014) for a discussion relevant to the United States.

87. These are rough extrapolations of growth between 1980 and 2013 that translates into linear growth rates of more than 0.2% per year, which would generate growth of around 10% by 2050. Because our analysis, which follows, shows modest land and greenhouse gas savings even from drastic declines in rates of obesity and overweight, we do not bother to try to tease out more precise statistical relationships.

88. Authors' calculations. Of these 3.1 billion people, 2.1 billion would be overweight and 1 billion obese.

89. WHO (2012); Campbell et al. (2006).

90. Papers finding limited health consequences of saturated fats include Chowdhury et al. (2014) and de Souza (2015).

91. After the Chowdhury (2014) paper was published, the authors found some errors and published corrections, but the errors had the effect of reducing the findings of the benefits of certain other types of fats, such as fish oils, rather than underestimating the consequences of saturated fats (Kupferschmidt 2014). Two more recent meta-analyses (Wang et al. 2016; Imamura et al. 2016) also find benefits to switching from saturated to polyunsaturated fats, particularly ones with higher omega-3 to omega-6 ratios.

92. Nutritionists define "red meat" as meat from mammals, which includes beef and other ruminant meats (sheep and goat), as well as pork.

93. Dwyer and Hetzel (1980); Armstrong and Doll (1975); Sinha et al. (2009); Larsson and Orsini (2013); Micha et al. (2017).

94. Binnie et al. (2014); Micha et al. (2012).

95. Bouvard et al. (2015). "Processed meat" refers to meat that has been transformed through salting, curing, fermentation, smoking, or other processes to enhance flavor or improve preservation. Most processed meats contain pork or beef but might also contain other red meats, poultry, offal (e.g., liver), or meat by-products such as blood.

96. WCRF and AICR (2007). Konde et al. (2015); Netherlands Nutrition Centre (2017).

97. Micha et al. (2017), Table 1.

98. GlobAgri-WRR model, using FAO (2019a) source data.

99. Lappé (1971). However, this book also popularized the myth that plant-based foods needed to be combined in single meals to meet protein nutritional needs (see Box 6-1 debunking this myth).

100. CAST (1999).

101. Foley et al. (2011).

102. Ripple et al. (2014).

103. Brown (2009).

104. Numbers cited in Brown (2009), a critic of meat efficiencies, are based only on human-edible feeds, while the Council for Agricultural Science and Technology (CAST 1999) generally defends the efficiency of meat production in significant part by arguing that only human-inedible feeds should count. Similarly, Fry et al. (2018) found that aquaculture and beef conversion efficiencies were similar, because their analysis did not take calories and protein from grasses into account. The aquaculture conversion efficiencies estimated in Fry et al. (2018), however, are similar to those calculated here.

105. See Figure 2.4 from Wirsenius et al. (2010).

106. FAO (2011e). Similarly, Mottet et al. (2017) state this case for protein: "Ruminant systems, together with backyard pig and poultry systems, produce close to 41 Mt of animal protein per year while consuming about 37 Mt of human-edible-feed protein."

107. With the help of the lead author in Wirsenius et al. (2010), Figure 6-5 adjusts the numbers of the original study by excluding bones from edible food in order to provide reasonable comparisons between meat, milk, and fish and also to provide figures that match how the FAO counts "edible" food calories. Excluding bones from the measures of "food out" modestly lowers the efficiencies as typically presented, and as shown in Wirsenius et al. (2010). "Edible output" refers to the calorie and protein content of bone-free carcass. Sources for terrestrial animal-based foods (adjusted from carcass weight values to bone-free carcass weight values through personal communication with S. Wirsenius): Wirsenius et al. (2010) (extra unpublished tables), Wirsenius (2000). Sources for finfish and shrimp: Authors' calculations based on USDA (2013a); NRC (2011); Tacon and Metian (2008); Wirsenius (2000); and FAO (1989).

108. The authors of a global FAO livestock analysis, Gerber et al. (2013), provided background information on protein efficiencies for poultry of 19% and pig meat of 12%. They are lower than the global estimates of protein efficiencies by Wirsenius (2010, 2000) (when bones are counted as in other analyses) of 26% for poultry and 18% for pork. CAST (1999) generally argued for focusing only on human-edible feeds but provided estimates for efficiencies using total feeds. However, it did so only in a few countries, primarily relatively developed agriculturally and not including India or China. But CAST's estimate of the energy efficiency of beef in Kenya, its one agriculturally low productivity country, was 1%. CAST's estimates of protein efficiency were similar where comparable. For example, CAST estimated identical protein efficiencies for poultry in the United States of 31%, and Wirsenius estimated 31% for poultry efficiencies in North America and Oceania. Using the same regional comparisons, CAST estimated protein efficiency for pork at 19%, compared to 23% for Wirsenius, and identical beef protein conversion efficiencies in these regions of 8%. The biggest difference in comparable areas was the energy efficiency of beef, at 7% for CAST versus 2.5% for Wirsenius. We are skeptical of this particular CAST estimate. The differences between energy and protein efficiencies are almost always large for all livestock in all regions, and CAST's estimated energy and protein efficiencies for U.S. beef are close.

109. The principal adjustment is that we assume that all new grazing land must come from woody savannas or forests because native grasslands capable of being grazed are already used. We are aware of no significant areas of truly native grasslands that are not in use. There are areas of woody savanna, particularly in Africa, where grazing use is limited, mainly because of tsetse flies, and these areas have grasses that could be consumed, but converting them to cattle production involves significant clearing of the woody vegetation. When we evaluate diets in a particular country, we assume that food used in that country is generated according to 2010 trade patterns (e.g., that if 80% of a food is generated domestically and 20% is imported, the same will be true of new production).

110. In other words, we divide the one-time loss of emissions from land conversion by 20 to obtain land-use-change emissions and then add them to annual agricultural production emissions. This follows the European approach to evaluating land-use change for biofuels and provides one rough way of evaluating the costs of emissions over time to reflect the added value of earlier emissions mitigation.

111. GlobAgri-WRR model. More precisely, the per person land use and greenhouse gas effects of each diet, as modeled in GlobAgri and shown in Figures 7-7 and 7-12, are the marginal effects of adding one additional person to the world population in 2010. This is why the per person land-use change emissions are higher than the agricultural production emissions; because yields and trade patterns are held constant, GlobAgri estimates the annual emissions that would result from converting the additional land (roughly 0.5 hectares for the average world diet and roughly 1 hectare for the average U.S. diet) from natural ecosystems to agricultural production.

112. GlobAgri-WRR model.

113. In the United States, nearly all ruminant meat consumption is beef consumption; very little sheep and goat meat was consumed in the United States in 2010 (FAO 2019a).

114. World Bank (2016a) estimated emissions from energy use per person per year at 4.7 tons CO_2e.

115. We estimate U.S. dietary emissions in 2010 at 16.6 tons CO_2e per person per year. Total U.S. energy-related emissions of 5,582 million tons CO_2 (EIA 2015), when divided by a U.S. population of 309.3 million, equal per capita emissions of 18 tons CO_2e in 2010. Land-use-change emissions of 332 tons CO_2e are therefore equal to 18.4 times average U.S. per capita energy-related CO_2 emissions in 2010.

    Energy-related CO_2 emissions are those stemming from the burning of fossil fuels. These estimates differ in that the dietary land-use-change emissions include the global consequences of diets, while the energy-related emissions calculate only those emissions from energy use within the United States. Factoring in a portion of energy emissions associated with imported products increases those U.S. energy emissions somewhat. For example, Davis and Caldeira (2010) estimate that U.S. consumption-based CO_2 emissions (defined as the amount of emissions associated with the consumption of goods and services in a country, after accounting for imports and exports) were 22 tons per capita per year in 2004.

116. This chart differs from similar charts in earlier reports in this series because it shows our estimates of consumption, after deductions of waste in households in restaurants, rather than "food availability." Food availability is a category produced by FAO that is intended to reflect food reaching households and retailers.

117. The numbers of obese are based on data in Ng, Fleming, et al. (2014). Our analysis factors in estimated numbers of overweight and obese people in each region, assumes that obese people consume on average 500 more calories per person per day than a person of healthy weight, and that overweight people consume only half these additional calories (250 more calories per person per day). This estimate of extra calorie consumption is based on the best estimate of

the excess calorie consumption for U.S. obese adults (BMI over 35) of roughly 500 kcal/day (Hall et al. 2011a). That represents the increased calorie consumption to maintain obese conditions for U.S. adults, and is actually more than double the increased calorie consumption necessary to become obese. This estimate represents a revised view upward compared to the traditional view of only around 200 kcal/day, which did not account for the greater calorie intake required to maintain the larger body size of the overweight or obese. The 500 kcal/day assumes that all obese children have a similar overconsumption. Similarly, FAO has estimated that consumption of 2,700 to 3,000 kcal per person per day will lead to obesity by people with sedentary lifestyles (FAO 2004). Using the midpoint of 2,850 kcal, and assuming that an acceptable diet would consist of 2,350 kcal per person, we estimate that the elimination of obesity would reduce consumption by 500 kcal per person per day.

118. Authors' calculations from Ng, Fleming, et al. (2014). Regionally, the smallest caloric reductions occur in lower-income regions (e.g., 1% in sub-Saharan Africa) with the largest reductions in higher-income regions (e.g., 4% in the United States and Canada).

119. Searchinger, Hanson, Ranganathan, et al. (2013); Ranganathan et al. (2016).

120. Ng, Fleming, et al. (2014).

121. Skinner et al. (2018).

122. As discussed further in Course 4, the 2050 baseline projection assumes a 10% decrease in wild fish catch relative to 2010, and it assumes that all increases in global fish demand are met by aquaculture (thus farmed fish make up a larger proportion of total fish consumption by 2050).

123. These reductions set maximum thresholds of animal-based foods of 613 kcal per person per day for the 10% reduction and 399 kcal for the 30% reduction (Figure 6-8). They also reduced the global increase in animal-based food consumption between 2010 and 2050 from 68% (baseline) to 51% (10% reduction) and to 18% (30% reduction).

124. In order to be conservative, for the diet scenarios explored in this chapter, whenever land use in 2050 was reduced below 2010 levels, we set land-use-change emissions between 2010 and 2050 to zero (rather than assuming perfect restoration of all "liberated" lands back into native vegetation by 2050).

125. Ranganathan et al. (2016), Figure 10. Using data on UK vegetarian diets from Scarborough et al. (2014), Ranganathan et al. (2016) found that a scenario that halved U.S. meat and dairy consumption reduced the proportion of animal-based food calories to total calories to 14%, whereas the typical UK vegetarian in Scarborough et al. (2014) consumed 18% of their calories in the form of animal-based foods (including dairy and eggs, but not fish or meat).

126. Scarborough et al. (2014).

127. A 10% global cut, relative to 2050 baseline, set a threshold level of 373 calories of meat per person per day, slightly above the level of meat consumption in the United States in 2010 (Figure 6-9). A 30% global cut in meat requires a threshold of 238 calories of meat per day, slightly higher than per capita meat consumption in Russia in 2010. These scenarios reduced the global increase in meat consumption between 2010 and 2050 from 71% (baseline) to 54% (10% reduction) and to 20% (30% reduction).

128. GlobAgri-WRR model using source data from FAO (2019a).

129. In addition to a "less ruminant meat, shift to poultry and pork" scenario, we could have also modeled shifts to other nonmeat animal proteins, such as fish, dairy, or eggs. Because fish, dairy, and eggs are of a similar level of resource intensity as poultry and pork (more resource-intensive than plant proteins, and much less resource-intensive than ruminant meats), the results in terms of closure of the food, land use, and GHG emissions gaps would have been similar.

130. Springmann, Godfray, et al. (2016).

131. Willett et al. (2019), Springmann et al. (2018). These authors, however, did not assess changes in pastureland use under their healthy diet scenario, which would have certainly shown a large decline given the pronounced move away from ruminant meat and, to a lesser extent, away from dairy.

132. For example, Springmann, Godfray, et al. (2016) estimated that 97 percent of the GHG emissions reductions in their "healthy global diets" scenario were attributable to the reductions in red meat consumption (and we assume the vast majority of those reductions were due to reductions in ruminant meat consumption, since pork is of similar resource intensity to poultry).

133. For the calculations in this section, we used 2010 global average production efficiencies (shown in Figure 6-6). GlobAgri-WRR can also analyze the addition to the world of a person in the United States alone, which would assign more production to the United States because it would follow existing trade patterns. We followed the global average approach because we wished to analyze the consequences of other people adopting this diet globally.

134. The Vegetarian Diet scenario, which uses data from Scarborough et al. (2014), actually includes very small amounts of meat, as "vegetarians" were self-reported.

135. FAO (2019a).

136. Beattie et al. (2010); Tootelian and Ross (2000).

137. Larson and Story (2009). However, studies have shown that labeling can provide an incentive to food companies to reformulate products to make them healthier (Vyth et al. 2010; Variyam 2005).

138. Capacci et al. (2012).

139. Dumanovsky (2011).

140. Hammer et al. (2009).

141. Winter and Rossiter (1988); McDonald et al. (2002).

142. Thaler and Sunstein (2008); Garnett (2014); Bailey and Harper (2015); Wellesley et al. (2015).

143. Stummer (2003); Cornish Sardine Management Association (2015).

144. Reardon et al. (2003).

145. Reardon et al. (2003); Reardon and Timmer (2012).

146. Reardon and Timmer (2012).

147. Reardon et al. (2007).

148. Pingali (2007).

149. USDA/ERS (2014a).

150. Hawkes (2008) in Garnett and Wilkes (2014).

151. USDA/ERS (2014b).

152. DEFRA (2014).

153. Suher et al. (2016).

154. Turnwald et al. (2017).

155. Bacon and Krpan (2018).

156. Keats and Wiggins (2014).

157. Haley (2001).

158. For example, based on average U.S. retail prices in 2013, the price per gram of protein ranged from 0.9 cents for dried lentils, 1.1 cents for wheat flour, 1.2 cents for dried black beans, and 2.3 cents for dried white rice, to 2.7 cents for eggs, 2.9 cents for milk, 3.1 cents for fresh whole chicken, and 4.4 cents for ground beef. Authors' calculations based on USDA/ERS (2015a); USDA/ERS (2015b); BLS (2015); and USDA (2013a).See also Lusk and Norwood (2016).

159. Adjoian et al. (2017).

160. Arnold and Pickard (2013).

161. Corvalán et al. (2013); Jacobs (2018).

162. Sharp (2010), Chapter 12.

163. Sharp (2010), Chapter 12.

164. Robinson et al. (2014).

165. Ruby and Heine (2011); Rozin et al. (2012); Sobal (2005).

166. Lea et al. (2006).

167. House of Lords (2011); Reisch et al. (2013). Beattie et al. (2010); Tootelian and Ross (2000); Capacci et al. (2012); Dumanovsky (2011).

168. Downs et al. (2013).

169. USDA and HHS (2015).

170. Smith (2008).

171. Hickman (2008).

172. Videl (2014).

173. Jha (2013); Hanlon (2012).

174. Maastricht University (2014).

175. Bello (2013).

176. Purdy (2017).

177. Impossible Foods (2017).

178. Oregon State University (2015).

179. Gewin (2017).

180. Henry (2015).

181. Close (2014).

182. Black (2014); Mushroom Council (2016).

183. *Economist* (2015).

184. Nasdaq Global Newswire (2015).

185. Upadhyay (2016).

186. MarketLine (2014).

187. House of Lords (2011).

188. See, e.g., Health Care without Harm (2017); Friends of the Earth (2017).

189. Humane Society International (2013).

190. Ecorys (2014); Thow et al. (2014); Nordström and Thunström (2009); Hawkes (2012); Thow et al. (2010); Jensen and Smed (2013); Colchero et al. (2016).

191. Thow and Downs (2014); Nordström and Thunström (2009); Hawkes (2012).

192. Gallet (2010).

193. USDA/ERS (2015b).

194. Haley (2018).

195. Dumortier et al. (2012).

196. *Economist* (2012).

197. Gallet (2010).

198. Springmann, Mason-D'Croz, et al. (2016).

199. Dong and Lin (2009).

200. Pearson-Stuttard et al. (2017).

201. Although FAO has cited this 10% figure in some publications, its own published estimates of global fuelwood amount to only about 3%. For example, the 2008 fuelwood harvest reported by FAO in its 2011 *State of the World's Forests* report amounted to 1.87 billion cubic feet, which by conventional conversion factors should contain roughly 17.5 EJ, relative to 2010 global energy demand of around 500 EJ.

202. Many papers have estimated that charcoal production is a major source of forest degradation. For example, Sedano et al. (2016) estimated that charcoal production in Mozambique had effects on forest carbon comparable to those of agricultural expansion, and fuelwood and charcoal production are the main components of forest degradation in Africa generally. Hosonuma et al. (2012); Chidumayo and Gumbo (2013). See Vinya et al. (2011), which focuses on Zambia, as an example of REDD+ (Reduced Emissions from Deforestation and Forest Degradation) plans that try to address charcoal production.

203. Nijhuis (2017).

204. For a good graphic display of the recovery of European forests, see Noack (2014). For the global decline of conventional forms of bioenergy (the vast majority of which occurred in industrialized countries), see Krausmann et al. (2013). For a discussion of the role that declining wood use for energy had on the recovery of eastern U.S. forests, see Hanson et al. (2015).

205. EIA (2013).

206. EIA (2013).

207. EIA (2013).

208. 1 exajoule = 238,902,957,619,000 kilocalories.

209. Authors' calculations based on biofuel production estimates from the U.S. Energy Information Agency, published information from diverse sources of feedstocks for ethanol and biodiesel in different countries, standard conversion factors for estimating energy in different crops, and data from FAOSTAT on total 2010 crop production. These calculations do not include the portion of food crops that produce useable by-products.

210. A 10% transportation fuel target would generate 2.5% of global final delivered energy on a gross basis, but because ethanol and biodiesel production requires more energy to produce than gasoline and diesel, the net gain would probably be no more than 2%.

211. GlobAgri-WRR model.

212. Haberl et al. (2010).

213. This calculation assumes 395 bushels of maize per hectare (equivalent to about 160 bushels per acre), 2.8 gallons of ethanol per bushel, and thus 1,106 gallons per hectare. It also assumes that 30% of the maize traditionally enters the animal feed supply chain as an ethanol by-product. This implies that 0.7 hectares produce the 1,106 gallons, and thus a full hectare would produce 1,580 gallons, which rounds up to 1,600 gallons.

214. The yields used by the EPA are described in Plevin (2010).

215. To match the yields of maize ethanol, perennial grasses must achieve yields of 16 metric tons of dry matter per hectare per year (t/ha/yr), and very high conversion efficiencies of 100 gallons (376 liters) per metric ton. Hudiburg et al. (2014) estimates that replacing maize and soybean rotations with switchgrass in the United States would achieve yields of 9.2 tons per hectare and miscanthus would achieve yields of 17.2 tons per hectare. The EPA estimated average switchgrass yields of 8.8 tons per hectare (Plevin [2010]), and average switchgrass yields today are 4.4 t/ha/year to 8.8 tons per hectare (Schmer et al. 2010). Although miscanthus might achieve slightly higher yields that maize, it presents a number of challenges, including reproducing rhizomatically, so that new rhizomes must be dug up and separated from existing plants and replanted elsewhere.

216. Searle and Malins (2014).

217. Searle and Malins (2014).

218. International Energy Agency Statistics (2018).

219. Chum et al. (2011); Creutzig et al. (2014).

220. The International Energy Agency, for example, has called for supplying 20% of global energy by 2050 with biomass. Although ambiguous, the IEA (2017) encourages this goal on top of any traditional uses of biomass for fuelwood.

221. This 20% is based on projected global energy use of around 900 EJ in 2050 (OECD 2011). Although 20% of 900 is only 180, biomass cannot be used as efficiently as fossil fuels, so more biomass would be needed. Exactly how much would depend on the form in which the bioenergy or fossil fuel is used. Primary energy measures the energy in the original fuel, e.g., wood or crude oil. Delivered energy is the energy in a useable form, such as electricity, gasoline, or ethanol. There is substantial loss of energy in the conversion process because of the energy needed to mine, produce, or refine feedstocks into liquid fuel, or the energy lost (primarily through waste heat) in turning a fuel into electricity. Our assumption is that, overall, the conversion of biomass into delivered energy would occur at 80% of the efficiency of fossil fuels, which is optimistic for bioenergy. This calculation looks at the total amount of useable energy generated, such as the energy in ethanol, versus the total biomass and fossil energy used to generate it. For calculations of the relative efficiency of converting crude oil and biomass into useable energy forms, see JRC (2011), chapter 9.

222. IPCC (2014); Rogelj et al. (2018).

223. Technically, this estimate is based on estimates of total biomass harvest for the year 2000 estimated in Haberl et al. (2007). These harvests in dry tons of biomass are multiplied by an average energy content of 18.5 GJ per ton of dry matter. There has probably been some modest growth since that time. A similar figure was used by the IPCC in Chum et al. (2011).

224. Malhi et al. (2002). Failing to maintain these carbon stocks by adding more carbon from new plant growth, as microorganisms consume and release the carbon to the air from old biomass, would increase atmospheric carbon dioxide concentrations and contribute to climate change.

225. Searchinger (2010).

226. Moomaw and Moreira (2001), Table 3.31.

227. Souza et al. (2015); van Vuuren et al. (2009); Hoogwijk et al. (2005).

228. Papers estimating the effects of bioenergy in woody savannas while counting the lost carbon have consistently found long periods before bioenergy would reduce emissions, and include Fargione et al. (2008); Gibbs et al. (2008); and Searchinger, Estes, Thornton, et al. (2015).

229. Smeets et al. (2007); Davis et al. (2012); Cowie et al. (2018).

230. See papers summarized in Searchinger et al. (2018). Researchers have made this finding while analyzing a broad range of forest types and a broad range of harvesting regimes. See, e.g., Holtsmark (2012); Hudiburg et al. (2011); Manomet Center for Conservation Sciences (2010); and Mitchell et al. (2012). The basic reason that harvesting forests for bioenergy leads to a carbon debt is that each ton of carbon in a forest that is harvested only leads to a quarter to a third of a ton of carbon savings in its typical use for electricity generation. This is because (a) some of the live carbon in roots and branches is left behind to decompose, and (b) burning wood is less efficient than burning fossil fuels to generate electricity. In addition, young or middle-aged forests, which are most frequently harvested in commercial operations, would typically grow faster and therefore accumulate more carbon for at least some years than a newly regrowing forest, which starts with seedlings or natural regeneration. That factor increases the carbon debt of using trees for energy. Eventually, forests that are not cut reach slow rates of growth, and regrowing forests will start to catch up. Eventually, the GHG reductions from reduced fossil fuel use will equal and ultimately exceed the increase in carbon in the air from the transfer from the forest. At that point, there are GHG benefits. But governments that have explicitly recognized and addressed this accounting have generally agreed to account for these bioenergy impacts in periods of 20 or 30 years, up to which bioenergy leads to likely emissions increases.

    One source of confusion in this analysis lies in the difference between the rate of uptake in any given year and the total carbon stored. Cutting a mature forest will typically increase the rate of carbon uptake (at least over many decades as a new forest grows), but at the expense of a large initial loss of carbon. And it will still result in a net release of carbon from the forest, and even a net release of carbon for decades, even when accounting for the reductions in fossil carbon emissions from the bioenergy use.

231. The exception is in cases where a tract of land generates biomass feedstocks that are additional to what otherwise would have grown, such as if a farmer were to plant winter cover crops during fallow seasons on some cropland and use those crops for bioenergy. Searchinger et al. (2018).

232. Agostini et al. (2014).

233. Although bioenergy is not typically called an "offset," offsetting is the physical mechanism by which bioenergy reduces carbon dioxide in the atmosphere. The principle of "additionality" is the same as for a regulatory offset for climate change. In regulatory systems, power plants are sometimes allowed to offset their emissions from burning coal by planting a new forest elsewhere on the theory that the carbon absorbed and stored by the additional trees offsets the carbon released from the coal. But a power plant cannot claim an offset by pointing to a forest that would grow anyway. Only *additional* forest growth counts for a forest-planting offset; the same principle is true for bioenergy. In effect, a forest-planting offset uses the additional plant growth to store more carbon in trees to offset fossil-based energy emissions, while bioenergy uses the additional plant growth to replace fossil fuels and leave more carbon underground. The concept of "additional" is the key to both forms of offsets.

234. Searchinger (2009); Haberl et al. (2012).

235. For more examples of bioenergy greenhouse gas accounting scenarios, see Appendix B in Searchinger and Heimlich (2015).

236. For two comparisons, see Decara et al. (2012) and Edwards et al. (2011).

237. Searchinger, Edwards, Mulligan, et al. (2015).

238. HLPE (2013); Dorward (2012).

239. See the discussion in Searchinger, Edwards, Mulligan, et al. (2015) of the IFPRI model, and the discussion in Berry (2011) of the GTAP model. Berry (2011) also includes a good discussion of the limited real economic evidence that higher demands spur yield growth.

240. See discussion in the supplement of Searchinger, Edwards, Mulligan, et al. (2015).

241. Berry (2011); Berry and Schlenker (2011).

242. Searchinger, Edwards, Mulligan, et al. (2015) discuss the IFPRI model used by the European Commission, which is structured so that the vast majority of increases in crop production to replace crops diverted to biofuels results from additional yield increases by farmers. Even so, estimated greenhouse gas reductions from grain-based biofuels are modest.

243. Dumortier et al. (2011), for example, assumed that expanded cropland in the United States and much of the world would first use idle cropland, which is the equivalent of assuming that expanded crop production results from an increase in cropping intensity (the percentage of cropland cropped in a given year).

244. World croplands continually shift and truly abandoned cropland regenerates carbon. There is also a category of land that comes in and out of crop production in part in response to fluctuations in demand and yields and in part in response to physical limitations on crop growth every year. Those fluctuations will continue to exist in a future with more biofuels, and that means there will always be this kind of cropland that comes in and out of production. The argument that biofuels will use this cropland confuses a structural change in demand with the effect of annual fluctuations in the demand for cropland. E4tech (2010) made similar assumptions for European biofuel production.

245. This assumption, for example, was implicitly built into the regulatory analysis by the EPA for its biofuel greenhouse gas regulations, and was also part of the assumptions in E4tech (2010). It derives from satellite studies that identify extensive "savanna" in Indonesia, while the savannas in Indonesia are in fact originally forest that has been cut and is typically in some kind of mosaic use if not in some level of reforestation.

246. Searchinger et al. (2017) review 12 modeling analyses of BECCS. In 9 of them, biomass is automatically treated as carbon neutral and effects on terrestrial carbon storage are not counted. In 3 models, the modelers project potential but only at high cost and only based on a number of unlikely conditions, including that governments worldwide perfectly protect forests and other high-carbon lands. The combination of this protection and high bioenergy demand saves land in the different models either because the cost of ruminant products rises so high that hundreds of millions of hectares of grazing land are converted to bioenergy or because governments also spend large sums of money to intensify agricultural production on existing agricultural land.

247. Searchinger et al. (2017).

248. When starches are fermented into ethanol, one gram of carbon is lost for each two grams of carbon in the ethanol, as shown in Searchinger, Edwards, et al. (2015).

249. Haberl et al. (2010).

250. Haberl et al. (2010) discusses the various estimates.

251. The Haberl et al. (2011) estimate is of 25 EJ of unused residues, which could generate 12.5 EJ of transportation biofuels according to high conversion efficiency estimates.

252. Smil (1999) provides a compelling analysis of the uses and needs for crop residues worldwide. Even in the United States, Blanco-Canqui and Lal (2009) found that at least in a part of the U.S. maize belt, the removal of residues resulted in substantially negative effects on maize yields.

253. Liska et al. (2014). Many studies have estimated conditions under which the removal of residues might not reduce soil carbon, but the more salient factor is the difference in soil carbon with and without the residues. If the residues would add to soil carbon, then their removal reduces carbon sequestration.

254. Author's calculations based on data from FAOSTAT and assumption that all tops and branches are available and equal to 30% of harvested roundwood.

255. Booth (2018).

256. Haberl et al. (2010).

257. IEA (2017).

258. Haberl et al. (2010).

259. Kladivko et al. (2014).

260. Hughes et al. (2012).

261. NRC (2012), 2.

262. Wigmosta et al. (2011). The water challenge exists in large part because algal biofuel production is expensive (estimated at US$300–US$2,600 per barrel in 2010, in Hannon et al. 2010), and strategies to achieve a reasonable cost require production in open ponds, from which much water evaporates. Although some other estimates of potential water use are lower, nearly all still estimate the need for large quantities, according to the NRC (2012). One possibility might be to use saline waters, but NRC (2012) concluded that some fresh water would be necessary.

263. Moody et al. (2014).

264. Waite et al. (2014).

265. See note 211.

266. Kissinger et al. (2012).

267. For example, one paper estimated land-use demands to meet existing electricity production in the United States in 2005 as varying from 1% to 9% for states east of the Mississippi (Denholm and Margolies 2008). This figure would obviously need to increase to meet the greater electrical generation needs of 2014. But it would decline if power were imported from the sunnier, drier, and less populated states in the U.S. West, as PV conversion efficiencies grow (and they have grown greatly even since 2008) and as costs come down, which permits more dense packing of PV cells in tilted configurations.

268. Authors' calculations. These numbers require information only about the solar radiation received in an area of production, the crop or biomass yields, the quantities of biofuels per ton of crop, and the energy of the biofuel. Brazilian sugarcane ethanol numbers assume average solar radiation of 2,000 kilowatt hours per square meter per

year in Brazilian sugarcane producing areas based on Solargis global solar radiation map, which yields 72,000 GJ/ha/yr. (Map available at http://solargis.info/doc/_pics/freemaps/1000px/ghi/SolarGIS-Solar-map-World-map-en.png). It also assumes a yield of 80 metric tons of sugarcane per hectare per year, dry matter (DM)content of 27%, and an energy content of 17 GJ/tDM, for 367.2 GJ/ha/yr. If sugarcane is produced every year, then it generates a 0.51% efficiency of the energy in sugarcane relative to solar radiation, but if it is produced only seven of eight years to factor in replanting, the efficiency is 0.45%. Assuming 75 liters per ton of sugarcane and 23.4 Mj/l, that results in 140 GJ/ha/yr of energy in ethanol. The result is 0.19% assuming both annual production and 100% of fossil fuels used in production are offset by an electricity energy credit from burning sugarcane bagasse. The energy in the biomass other than sugar, the bagasse, is therefore counted in this net calculation.

269. For maize ethanol grown in Iowa, the figures are around 0.3% into biomass and 0.15% into ethanol, even when fully accounting for the feed by-product. These figures, calculated for Iowa, assume 9.7 tons per hectare (180 bushels per acre) of maize, 487 liters of ethanol per ton (2.8 gallons per bushel), a 35% reduction in land-use estimates to recognize feed by-product, 23.4 MJ/liter of ethanol, and solar radiation of 1,600 kWh per square meter per year (~57,500 GJ/hectare/yr). This calculation also assumes optimistically that the net energy yield of maize ethanol is 50% after accounting for all the energy used in its production.

    For cellulosic ethanol, using the highest projected future switchgrass yield by the Department of Energy at any point in the United States of 24 tCM/ha/yr, Geyer (2013), and the assumption of 100 gallons of ethanol per ton of dry matter implies a conversion efficiency of solar radiation into fast-growing grasses of perhaps 0.7%, and into ethanol of 0.35%. (Switching to less productive land would reduce this efficiency because the solar energy would remain generally the same or grow but the biomass output would decrease.)

270. Calculations for rooftop solar and solar farms differ. This figure for rooftop solar assumes a 16% photovoltaic cell, a 20% loss in actual operation of a rooftop solar installation, including losses from conversion of DC power to AC power and a further 11% cost for paying back the energy used to construct and install the system. Photovoltaic efficiencies and payback times are from Fthenakis (2012), and the 20% efficiency loss is based on typical conversion cost figures using the PVWatts calculator website by the National Renewable Energy Laboratory of the U.S. Department of Energy (http://pvwatts.nrel.gov/pvwatts.php).

271. See the explanation in the following note.

272. This calculation was originally performed for Installment 4 in this series, "Avoiding Bioenergy Competition for Food Crops and Land" (Searchinger and Heimlich 2015) and was subsequently published in peer-reviewed literature in Searchinger et al. (2017). The supplement to that paper explains this calculation as follows:

    The global solar energy vs bioenergy comparative calculation was based on a GIS (geographic information systems) analysis, which compared the net energy output of potential bioenergy production against the output of photovoltaics. The area analyzed excluded area covered permanently by ice and the driest deserts because such areas could not produce bioenergy although they could produce solar energy.

    Biomass production was estimated by cell using a modified version of the LPJmL model (Beringer et al. 2011; Searchinger, Estes, Thornton, et al. 2015) that simulates energy crop productivities comparable to net primary productivity (NPP). This model adjusts LPJmL biomass production to match the NPP of the native vegetation of a cell. In general, agricultural biomass production rarely exceeds that of native vegetation (Field et al. 2008; Haberl et al. 2013). We further assumed production of 379 liters per metric ton of biomass as discussed above, and that all energy used to produce and transport biomass and refine it into ethanol would be either provided by the biomass itself or offset by electricity by-products. Using ethanol, these assumptions imply that 47 percent of the gross energy in the biomass becomes useable energy.

    For PV production, this analysis used a global data set of Global Horizontal Irradiance (GHI) available from the U.S. National Renewable Energy Laboratory. The GHI is the total solar radiation received by a horizontal PV cell and is a weighted sum of the Direct Normal Irradiance (DNI) and the diffuse light (all sunlight that comes to the panel from other areas of the sky except the narrow beam from the sun. (https://eosweb.larc.nasa.gov/sse/global/text/22yr_swv_dwn).

    We used a net efficiency of 10% for solar radiation. This efficiency is based on the 17% PV efficiency of standard PV cells today, and an 85% performance ratio (halfway between standard 80% and 90% ratios today) (ISE 2016), plus our estimate from above that 11% of the energy generated by the PV is used to pay back the energy used to produce and install the PV. We then further assume a coverage factor of 78%. As noted above, coverage factors can vary greatly for PV in practice, in part because PV is typically installed on infertile land, for which land area needs are not a concern. As the primary purpose of this analysis is to compare PV on land that might grow bioenergy reasonably well, we assume that some effort would be made not to use land unnecessarily. Where tilting is still desired, for example, solar arrays, can be spaced to allow grazing to occur between arrays, and as they become cheaper, tilting becomes less important. With space constraints varying from 50% to nearly full coverage, we deliberately chose 78% in part to generate an even 10% to avoid creating a false sense of precision in this analysis.

Although we are counting energy used for PV to obtain net efficiencies, we are not incorporating production energy use into the efficiencies for bioenergy.

This analysis calculated that on 73% of the world's land, the useable energy output of PV would exceed that of bioenergy by a ratio of more than 100 to 1. For the remaining quarter of the world's land, the average ratio is still 85 to 1, and the lowest ratio is 40 to 1. This relatively "better" land for bioenergy consists primarily of areas whose native vegetation would have been dense forest, and which today includes the world's densest remaining tropical forests and the North American and European areas of the world's best farmland. This land is therefore the land most valuable for carbon storage, food, and timber. If energy production chose from the top 25% of land with the highest efficiency advantage for PV, the minimum ratio of PV to bioenergy production would be 5,000 to 1.

This analysis should be viewed only as illustrative. At finer resolution, much land, such as some steeply sloped land, would be suitable neither for biomass production nor for PV.

273. See Table 3 in Searchinger et al. (2017).

274. Searchinger et al. (2017).

275. Calculations are shown in Searchinger et al. (2017).

276. These numbers actually understate the real differences in efficiency for three reasons. First, the cellulosic ethanol figures compare solar PV conversion efficiencies in commercial operation today with ethanol production that assumes large future improvements both in growing grasses or trees and in refining them into ethanol. Although progress in cellulosic ethanol has been slow, increases in solar PV conversion efficiencies have been proceeding at a rapid rate, and if and when cellulosic bioenergy achieves the efficiencies we cite, PV land-use efficiencies will very likely have grown as well.

    Second, solar cells do not require land with plenty of water and good soils. Because of the increases in global demand for food and timber, highly productive lands are already needed for these uses, not for energy generation. On less fertile land, the efficiency of bioenergy drops greatly, but the efficiency of converting the sun's rays to electricity via solar PV is unchanged. And the overall performance and economics of solar PV would even improve if the less fertile land has more solar radiation per square meter than more fertile lands—for example, the U.S. desert West relative to the U.S. maize belt. Even assuming high future cellulosic yields, PV systems available today would generate more than 100 times the useable energy per hectare over a majority of the United States. Because the United States has highly productive agriculture, it is reasonable to assume that this figure would be equally true of the globe.

    Third, at least for transportation, shifting to solar implies even greater efficiency gains. Internal combustion engines convert at best around 20% of the energy in either fossil fuels or biofuels into motion, while electric engines today convert around 60%, a threefold increase. Today, much of that increased efficiency is lost by the high energy needs for building car batteries. But if battery production can become more energy efficient and batteries longer lasting, a combination of solar energy and electric engines could become 200–300 times more land-use efficient than biofuels.

277. IEA (2014).

278. See HLPE (2013).

279. Steenblik (2007); Koplow (2007); Koplow (2009).

280. Sperling and Yeh (2010).

281. Searchinger, Edwards, Mulligan, et al. (2015).

282. Kitzing et al. (2012).

283. IEA (2013); Brack and Hewitt (2014).

284. Bernier and Paré (2013); Holtsmark (2012); Hudiburg et al. (2011); McKechnie et al. (2011); Mitchell et al. (2012); Manomet Center for Conservation Sciences (2010); Zanchi et al. (2012).

285. Authors' calculations using FAO (2019a). This figure is calculated by using FAO's total reported timber harvest, using conversion factors to estimate their energy content, and comparing them to estimates of global energy consumption. See also a February 9, 2015, letter to U.S. EPA Administrator Gina McCarthy by more than 70 scientists, available at http://www.caryinstitute.org/sites/default/files/public/downloads/2015_ltr_carbon_biomass.pdf.

286. Massachusetts regulations can be found at http://www.mass.gov/eea/docs/doer/rps-aps/rps-class-i-regulation-225-cmr-14-00.pdf. The approach properly calculates both the savings in fossil fuel carbon and the reductions, and therefore emissions, from harvesting trees and calculates the balance over a period of 20 years.

287. Searchinger et al. (2009). See Appendix A in Searchinger and Heimlich (2015).

288. For different estimates, see Mallory et al. (2012); Tyner (2010); and Abbott (2012).

289. Abbott (2012).

290. UNDESA (2017). Total population by major area, region, and country ("medium-fertility variant" or medium growth scenario).

291. The fertility rate refers to the number of children per woman. More specifically, the total fertility rate is "the average number of children a hypothetical cohort of women would have at the end of their reproductive period if they were subject during their whole lives to the fertility rates of a given period and if they were not subject to mortality" (UNDESA 2017).

292. Statistics New Zealand (2013). http://www2.stats.govt.nz/domino/external/omni/omni.nsf/wwwglsry/replacement+level.

The level allows for the sex ratio at birth (roughly 105 males born for every 100 females) and for some mortality of females between birth and childbearing. The actual replacement level will vary slightly from country to country and over time depending on the sex ratio at birth and mortality rates.

293. UNDESA (2017). Total population by major area, region, and country (medium-fertility variant).

294. For studies showing strong statistical correlations between declines in fertility and increases in girls' education, increased access to family planning, and declines in infant mortality, see Shapiro and Gebreselassie (2008); Leeson and Harper (2012); and Upadhyay and Karasek (2010).

295. The correlation between female education, a decrease in fertility rates, and an increase in contraceptive use is well documented in both developed and developing countries, including across sub-Saharan Africa. For example, see Shapiro and Gebreselassie (2008); Bbaale and Mpuga (2011); and Bloom and Canning (2004). Shapiro and Gebreselassie (2008); Bloom and Canning (2004); and Bbaale and Mpuga (2011) also show that education is correlated with declining family size and increased use of condoms in Uganda.

296. Ethiopia Central Statistical Agency (2017).

297. Schmidt et al. (2012).

298. Chaaban and Cunningham (2011).

299. Shapiro and Gebreselassie (2008); Bongaarts (2005); Bbaale and Guloba (2011); Bbaale and Mpuga (2011).

300. UNDESA (2015). According to Sing and Darroch (2012), 58 million women in Africa—including 53 million in sub-Saharan Africa—would like to space or limit their next birth but do not use contraception.

301. WHO and UNICEF (2013).

302. Shapiro and Gebreselassie (2008) found that in 24 sub-Saharan African countries, progress in women's education and reductions in infant and child mortality were the key factors contributing to sustained declines in fertility rates since the early 1990s. They also found that in countries where these education and mortality indicators had stopped improving or were deteriorating, fertility rates tended to stall instead of drop further. Hossain et al. (2005) found that reduced mortality rates correlated with reduced fertility in Bangladesh.

303. WHO (2013a); WHO (2013b); CIA (2013).

304. Pool (2007).

305. Bloom et al. (2003); Bloom and Williamson (1998); Bloom et al. (2000); Mason (2001). Locations where the demographic dividend contributed to economic growth include Hong Kong, Malaysia, Singapore, South Korea, Taiwan, and Thailand.

306. Sippel et al. (2011).

307. According to UNDESA (2017), the "low variant" simply uses a projection of 0.5 children below the fertility rates in the "medium variant" over most of the projection period—starting from a downward adjustment of -0.25 child from 2015 to 2020, -0.4 child from 2020 to 2025, and -0.5 child from 2025 onward.

308. UNDESA (2017). This replacement level (2.16) is higher than 2.1, likely due to higher-than-global-average rates of female infant and child mortality in sub-Saharan Africa.

309. To estimate the lower population under this scenario, we made several assumptions. We first compared UNDESA's (2017) "high-fertility" scenario for sub-Saharan Africa (3.7 fertility rate) to its "medium-fertility" scenario (3.2 fertility rate) and found a difference in population of 226 million people in 2050 between the two scenarios. We then compared the "medium-fertility" scenario to the "low-fertility" scenario and found a difference in population of 216 million people. We then assumed that the population difference between a "low-fertility" and a "replacement fertility" scenario with a 2.16 fertility rate would be proportional to the differences between "high fertility" and "medium fertility," and between "medium fertility" and "low fertility," estimating a population difference of 230 million people between "low fertility" and "replacement-level fertility." We distributed that population difference of 230 million people (across sub-Saharan Africa) proportionally across all countries. The "replacement-level fertility" scenario led to a population of 1.8 billion in sub-Saharan Africa in 2050—very similar to an earlier estimate of 1.76 billion by the Oxford Institute of Population Ageing for a paper earlier in this report series (Searchinger, Hanson, Waite, et al. 2013).

310. Authors' calculations from GlobAgri-WRR model. Projected growth in crop calorie production in sub-Saharan Africa between 2010 and 2050 is approximately 1,840 trillion kcal.

311. Robinson (2016) notes that two-thirds of sub-Saharan African countries adopted national population policies since the 1980s to reduce population growth, and that countries with such policies experienced statistically greater declines in fertility rates between 1987 and 2002 than those without.

312. Shapiro and Gebreselassie (2008). The 14 countries with a declining trend in national total fertility rates between the 1990s and mid-2000s were Benin, Burkina Faso, Chad, Côte d'Ivoire, Eritrea, Ethiopia, Madagascar, Malawi, Namibia, Nigeria, Senegal, Togo, Zambia, and Zimbabwe. Three countries (Mali, Niger, and Uganda) were classified as "pre-fertility transition," with no significant declines in fertility rates; and seven countries were classified as "stalled fertility decline," with fertility rates that had initially declined but then stalled during the study period. Across all countries, fertility declines tended to be stronger in urban areas.

313. UNDESA (2013). Since this 2013 publication, the United Nations has twice revised sub-Saharan Africa's projected population upward (in 2015 and 2017), presumably for the same reasons.

314. World Bank (2011a).

315. Athena Ballesteros (senior associate, Institutions and Governance Program, World Resources Institute), personal communication, July 12, 2013.

316. Oxfam (2007); Inter Press Service (2016).

317. Pingali et al. (2008); Lynd et al. (2015); Lynd and Woods (2011).

318. HLPE (2011); Wright (2014).

319. Oxfam (2012); ActionAid (2012).

320. Pingali et al. (2008).

321. Lau et al. (2015).

322. World Bank (2008).

323. Dorward (2013).

324. World Bank overview of poverty numbers, available at http://www.worldbank.org/en/topic/poverty/overview.

325. Filipski and Covarrubia (2010); Jayne et al. (2010).

326. Dorward (2012); Ivanic et al. (2011).

327. Headey (2014); Jacoby (2013); Ivanic and Martin (2014).

328. FAO (2012b), 104, Fig. 33; van Ittersum et al. (2016).

329. See discussion in Searchinger, Edwards, Mulligan, et al. (2015). When there are independent (exogenous) sources of growth in demand for crops, crop prices rise as a consequence. These price increases stimulate additional supply and production by farmers, and reduced demand and less consumption by preexisting consumers. The percentage of the crops that are not replaced due to reduced consumption depends on the ratio between these responses, which is reflected in the ratio of the supply and demand elasticities. Although there is some uncertainty about those elasticities, estimates of individual crop supply and demand elasticities usually place the demand response as lower than the supply response but still a substantial fraction of that response. For typical estimated supply and demand elasticities, see elasticities referenced in Hochman et al. (2014). One paper (Roberts and Schlenker 2013) estimated the global supply and demand responses for calories from the world's major crops and indicated that 20% of crops going to satisfy new demands will not be replaced.

330. HLPE (2011); Muhammad et al. (2011).

331. Bobenrieth et al. (2013). The trends in crop prices discussed in this paper provide an excellent example and reflect the fact that demand growth that results in temporary shortages has a greater price effect in the short term than the long term. See also discussion in Wright (2014) and in the supplement to Searchinger, Edwards, Mulligan, et al. (2015).

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PHOTO CREDITS

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COURSE 2

Increase Food Production without Expanding Agricultural Land

In addition to the demand-reduction measures addressed in Course 1, the world must boost the output of food on existing agricultural land. To approach the goal of net-zero expansion of agricultural land, improvements in crop and livestock productivity must exceed historical rates of yield gains. Chapter 10 assesses the land-use challenge, based on recent trend lines. Chapters 11–16 discuss possible ways to increase food production per hectare while adapting to climate change.

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CHAPTER 10

ASSESSING THE CHALLENGE OF LIMITING AGRICULTURAL LAND EXPANSION

How hard will it be to stop net expansion of agricultural land? This chapter evaluates projections by other researchers of changes in land use and explains why we consider the most optimistic projections to be too optimistic. We discuss estimates of "yield gaps," which attempt to measure the potential of farmers to increase yields given current crop varieties. Finally, we examine conflicting data about recent land-cover change and agricultural expansion to determine what they imply for the future.

The Challenge

The baseline scenario we use to define our "gaps" assumes the continuation of crop and pasture yield gains similar to those achieved in the 50 years since the Food and Agriculture Organization of the United Nations (FAO) first began estimating global yields in 1961. But even achieving such baseline yield gains will be difficult because many of the major transformative factors that drove yield gains for these decades—a period that encompassed the Green Revolution—have already been heavily used. For cropland, these transformations have come in three areas:

- **Fertilizers.** Farmers worldwide used very little synthetic fertilizer in 1960. Today, most of the world heavily exploits synthetic fertilizers, and some countries apply far more than needed. Only sub-Saharan Africa as a region uses little fertilizer, and it could make large gains by applying more.[1]
- **Irrigation.** From 1962 to 2006, irrigation area roughly doubled.[2] However, because few additional areas remain that can plausibly be irrigated with available water, FAO projects that irrigated land will expand by only an additional 7 percent between 2006 and 2050.[3]
- **Seeds.** In 1962, most of the world used seeds improved only by farmers. But in the subsequent five decades, much of the world adopted scientifically bred seeds, although use of improved seeds remains low in Africa.[4]

Although technology is still improving, the agricultural community will have a hard time matching the effect of introducing—for the first time—such fundamental technologies as fertilizers, irrigation, and scientifically bred seeds.

A major factor in the improvement of pasture and the efficiency of livestock production has been the replacement of animal power with fossil fuel power. In much of the world, even in 1960, animal power played a major role in agriculture and transportation. Switching to fossil fuels reduced the need for vast areas of pasture that would have been devoted to grazing and growing feed for animals. Fossil fuels also reduced the energy and therefore feed burden on multipurpose animals, allowing them to use the energy in their feed exclusively for building weight or producing milk rather than for producing power. Although the effects of these transformations have been quantitatively estimated carefully in only a few countries,[5] these transformations have occurred worldwide to a greater or lesser extent.

The shifting of agricultural production toward developing countries presents another yield challenge. Because food demand is growing mostly in these countries, and most of the demand will be met through domestic production rather than through imports, the share of global cropland located in developing countries is projected to grow. Average yields in those countries currently are lower than they are in the developed world. This shift in cropland toward developing countries thus will drag down global average yields until developing world yields catch up. For example, even if annual maize yields were to roughly triple in East Africa between 2010 and 2050, every additional hectare produced in Africa would still generate only slightly more than half the yield that a U.S. hectare produced in 2010.[6]

Even matching historical rates of yield growth overall will not be enough. Absent efforts to reduce growth in food demand, the amount of absolute growth in annual food production that will be needed each year from 2010 to 2050 is larger than the increase in food production that was achieved each year in the previous 50 years. And between 1962 and 2006, even though yield growth supplied 80 percent of all the growth in crop production (measured by weight), cropland area still expanded by 220–250 million hectares (Mha), equivalent to roughly 30 percent of the continental United States and more than total U.S. cropland.[7] Demand for milk and ruminant meat is also likely to grow at a substantially faster rate in the next four decades than it did in the previous five decades.[8] Therefore, going forward, both crop output per hectare and milk and meat output from ruminants per hectare must grow each year more than they did historically if we are to avoid net land-use expansion.

Table 10-1 | Selected projections of future agricultural land requirements

FEATURE	OECD / IMAGE	FAO	GLOBIOM	BAJZELJ ET AL.	TILMAN ET AL.	GLOBAGRI-WRR (THIS REPORT)
Time period	2010–50	2006–50	2000–50	2009–50	2005–50	2010–50
Cropland	-8 Mha	+69 Mha	+266 Mha	+655 Mha	+1,000 Mha	+192 Mha
Pastureland	-52 Mha	N/A	+121 Mha	+426 Mha	N/A	+401 Mha
Natural ecosystems	N/A	N/A	-503 Mha gross	N/A	N/A	-593 Mha net
Comment	Cropland increase of 110 Mha from 2010 to 2030, but net decline of 8 Mha by 2050	Cropland increase of 107 Mha in tropics, offset by decline of 48 Mha in temperate zone Projection on low side because 2050 UN population projections have since grown by 0.6 billion people	Decline in natural ecosystems offset by 103 Mha of plantation forest growth	Based on the continuing growth of crop and pasture yields at historical rates	Extrapolation from current trend lines in yield growth, income growth, and demand for crop calories	See Chapter 2 for assumptions

Note: N/A signifies that data are not available or not discussed in the respective study.
Sources: GLOBIOM analysis prepared by Schneider et al. (2011); FAO projection from Alexandratos and Bruinsma (2012); OECD projection prepared by the Netherlands Environmental Assessment Agency and reported in OECD (2011); Bajzelj et al. (2014); and Tilman et al. (2011).

Understanding Other Estimates of Agricultural Land Expansion

As with our own GlobAgri-WRR projections, most other agricultural modeling teams project large growth in agricultural area in their baseline 2050 scenarios (Table 10-1). Schmitz et al. (2014) compared 10 separate agro-economic models of cropland expansion, using similar population assumptions to ours. Six of the 10 model results projected an amount of cropland expansion at least as large as that in our baseline while only one projected a decrease.[9] Similarly, five of the eight economic models that made pasture area projections estimated increases in pasture area, with the largest estimate of approximately 400 Mha coming from the Global Biosphere Management Model (GLOBIOM) runs used at the time.[10]

Noneconomic models and projections using recent trend lines tend to predict even larger expansion of agricultural land. For example, Bajzelj et al. (2014) estimate a total of 1.1 billion ha of cropland and pastureland expansion between 2009 and 2050,[11] Tilman and Clark (2014) project a 600 Mha increase in cropland alone, and an earlier projection of cropland expansion by Tilman et al. (2011) was even larger, at roughly 1 billion ha (in part due to substantially higher meat demand projections at the time).[12]

Some analyses are much more optimistic. Of the agro-economic models compared in Schmitz et al. (2014), one projected a decline in cropland area, and three models projected declines in pastureland.[13] A 2011 modeling analysis by the Organisation for Economic Co-operation and Development (OECD) using the Integrated Model to Assess the Global Environment (IMAGE) predicted a very small decline in cropland area by 2050, despite increases until 2030.[14] The FAO projection in 2012 foresaw only modest net cropland expansion of 69 Mha.

Although no one can know for certain what future growth will be, we consider key parts of the analyses underlying the more optimistic baseline projections to be too optimistic because of their reliance on out-of-date population estimates or overly optimistic yield growth estimates.

Estimates of Yield Growth May Be Overly Optimistic

Population estimates. Some of the more optimistic projections are now out of date because population projections have been revised upward since the original analysis was completed. For example, the 2012 FAO projection used UN population projections of 9.1 billion for 2050, while the most recent midlevel UN projections estimate 9.8 billion people by 2050.[15] As a result, the amount of projected population growth between 2010 and 2050 is now nearly one-third higher than previously estimated. Because we use FAO projected yields in 2050 and account for the larger food demands of a higher population, our cropland expansion estimates are higher.



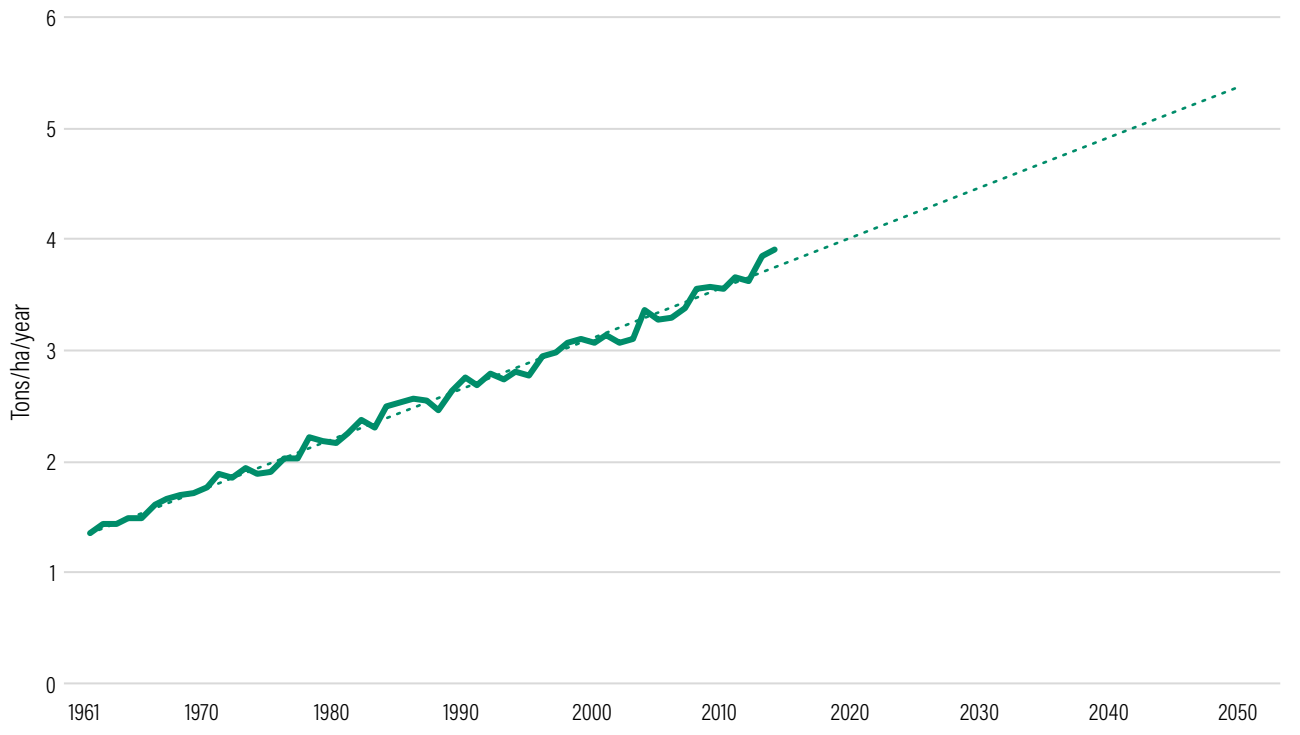
Yield growth estimates. Some models assume faster yield growth than others. On balance, the FAO estimates that we use project yield gains from 2006 to 2050 at roughly the same rates as those achieved from 1962 to 2006 in terms of absolute annual increases in production (additional kilograms per hectare per year [kg/ha/yr] relative to the immediately preceding year).[16] By contrast, the OECD/IMAGE projection, citing essentially stable cropland (Table 10-1), projects yield growth by 2050 that is 25 percent higher than forecast in the 2012 FAO projections. Although no one can legitimately predict the future with high confidence, we are skeptical of very high growth rates in crop yields or meat and dairy output per hectare of grazing land, for a number of reasons that we discuss in the subsections below.

Use of compound (instead of linear) crop growth rates

Some projections have mistakenly assumed that yields have percentage growth rates that compound each year, instead of growing in a linear fashion.[17] Compound, or exponential, growth rates are like bank interest: to generate the same *percentage* growth in yield over time, the *absolute* increase in yield must get larger each year.[18] However, crop yields have usually grown linearly. The global yield of cereals, for example, has grown for more than 50 years at a surprisingly consistent rate on an absolute basis, with each hectare globally producing roughly 45 kg more each year than it did the previous year (Figure 10-1). Careful analyses have shown that even regional growth rates in crop yields—although they have varied by region, crop, and period—are best represented by linear growth.[19] The assumption of compound growth rates by some studies has therefore led to assessments of future yields that are far too optimistic (Box 10-1).



Figure 10-1 | Global cereal yields have grown at a linear rate over the past five decades



Source: WRI analysis based on FAO (2019a).

BOX 10-1 | The significance of linear yield growth for predicting future land-use needs

A poorly grounded assumption that explains several overly optimistic projections of future crop yields and land-use needs is that yields grow by a stable percentage each year. In other words, if yields grow by 1.5 percent this year, they will continue to grow at 1.5 percent year after year and, like a bank account, the growth will compound. This assumption of compound growth leads to large absolute yield growth over time, as illustrated by a figure borrowed from Grassini et al. (2013), which shows how compound growth rates used by six separate studies led to projections of high future yields (Figure 10-2).

In fact, as Grassini et al. (2013) also showed, although yields grow at different rates in different places at different times, when yields grow, they almost always grow in linear fashion. In other words, as illustrated in Figure 10-2, U.S. maize yields increase by a consistent number of kilograms per hectare each year. Papers that use compound growth rates are overly optimistic, such as one paper claiming that the world had reached "peak farmland," meaning that the world would no longer need to expand cropland to meet rising food needs.[a]

By contrast, other papers improperly project an alarming future by pointing out that percentage growth rates for cereals have been declining: they were 3 percent per year in the 1960s and are now around "only" 1 percent. From this decline, the studies infer a decline in technical improvements and grave problems in the future.[b] But linear growth means that the percentage growth rate declines. When average world cereal yields were only 1.5 tons per hectare per year (t/ha/yr) in 1962, producing an additional 45 kg/ha each year meant 3 percent growth. By 2017, once world yields reached 4.1 t/ha/yr, that same 45 kg/ha means growth closer to only 1 percent.[c]

Studies can also mislead when they express future growth in demand as a compound growth rate. Future demand growth out to 2050, measured linearly, is going to be larger than previous growth. Yet because of the same fundamental math, the same absolute increase in demand for food each year will result in declining compound (percentage) growth rates in demand. As a result, using a compound growth rate for demand can make it seem as though the rate of growth in demand is declining. A seminal report by the FAO, which recognized that yield growth rates are linear, nevertheless characterized growth in demand as declining using compound rates.[d] Using linear rates correctly to characterize growth in yields but compound growth rates incorrectly to characterize declining growth rates in demand can lead to a mistaken impression that land use will not expand.

Notes and sources:

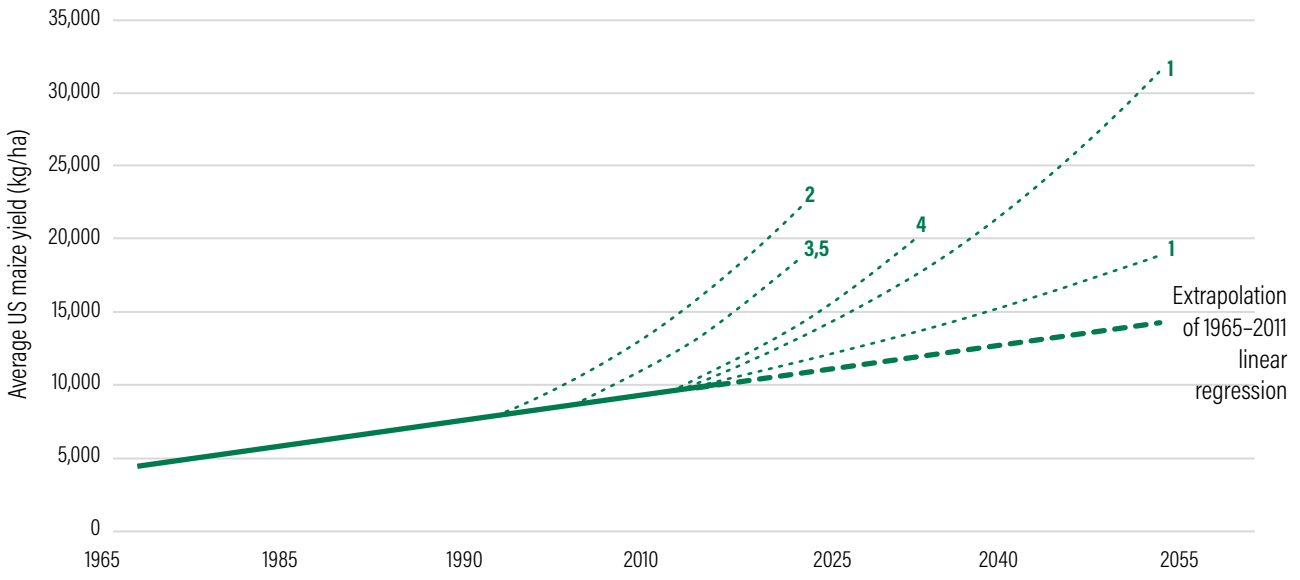
a. Ausubel et al. (2012). In this paper, the compound growth rate is complicated by the fact that the authors analyzed different contributions to yield growth, but the overall effect was to use a compound rate.

b. For example, Alston et al. (2010) include a chart showing large declines in annual crop yield growth rates from the period 1961–90 versus 1990–2007. See also Foresight (2011a).

c. Authors' calculations from FAO (2019a). This comparison is between the average yield from 1961–63 and the average yield from 2012–14.

d. Alexandratos and Bruinsma (2012).

Figure 10-2 | The example of U.S. corn (maize) shows how compound yield growth rates lead to overly optimistic future projections



Note: Each line with a number in this figure refers to a separate study as follows: (1) Nelson et al. (2010); (2) Reilly and Fuglie (1998); (3) Heisey (2009); (4) Edgerton (2009); (5) Hertel et al. (2010).
Source: Grassini et al. (2013).

Inconsistency with trend lines

Our "alternative 2050 baseline" scenario, which uses more recent (and slower) crop yield growth trends from 1989 to 2008,[20] projects even larger cropland expansion than our 2050 baseline (Figure 2-4). Thus, estimates that use FAO's projected (faster) yield growth based on 1962 to 2006 rates of gain may be too optimistic. One study that used detailed agricultural census data for subnational units found some worrisome conditions over the 1989–2008 period, including stagnating wheat yields in Bangladesh and in some parts of India and Europe.[21] This study also showed that yield growth had, at best, plateaued over more than one-quarter of all lands producing wheat, maize, soybeans, or rice.

Overly optimistic estimates of economic responses to demand

The Future Agricultural Resources Model (FARM) model, which is the only model in the 10-model comparison by Schmitz et al. (2014) that predicts a decline in cropland area, builds in an assumption that, as demand increases, yields also increase substantially and these gains are enough to lead to cropland area decline.[22] Other models also incorporate such an assumption to varying degrees, including GLOBIOM, the Global Trade Analysis Project (GTAP), and Modelling International Relationships in Applied General Equilibrium (MIRAGE) models.[23] This important assumption warrants discussion.

There are many reasons why yields are likely to increase over time. For example, improvements in technology will increase yields. In addition, as countries develop economically, the relative costs of nonland inputs decline due to such factors as improved transportation, manufacturing, and distribution, and even improved education and training. As a result, agricultural yields are likely to grow, just as productivity grows in other sectors. In addition, as wages increase with development, use of machinery becomes more economical relative to labor. Mechanization increases the benefit of using flatter, often more productive, lands, which favor use of larger machines.

Yet none of these drivers of yield growth mean that demand growth itself will push up yields even more. Yields today represent a mix of different inputs, including fertilizers, water, seeds, machinery, labor, and land. Yield increases generally require a shift by farmers toward proportionately greater reliance on inputs other than land, or they require gains in the efficiency of use of all assets (which economists call gains in total factor productivity). Implicit in the claim that increases in demand and prices will cause producers to increase their yields is a claim that higher crop prices will cause producers, when they expand production, to use less additional land and more additional inputs of other kinds (such as fertilizers, pesticides, labor, and machinery). That would cause food production to expand via higher yields rather than via use of more land with existing or even lower yields. However, there is no inherent theoretical reason why this should occur.

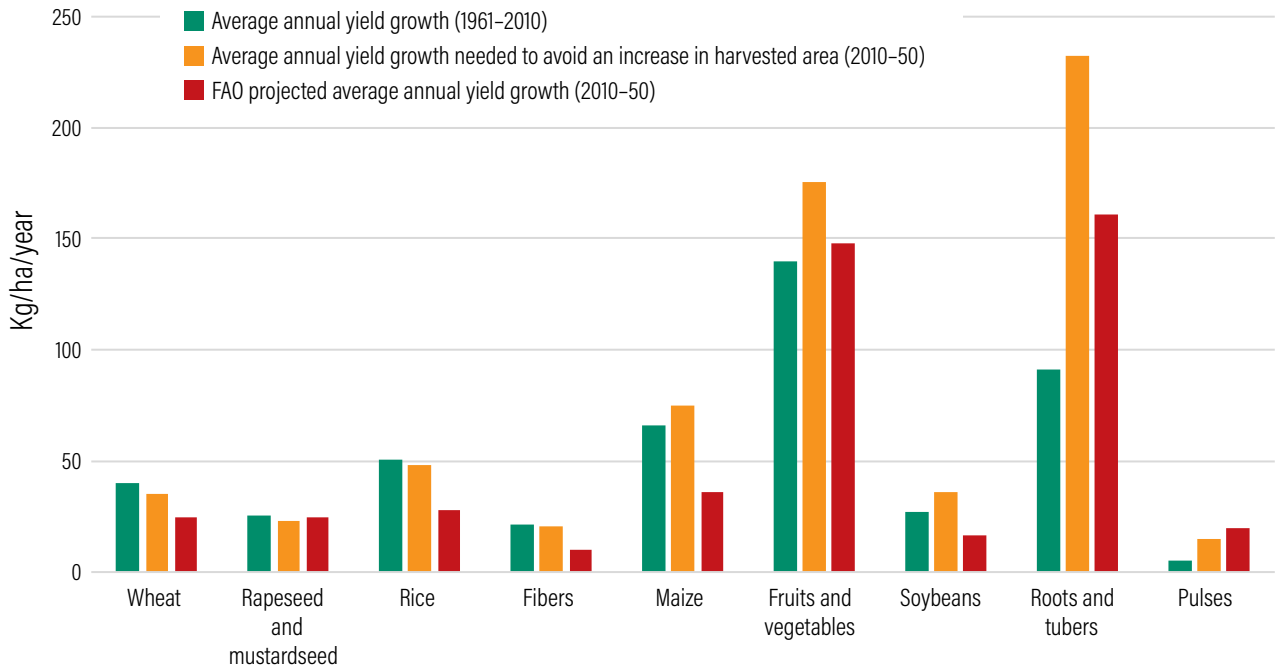
In areas where land is limited, farmers may boost yields because increasing production by means of nonland inputs is, on average, cheaper than accessing new land. This scenario would seem more likely to occur in relatively land-constrained areas, such as Asia and North America. But in other regions where extending agricultural land is cheaper, such as parts of Africa and Latin America, land expansion will play a larger role. Because yields are also lower in these regions, any expansion of production there due to increased demand will lower global average yields. The effect on global yield depends on the global average response to increased demand.

Although demand growth may push up yields, there is little rigorous economic evidence to show that it actually does—as we discuss in Chapter 7 on bioenergy.

Overly narrow focus on grains

Although modeling studies tend to address all crops, some papers focus only on grains, which creates a more optimistic picture because demand for grains is likely to grow more slowly in the future than in the past. For example, as shown in Figure 10-3, wheat and rice yields would not need to grow at their historical rates to meet future demand without land expansion, but fruits and vegetables, soybeans, pulses, and roots and tubers would need to grow significantly faster. Overall, as discussed in Chapter 1, yields would have to grow roughly 10 percent faster from 2010 to 2050 to meet our projected demands without net expansion of agricultural land.[24]

Figure 10-3 | Future yield growth in many crops will need to be higher than in the past to meet projected food demand on existing agricultural land



Source: GlobAgri-WRR model, WRI and ACE analysis based on Alexandros and Bruinsma (2012).

Overly optimistic estimates of government and private action

Some analysts adopt a baseline that represents their best estimate of what will happen in the future, including changes they anticipate in government policies, technology, and corporate or farmer behavior. For example, the Model of Agricultural Production and its Impact on the Environment (MAgPIE) model assumes that governments faced with the prospect of higher demand and crop prices will increase their investments in agricultural productivity. This in turn is assumed to lead to larger future yield gains than those that have occurred in the past or that would occur in the future without this additional investment.[25] Such an optimistic approach raises important questions about how most usefully to set a baseline.

It is true that growth in yields between now and 2050 will in part reflect government and private policies that respond to the challenge of a sustainable food future. But if a baseline projection predicts bold, helpful responses, observers might perversely interpret such an optimistic baseline scenario as a signal that there is no problem that needs fixing. The bold responses would then never materialize. We think the most useful "business-as-usual" 2050 scenario should more or less reflect historical trends in food production and consumption patterns so that policymakers can compare the future challenge with what has occurred in the past.

Overly optimistic estimates of pasture efficiency gains

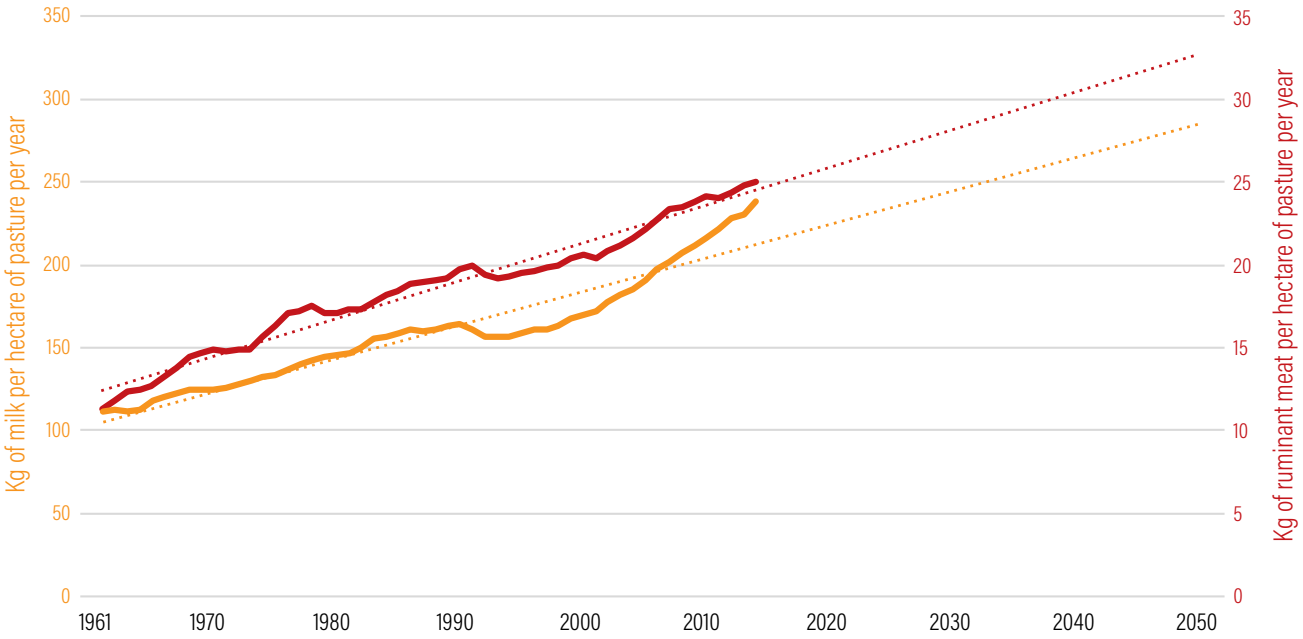
Projecting the future need for pastureland is inherently challenging. Too few solid data exist on which to make projections of increasing yields of ruminant meat and milk per hectare of grazing land. This "pasture yield" depends on the growth in the share of ruminant feed that is derived from crops and other nonpasture sources, on increasing efficiency in turning each kilogram of feed into a kilogram of meat or milk, and on increasing production or offtake of grass from each hectare of grazing land. Unfortunately, the data for each of these three factors are poor for recent years, and worse to nonexistent for previous decades. Small changes in any of these projections can result in very large changes in pasture area requirements because the world already has so much pasture area—more than one-quarter of the world's vegetated land (roughly 3 billion ha). Our projections use indirect ways to estimate each of these numbers, and all of them are debatable.

It is very hard to determine why some models have low pasture expansion projections because the underlying assumptions are rarely described adequately. Nearly all economic models have extremely rough representations of the livestock sector in general. The decline in pasture area predicted by the Global Change Assessment Model (GCAM), which projects one of the larger declines, is due to a larger assumed increase in agricultural productivity than we project and a smaller increase in demand for milk and meat than we project. Chapter 11 on increasing livestock efficiency describes the challenges in greater detail.

There are enormous challenges in estimating total pastureland area, but we are skeptical of optimistic baseline estimates of declining pasture area by 2050 for several reasons:

- As described below, recent years have witnessed large-scale gross clearing of forest and woody savannas for pasture.
- Just as shifts in crop production to lower-yield countries will hold down average global rates of crop yield growth, so will those geographic shifts in meat and milk production hold down average global pasture yields.
- Most important, a simpler way of projecting trends leads to even more pessimistic results than our baseline. A simple projection would merely examine previous average global growth trends in meat and milk per hectare of pastureland over time and project that growth forward to 2050. This simple ratio of output per hectare of grazing land would reflect all different drivers of efficiency gains (more output per kilogram of feed, more use of crops as feed, more grass per hectare, and shifts in locations of production). Although we do not truly know how much grazing land is used for meat versus for milk, dividing all meat and milk production by the total pastureland area leads to trend lines that project only 30 to 35 percent increases in meat and milk per hectare by 2050 relative to 2010 (Figure 10-4).[26] In contrast, expected increases in global demand of 88 percent (for ruminant meat) and 67 percent (for dairy)—described in more detail in Chapter 6 on shifting diets—mean that meat and milk output per hectare of pastureland must grow at well above historical rates to avoid pastureland expansion.

Figure 10-4 | Historical growth in pasture output per hectare shows a linear pattern



Source: WRI analysis based on FAO (2019a).

Our own baseline scenario for 2010–50 projects 53 percent growth in dairy output, 62 percent growth in beef output, and 71 percent growth in sheep and goat meat output per hectare. These projections are based on more complicated methods of estimating historical trends that attempt to tease out separate trends in output per animal, increases in the use of crop-based feeds, and increases in the quantity of grass consumed per hectare of pasture. Although these growth rates are faster than the historical trend measured just as output per hectare, they are not enough to prevent pastureland from expanding by 401 Mha between 2010 and 2050.

Using "yield gap" analysis to estimate potential to meet food needs without expanding agricultural land

One way of analyzing the potential to increase food production while maintaining the same net area of agricultural land is to estimate "yield gaps." Yield gaps represent the difference between the actual yields that farmers currently obtain and the potential yield that they could obtain. Farmers can increase yields either by planting crops that have been bred for a higher potential yield, or by improving farm management so that actual yields come closer to achieving the crops' yield potentials (i.e., closing the yield gap).

The definition of yield potential is not straightforward, and researchers use different methods to estimate that potential, which effectively establish different meanings of the "gap." Several approaches focus on "technical potential," but even they use different standards for estimating this potential. Researchers compare actual yields to potential yields that can be estimated in three different ways: as the highest global yield, as the yields achieved by researchers in the region under careful management, or as the yields estimated by crop models assuming excellent management without pests or pathogens.[27] Each method of comparison will generate a different yield gap.

One persuasive analysis, however, has estimated that farmers are unlikely to achieve more than 80 percent of potential yields in the real world, in part because of economic constraints and in part because of the significant role played by chance in determining annual yields.[28] Applying this "80 percent rule" to technical potential is one way of estimating a "practical" yield potential and, by comparing with existing yields, of estimating "practical" yield gaps.

Another approach to estimating a "practical potential" involves comparing average yields of one set of farmers with yields achieved in comparable agroecological settings by other farmers. These other farmers may be nearby or anywhere in the world deemed to have comparable agroecological conditions. For example, yield gaps may be defined as the difference between the average yields farmers actually achieve and yield levels that are just higher than yields achieved by 90 percent of farmers in the same conditions.[29]

A challenge of this approach is that farms that appear comparable will often have important site-specific differences. In reality, high and low performers often use lands of different qualities even within the same region. In addition, some farms generate high yields in some years because farmers plant at just the right time—planting is followed by the right rainfall patterns and temperatures during growth, reproduction, and harvesting. Yet planting decisions involve a significant element of luck. The element of luck means that different farmers tend to be high performers in different years,[30] and using the highest yields will overestimate what even the best farmers can achieve on a consistent basis. Both of these challenges mean that estimates of yield gaps using these methods will tend to be too large.

An even more fundamental factor in overestimates of yield gaps is the effect of data errors, even when they are random. Yield gap studies use different data sets to find differences in yield that can be explained only by management, and these data sets in effect create two basic maps. One map shows yield potential and the other shows actual yields. Errors in the maps that lead to a higher yield potential than actually exists, or that lead to lower actual yields than really occur, will each lead to erroneously large "yield gaps" between the actual and potential. Moreover, errors in opposite directions will not offset each other and balance out the estimates of aggregate yield gaps because yield gaps are based on the high estimates of yield potential and, often, the low estimates of actual yields. It is the spread between potential and actual yields that defines the gaps, and, because data errors lead to larger spreads than actually exist, they lead to higher gaps than actually exist.[31]

Beyond this tendency to overestimate yield gaps, different yield gap analyses often generate widely varying results, even when they focus on a relatively small local area.[32] Global analyses face greater challenges because of data quality, which Neumann, Verburg, et al. (2010) forthrightly acknowledge "might even outrange the yield gap itself." Even when analyses generate similar aggregate estimates, they may hide widely varying results at national and regional level. For example, two well-known global exercises both found large, somewhat consistent global yield gaps—a 58 percent gap for total calories in Foley et al. (2011), and roughly 50 percent gaps for wheat and rice and a 100 percent gap for maize in Neumann, Verburg, et al. (2010). Yet Foley et al. (2011) found that the largest yield gaps exist among farmers in intensively managed regions, not among farmers in less intensively managed regions. The farmers in the former regions, such as India, northeastern China, and parts of the United States, had gaps of more than 4 t/ha/yr, whereas yield gaps in most of sub-Saharan Africa were mostly less than 1 t/ha/yr.[33] These results would be discouraging because high crop prices, government support, and infrastructure already provide farmers in the high yield-gap regions of India, China, and the United States with high incentives to boost yields. However, in complete contrast, the global yield gap study by Neumann, Verburg, et al. (2010) estimated large maize yield gaps in Africa (5–9 t/ha/yr) and much smaller gaps in the United States (less than 2 t/ha/yr in most areas). All of these limitations suggest that yield gap analyses should be used with great caution.

Nevertheless, a wide variety of studies, using a wide variety of methods, find substantial yield gaps. Fischer et al. (2014) used this range of evidence, and good scientific judgment, to estimate yield gaps crop by crop and region by region. The study amounts to a case for both optimism and caution when summed to global averages. Among the major crops, the review found that the largest potential

for closing yield gaps exists for maize, with a global weighted yield gap of roughly 100 percent (i.e., a potential for doubling), with generally much larger gaps in developing countries. The rice yield gap was similarly found to be large, at roughly 70 percent. The review also found high yield gaps of 100 percent or more in the developing world for other important food crops, including sorghum, millet, and cassava. By contrast, global estimated yield gaps were only roughly 50 percent for wheat, and 30 percent for soybeans. In the case of soybeans, the lower yield gap is explained mainly by the fact that all three countries that dominate global soybean production—the United States, Brazil, and Argentina—have high yields already.

These yield gaps are grounds for tempered optimism, but applying the 80 percent rule of practical yields achievable by farmers leads to more sobering results. For example, applying the 80 percent rule to wheat results in only a 40 percent gap. That is roughly enough to meet projected demand for wheat consumption, but only if all farmland everywhere achieves this practical potential—a big challenge.

Ultimately, we derive three lessons from this review. One, although the world has significant technical potential to increase yields even on rain-fed land, the potential is not so great that achieving necessary yield gains will be easy. Two, because the existing practical potential is not huge, the world cannot afford to waste any farmland, or "leave any farmland behind." Three, in addition to just closing yield gaps, crop breeding will probably be necessary to increase yield potentials. The ability to increase potential yields has probably diminished as yields grow higher and higher, and researchers mainly estimate potential by focusing on recent rates of change. Yield potentials continue to grow rapidly for some crops, such as maize, while others grow more slowly.[34] Only new breeding can increase potential yields, and we focus on that along with other breeding opportunities in Chapter 12.



Data Limitations Obscure the Extent of Agricultural Land Expansion

What can we learn from recent evidence regarding agricultural land expansion? The answer, unfortunately, is unclear due to imperfect data. The answer also involves three different analytical challenges: the analysis of gross forest-cover loss, which can be driven by agricultural conversion but also by logging or fire; the analysis of gross forest-cover gain in separate areas, and therefore the calculation of net forest-cover loss that must combine gross forest-cover loss and gain; and the allocation of forest-cover losses and gains to different drivers. Overall, there is very strong evidence that gross tree-cover loss is continuing at high rates and probably accelerating, good evidence that gross agricultural conversion is a major driver of that conversion, and less clear evidence of what is occurring on a net basis. We briefly review the different kinds of evidence.

Satellite studies of cropland and pasture

Perhaps the best evidence of trends in land use comes from studies of satellite imagery. Most historical satellite-based land-use change studies use satellite images from the Landsat program of the U.S. National Aeronautics and Space Administration. These images cover the majority of the earth's surface many times each year, and analyzing such large data quantities in many regional contexts still remains a scientific challenge. Different research groups develop different computer algorithms to interpret what land changes are occurring based on the amount of light reflected from the sun in various ranges of the electromagnetic spectrum. These algorithms often result in very different interpretations of land-cover change.

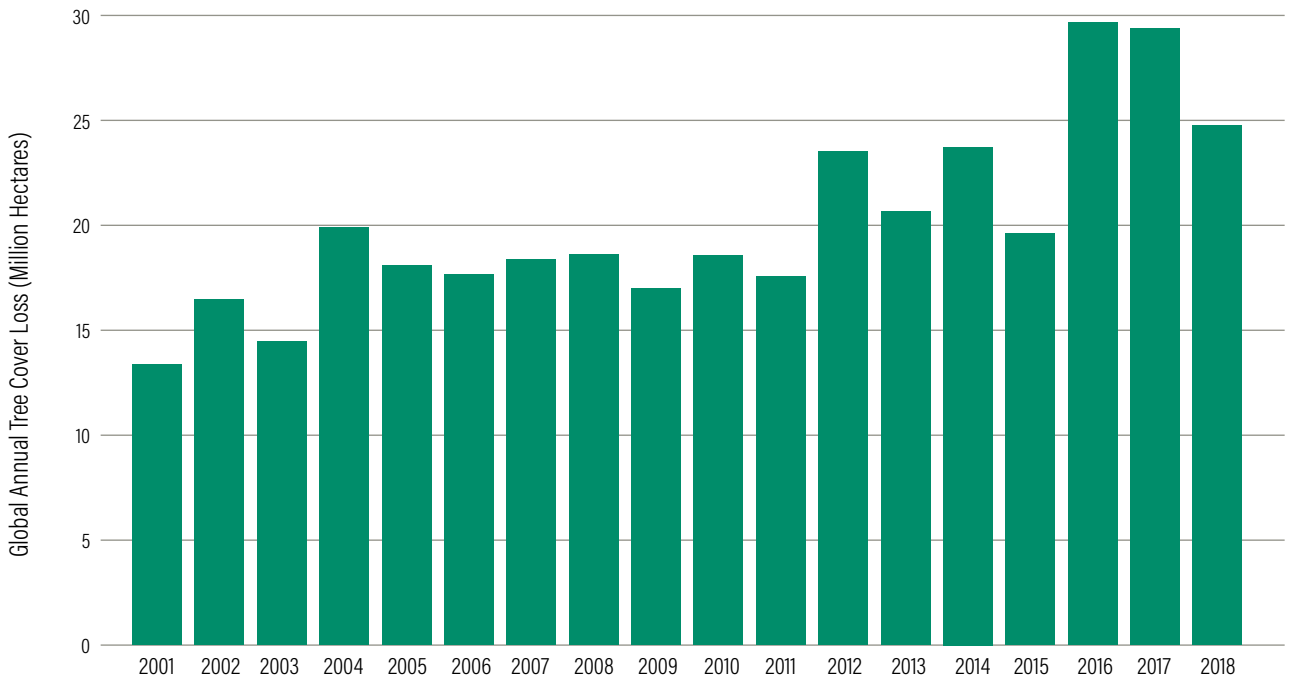
Satellite images cover the whole earth but the images are grainy. Human interpretation of large areas is not practical, although human interpretation is usually more accurate than computer algorithms when analyzing individual satellite images for changes in land use and land cover. As discussed below, large discrepancies in different satellite mapping programs are reported in the literature, as are higher rates of inaccuracy when comparing these automated global mapping interpretations to more reliable manual interpretation using higher-resolution imagery available on aerial photography platforms such as Google Earth.[35]

WRI's Global Forest Watch (GFW) publishes maps of loss of "tree cover" using estimates from the Hansen data set based on algorithms developed at the University of Maryland (UMD).[36] According to Zeng, Estes, et al. (2018), this data set has a higher rate of accuracy (that is, the percentage of land-cover classes that was correctly determined) than other global land-cover mapping data sets, as determined by comparisons with manual interpretation of high-resolution aerial photographs in selected geographic locations.[37] On the basis of this data set, GFW estimates that the world had average "gross" losses of 20 Mha of forest cover each year from 2001 through 2018 (Figure 10-5). Moreover, the levels of forest-cover loss have been rising unevenly but substantially from an average of roughly 15 Mha in 2001 and 2002 to almost 30 Mha in 2016 and 2017.

Tree-cover loss may be due to causes other than agricultural expansion, including forestry and fire. Curtis et al. (2018) analyzed forest loss data from 2001 to 2015 and estimated that roughly half of tree-cover loss was due to forestry and wildfires while the remainder, roughly 10 Mha per year, was due to conversion to agriculture.

Curtis et al. (2018) attributed roughly half of the agricultural conversion to a category they called "shifting agriculture," which was not considered "deforestation" because the authors theorized that agriculture was not expanding but just shifting around within an area in long-term rotations of agriculture and forest. "Shifting" or "swidden" agriculture is a type of agriculture long recognized and practiced by farmers with limited access to fertilizers to allow crop fields to regain fertility through natural regrowth.

Figure 10-5 | The world lost more than 360 million hectares of tree cover between 2001 and 2018



Source: Hansen et al. (2013). Accessed through Global Forest Watch on June 20, 2019. http://www.globalforestwatch.org.

We disagree that the actual areas cleared should be characterized as "shifting agriculture" rather than as agricultural expansion and therefore new conversion, on the basis of the methodology used in the study. We believe that a more appropriate term is "mosaic" agricultural conversion. The most significant criterion used by Curtis et al. (2018) to designate "shifting agriculture" was that, in any 100 square kilometer grid cell, if more than a minimal part of the cell was reforesting then all the expansion would be characterized as "shifting agriculture" and not "deforestation." That definition encompasses a wide array of areas that would be experiencing true expansion of agricultural land area if any of the following were also present in these areas:

- Some true rotational agriculture
- Some agricultural abandonment (regardless of whether the farmers who abandon the land are shifting to other parts of the area)
- Some regrowth of forest area from local clearing of forest for wood products

This method results in nearly all agricultural expansion in Africa being defined as "shifting agriculture" and not "deforestation"—a problem acknowledged by the authors—even though multiple studies, including by many of the same authors, have found that agricultural expansion into new areas is occurring in Africa on a large scale.[38] Not only are completely new areas being cleared in Africa, but some farmers who have long practiced shifting agriculture also are reducing the length of their rotations, thus allowing less forest regrowth.[39] That is also a form of net agricultural expansion. In addition, the methodology explains, for example, why Curtis et al. (2018) generally attribute agricultural clearing in northern Thailand as being for "shifting agriculture" and not "deforestation." However, separate, more detailed local analyses have shown that agriculture is not just shifting around in this region but also expanding, both in lowlands and in mountains areas.[40] While expansion is carried out by smallholder farmers, they are not practicing subsistence agriculture. They are predominantly producing commodity crops such as maize and should be viewed as part of the global response to increased food demands.[41]

At the global level, the Hansen maps incorporated into Global Forest Watch (GFW) support the proposition that gross global agricultural conversion of forests has amounted to at least 10 Mha per year since 2001, and that this level of conversion has likely been increasing. These estimates also leave out some additional areas of agricultural expansion. For example, they will not capture some conversion of natural forests to tree crops, such as rubber. Nor will they include conversion of many woody savannas and grasslands because the Hansen maps apply only to clearing of forests with 30 percent tree canopy or more (meaning that at least 30 percent of the ground is covered by leaves on trees).

Satellite-derived maps that try to interpret conversion of sparser, savanna woodlands are less likely to be accurate. Other studies, some using radar-based approaches, find that substantial conversion of such woodland savanna areas is occurring as well.[42] These savanna landscapes occupy large portions of Africa and Latin America that are known to be areas of agricultural expansion.[43]

Gross expansion, however, is not the equivalent of net expansion. Although areas identified by Curtis et al. (2018) as expansions of shifting agriculture should be viewed as gross deforestation, the reforestation found in these areas suggests that some agricultural land is being abandoned both long-term and as a part of the multiyear rotations of croplands and forest that are a part of traditional "shifting" or "swidden" agriculture. Even in large-scale commodity agriculture, as we discuss in Course 3, substantial areas of land may be abandoned as agriculture shifts to other areas that can be hundreds of kilometers or even continents away. GFW researchers estimate that roughly one-third of total deforestation between 2001 and 2012 was offset by reforestation of some kind of forest somewhere in the world. They further estimate that the greater part of reforested area was likely regrowth following previous fire or forestry and not agricultural abandonment.[44] But the method used for this part of the analysis was unlikely to capture all reforestation.[45]

Although we focus here on the implications of GFW studies, a variety of alternative analyses of deforestation and other land-use changes complicate the lessons. Some studies are broadly consistent with GFW. For example, one study by Kim et al. (2015) of the 34 tropical countries with extensive forest areas found gross forest loss rates of 7.8 Mha per year, and net loss of 6.5 Mha per year. This is comparable to GFW's estimate of gross annual loss of 7.5 Mha per year and net loss of 5.5 Mha per year in these same 34 countries between 2001 and 2012. Other analyses are inconsistent with GFW and find lower rates of gross and net forest loss.[46] In part reflecting these lower forest loss rates, they also sometimes find only modest net expansion of cropland and pasture area since 2000, which GFW does not explicitly estimate although its results suggest much more.

There are other methodological differences, but one important factor may be the spatial resolution of satellite images used. The GFW and Kim et al. (2015) analyses used Landsat images that cover, on average, about one-tenth of a hectare, whereas alternative analyses that find less net forest loss are often derived from images with coarser resolution, with pixels representing 6 or 10 ha, or even larger areas on the ground.[47] In landscapes that have a mix of patches of forest and cropland, it is often difficult to interpret both land-cover and land-use changes from satellite images with larger pixel sizes.[48] The evidence indicates that analyses using images with larger pixel sizes tend to detect fewer small farm fields[49] and therefore may leave out expansion of small farm fields in complex landscapes.

Overall, the implications of the GFW estimates we have presented are that gross conversion of forest for agriculture, both cropland and pasture, has likely been greater than 10 Mha per year since 2001. Additional conversions of savannas and natural grasslands to agriculture are likely, though not reflected in these data.

FAO cropland data

FAO reports two kinds of data regarding cropping, one suggesting an unprecedented expansion, the other suggesting meaningful but more modest expansion.

Harvested area refers to the number of hectares actually harvested each year, which is different from the area classified as "cropland." If farmers plant and harvest two crops on a hectare in a year, it counts as two harvested hectares, and if they do not plant or harvest crops on a hectare in a year, it counts as zero. *Cropland*, according to FAO's definition, is supposed to refer to any land that has been planted to a temporary or perennial crop at any time over the previous five years, although FAO does not actually insist that countries use this definition, and at least some do not.

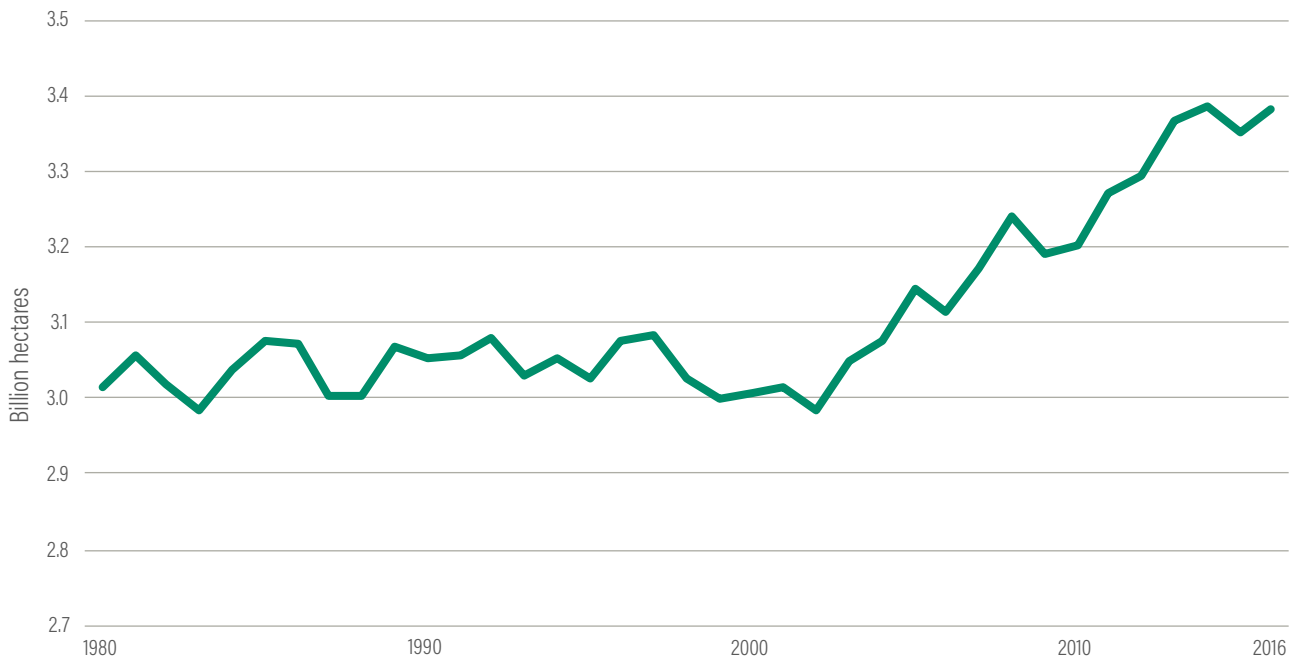
According to FAO data, global harvested area expanded from 2002 to 2016 at an unprecedented rate of 15.1 Mha per year.[50] (That increase compares to an average annual increase of only 4 Mha from 1982 to 2002; see Figure 10-6.)[51] By contrast, according to FAO data, global cropland has been expanding at a rate of roughly 4.3 Mha per year since 2002.[52]

In theory, the difference between harvested area and cropland area could reflect a large increase in double-cropping, or a large decrease in the number of hectares left fallow. Both practices increase harvested area without increasing cropland. Some researchers interpret the data in these ways.[53] However, we believe that independent data do not support this explanation, and that the discrepancy probably represents flaws in the data for cropland, or harvested area, or both. For example, the few specific analyses of changes in double-cropping do not support the idea of large increases in the practice. Independent reports suggest that double-cropping in Brazil increased by a total of roughly 6.5 Mha from 2002 to 2014, with nearly all the

double-cropping involving maize after soybeans.[54] But elsewhere, the independent data do not show large increases in double-cropping. For example, FAOSTAT data on harvested area versus cropland area would logically imply either an increase in double-cropping or a decline in fallow area of 13 Mha in China from 2000 to 2011.[55] However, a remote-sensing study found a 4 Mha decline in double-cropping and an increase—not a decrease—in fallow lands of 1 Mha during this time period.[56] In the United States, although FAO data might suggest an increase in double-cropping, there was virtually no change in double-cropping from 1991 to 2012, according to U.S. Department of Agriculture (USDA) statistics.[57]

One explanation is that some countries are probably undercounting their expansion of cropland by not reporting cropland in ways that meet the FAO definition. For example, FAOSTAT reports a 20 Mha decline in U.S. cropland from 2002 to 2012, which reduces the global expansion of cropland reported by FAOSTAT. This decline reflected reporting by the USDA, but, according to the USDA, true cropland area did not decline in the United States.[58] The decline in "cropland" reported was due instead to a decline in reported area of "cropland pasture," that is, land that the U.S. government had characterized as cropland because of historical use as cropland but much of which had long been used for pasture. The decline in cropland area thus

Figure 10-6 | Harvested area for 15 major crops has expanded by about 125 million hectares since 2002



Note: The 15 major crops are barley, cotton, groundnuts, maize, millet, oats, rapeseed, rice, rye, sorghum, soybeans, sugar beet, sugar cane, sunflower seed, and wheat.
Source: WRI analysis based on FAO (2019a).

appears to be mainly a consequence of a recategorization of land, most of which should not previously have been considered cropland according to FAO definitions because it had not been cropped for at least five years. According to FAO definitions, the United States should also have declared a 4 Mha increase in cropland between 2002 and 2016[59] due to the return to cropping of land previously taken out of production for more than five years in the Conservation Reserve Program. However, the United States did not report an increase in cropland because it had continued to report land in the program as "cropland" even though it had been planted in grasses and trees for more than five years.

Although such underreporting may play a role, the reality is that we do not really know what explains the discrepancy between the expansion of harvested area and the expansion of cropland because the data are just too uncertain. FAO uses data reported by countries, and there is no independent way of evaluating the data on harvested area or even any integrated source of information on the different methods countries use.

Cropland area might appear to be easier to estimate because of the potential use of aerial or satellite photographs, but at this time, the challenges, uncertainties, and discrepancies in satellite interpretations create major uncertainties. Even reports from advanced agricultural countries that devote substantial resources to assessing cropland appear to have limitations. In one unsettling example, a 2018 satellite study suggests that Brazil has been widely misreporting its cropland. Although FAOSTAT reports Brazilian cropland as increasing from 65 Mha to 86 Mha between 2000 and 2004, this study found that Brazil's cropland was actually only 26 Mha in 2000 and had expanded to 47 Mha by 2014. The study suggested that part of the discrepancy probably occurred because Brazil had been reporting harvested area as cropland, but much of the discrepancy could not be explained.[60] Because Brazil is renowned for its satellite studies of land use and for its agricultural research agency, this result raises questions about data from countries with fewer resources available for such analyses.

Overall, substantial uncertainty remains. There appears to be a large and perhaps unprecedented increase in harvested area globally. The cropland data do not show a similar increase. The discrepancy cannot be well explained by an increase in double-cropping or a decline in fallow lands. Some of the discrepancy—at least in the United States—appears to be due to an underreporting of cropland. In general, however, the data are too uncertain to be reliable and data discrepancies raise questions that cannot now be answered.

FAO pastureland data

FAOSTAT pastureland data report that global pasture area actually *declined* by 140 Mha from 2001 to 2016. If true, these data would indicate a trend toward future pasture area declines, but a closer look suggests otherwise.

Of the reported decline, 81 Mha occurred in Australia—the result of a decision to no longer characterize some extremely dry grazing lands as permanent pasture. An additional 36 Mha of the reported decline occurred in Sudan (both Sudan and South Sudan), which might be the result of drought but given changes in government may also be the result of an estimation or accounting change. Some real, but much smaller declines do seem plausible in places such as China, due to reforestation programs on dry, hilly pastures.[61]

The challenges with Australian and Sudanese pastureland data are emblematic of much larger challenges, which start with an ambiguity about what constitutes pasture in the first place.[62] Estimates of pastureland area range from less than 2 billion ha,[63] to 2.8 billion ha (based on adjustments to FAO data),[64] to 3.35 billion in FAOSTAT as of 2010, and reach 4.5 billion ha in another study.[65] The largest estimate includes wide areas assumed to support occasional browsing by animals even if not consistently grazed. Among the critiques of the FAO figure, one research team found that 500 Mha of pastureland reported by FAO, on the basis of country reports, were simply too dry to support permanent grazing on any meaningful level (e.g., large areas reported by Saudi Arabia).[66]

One puzzle is that FAOSTAT reports an increase in pastureland in Latin America of only 11 Mha from 2001 to 2013.[67] Both a region-wide study and numerous local studies have documented that much larger gross deforestation in Latin America is largely and probably primarily due to expansion of pasture.[68] Between 2001 and 2013, a study using Moderate Resolution Imaging Spectroradiometer

(MODIS) satellite images found gross pasture expansion of 97 Mha.[69] A 30 Mha conversion of pasture to cropland reduced this net expansion, as well as some unknown amount of reversion to forest, but the gross figures still suggest a large net expansion of pasture.

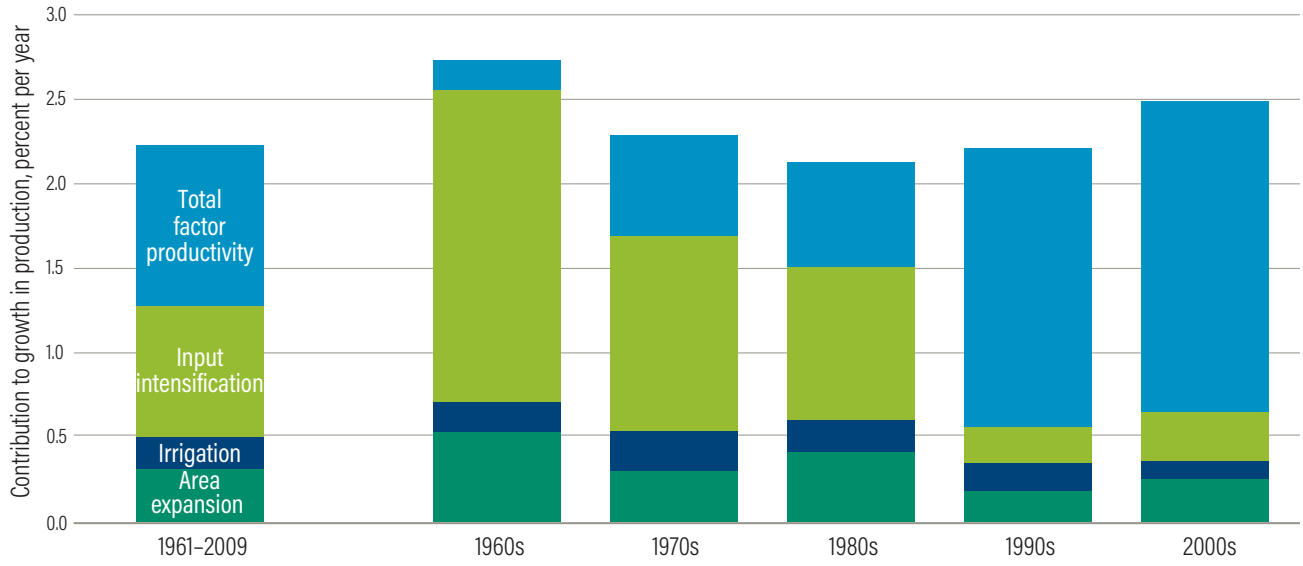
For these reasons, we do not consider FAOSTAT data on pasture reliable and think that net pasture expansion is likely occurring based on the analyses in Latin America. However, on a global and probably also regional basis, there also appears to be a shift from drier, less productive grazing land, such as that being reforested by Chinese conservation programs, toward wetter, more productive grazing land, such as that in Latin America. This shift in effect uses more of the productive potential of land even if land area does not expand.

Reasons for Optimism: Smarter Agriculture

Although the ability to increase output simply by adding fertilizer or water has been declining because fertilizers are already heavily used in most areas and additional water resources for irrigation are limited, agricultural output has continued to grow. Since 1960, the annual growth rate of agricultural production, as measured by economic output, has remained constant. (The increase in economic output is not exactly the same as an increase in yield but they are closely related.)[70] Yet the role of increased inputs and land in this growth declined from 95 percent in the 1960s to only 25 percent in the 2000s.[71] Instead, 75 percent of the gain in output in the 1990s and 2000s resulted from improvements in total factor productivity, which means improved technology or better use of existing technology (Figure 10-7).[72] Much of the gain has resulted from the spread of advanced farming technologies, particularly to China, Brazil, and Argentina. Although these farming improvements have not been sufficient to eliminate agricultural land expansion altogether, they suggest the potential power of farming advances.

The following chapters discuss a variety of menu items for farming smarter and "leaving no farmland behind."

Figure 10-7 | The primary source of growth in agricultural output has shifted from input increases to improvements in total factor productivity



Source: Fuglie (2012).



CHAPTER 11

MENU ITEM: INCREASE LIVESTOCK AND PASTURE PRODUCTIVITY

Global attention has tended to focus on achieving increases in crop yields. But given the much greater extent of pastureland and the importance of croplands in providing animal feed, increases in the efficiency of livestock farming are at least equally important. This menu item explores opportunities to boost livestock productivity to reduce both land use and greenhouse gas (GHG) emissions.

The Challenge

The world's farmers now annually raise roughly 1 billion pigs, 1.7 billion cows and buffalo, 2.2 billion sheep and goats, and 61 billion chickens,[73] and use more than 3 billion ha of pasture land and hundreds of millions of hectares of cropland to do so. These animals are responsible for generating most of the GHG emissions associated with production processes (as opposed to land-use change) in the agriculture sector. (This issue is discussed in more detail in Course 5.)

With projected increases in animal-based foods overall of 68 percent, increases in dairy of 67 percent, and in ruminant meats of 88 percent,[74] the world's farmers and ranchers will have to produce far more milk and meat per hectare and per animal if the world is to avoid billions of hectares of expansion of pasture area and cropland for feed and vastly increased GHG emissions from livestock alone.

Improving the efficiency of milk and meat production is critical. If the world were to achieve no further productivity gains after 2010 (efficiencies remain at 2010 levels), meeting expected demand for meat and milk in 2050 would require cropland and pasture area to expand by 2.5 billion ha. This enormous amount of land clearing would release an average level of 20.6 Gt CO_2e in land-use change emissions each year.[75] This level amounts to almost the entire global "budget" of 21 gigatons for all GHG emissions by 2050, as discussed in Chapter 2.

Increases in the efficiency of milk and meat production are also critical for holding down production-related emissions from livestock. In our base year of 2010, livestock generated 3.3 Gt CO_2e, or roughly 7 percent of total human-caused GHG emissions excluding land-use change and production of animal feeds. Without any efficiency gains in livestock production, those production emissions would rise to 6.3 Gt by 2050. In our baseline scenario, efficiency gains hold those increases to 4.9 Gt by midcentury.[76]

Projected Efficiency Gains

Fortunately, past experience suggests that milk and meat efficiencies are likely to grow. Between 2010 and 2050, at the global level, our baseline projection assumes a 53 percent increase in dairy products produced per hectare of grazing land, a 62 percent increase in beef produced per hectare, and a 71 percent increase in sheep and goat meat per hectare. These increases are the synergistic effect of three separate changes:

- More crop feeds. We project an increased use of crops in animal diets, with those crops mostly replacing crop residues, which have poor nutritional qualities for animals.
- An improvement in the efficiency of converting each kilogram of feed to meat or milk. Based on analysis of historical trend lines, we assume each ton of feed will produce 20 percent more beef, 22 percent more sheep and goat meat, and 16 percent more milk globally.
- Each hectare of land used for grazing or for cut forage will provide on average 23 percent more forage.[77]

For poultry and pork production, on a global basis, our projections assume roughly 20 percent increases in output of meat per kilogram of feed for poultry and pork meat, and 10 percent for eggs. We extend the projections of Wirsenius et al. (2010) to 2050, which assume modest gains in feed efficiency in developed countries but large gains in developing countries.

Realizing these global efficiency gains even in our baseline, however, will be very challenging. One reason is that demand for livestock products is growing most where livestock productivity is lower. Even if these regions greatly improve their efficiency, the shift of some share of production from developed countries to developing countries has the effect of lowering average global efficiency levels. Another reason is that, as discussed in Chapter 10, our estimates project overall increases in output of ruminant meat and milk per hectare of grazing land that already exceed simple extensions of historical trend lines (Figure 10-4). Finally, climate change will cause many challenges for livestock production: high heat tends to stress animals, reduce production, and increase disease. In many locations, increasing temperatures also can reduce water availability.[78]

Yet even with such optimistic estimates, which include efficiency improvements in every world region, our baseline still projects pastureland expansion of 401 Mha between 2010 and 2050. A less optimistic projection, involving a 25 percent slower rate of feed efficiency gain between 2010 and 2050, would see pasture area expand by 523 Mha between 2010 and 2050, and annual emissions from land-use change rise from 6 gigatons (in our 2050 baseline) to 7.1 gigatons.

The Opportunity

The scale of opportunities for productivity gains differs between pork and poultry, on the one hand, and ruminant meat and dairy, on the other.

Pork and poultry

Concentrated production systems for pork and poultry in developed countries have achieved such high levels of efficiency in meat and egg production, both per animal and per ton of feed, that most analysts believe they are approaching biological limits—as well as limits on humane conditions for raising animals. A European research effort concluded in 2012 that pig and poultry production in Europe was likely to improve in feed efficiency by only 1 percent or less.[79]

In developing countries, there is ample room to increase the feed conversion efficiency of "backyard" pork and poultry production by shifting to crop-based feeds, but those shifts do not save land overall because backyard systems rely heavily on local wastes and scavenging, which our analysis treats as "land free." Future land-use savings are likely to be achieved primarily by farmers in developing countries adopting developed-world production techniques. This development is already the principal driver of pork and poultry expansion in emerging economies such as Brazil and China. Although at least one paper has speculated that there is still more room for productivity gains in advanced systems such as those in Europe,[80] we consider the global efficiency gains from 2010 to 2050 in our baseline scenario already high and thus we do not model additional increases in efficiency of pork and poultry systems.

A major focus in the future should be on raising pigs and poultry in concentrated conditions that are more humane and create less air and water pollution. Good animal husbandry requires increasing space for animals and better waste management. Some analyses have found that raising animals in more humane conditions reduces efficiency,[81] but other studies have found that it can reduce mortality and lower stress, thereby increasing productivity and reducing emissions.[82] The details obviously matter, and we believe these kinds of improvements should receive substantial attention.

Ruminant meat and dairy

In contrast to poultry and pigs, the evidence indicates broad technical potential to increase the efficiency of meat and milk from cattle, sheep, and goats. These ruminants are responsible for more than 90 percent of estimated direct emissions from livestock both in 2010 and in our 2050 baseline scenario,[83] and their feeding uses all pastureland and roughly 20 percent of all crops devoted to livestock.[84] Three interrelated efficiency gains for ruminants are important to reduce both land-use demands and direct production emissions from these forms of livestock:

- *Production per hectare of land.* Growing improved grasses and shrubs, and fertilizing and grazing them well, will improve both the quantity and quality of forage the land produces and the percentage of the forage ruminants will consume.
- *Production per kilogram of animal feed.* The quality of feed, which is based largely on its digestibility and protein content, determines both how much forage a ruminant will consume and how much growth and milk the ruminant will produce from the forage. Because animals first use food energy to maintain themselves before gaining weight or producing milk, eating feeds with low digestibility provides little additional energy to add weight or produce milk. Once maintenance thresholds are met, improving feed quality results mainly in more growth or milk, which means output grows disproportionately with higher-quality feed.[85]
- *Production per animal.* Even when ruminants consume no more energy than they need to maintain themselves, they still produce GHGs. In general, faster-growing or higher-milk-producing animals that receive higher-quality feed direct more of their feed into milk or meat

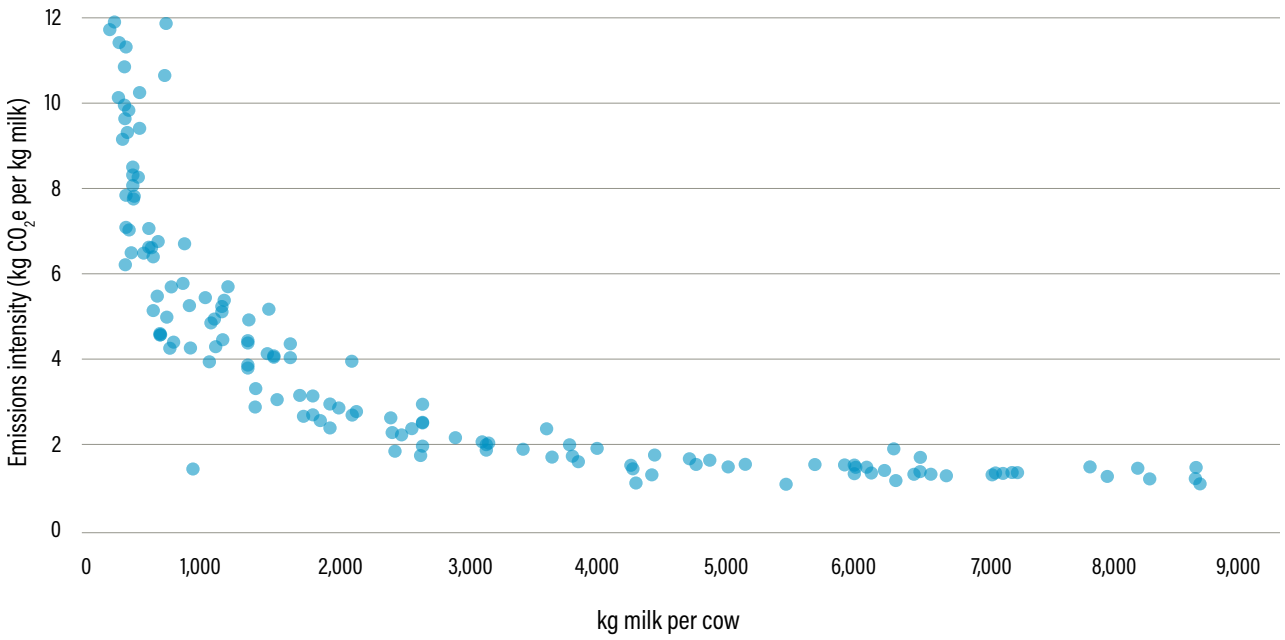
and less into just maintaining themselves. The effect is to reduce the GHG emissions per kilogram of meat or milk produced. Judged on the basis of a whole herd, the gains are even larger. Much of the feed consumed or emissions generated by a herd of cows, sheep, or goats is by mothers engaged in producing their young. And some feed is consumed and some emissions produced by animals that die before being slaughtered or finishing their milk production. As animals increase their reproductive rates and as their mortality declines, they will also increase the amount of meat and milk produced per kilogram of feed or per ton of GHGs. Figure 11-1 illustrates the close relationships between production emissions and output per animal in the case of milk.

Each of these efficiency gains reduces both land-use demands and associated GHG emissions, particularly of methane emissions—the dominant form of emissions from ruminant production (excluding land use).[86]

A striking feature of Figure 11-1 is that improving the most inefficient systems generates the largest marginal returns in the form of reduced emissions. Once milk or meat production is already efficient, additional efficiency measures (e.g., shifting to even more crop-based feed), achieve only modest additional increases in GHG efficiency. Helping inefficient livestock systems—often those of small farmers—to improve therefore provides large opportunities for environmental gains.

Improving inefficient livestock systems also provides large opportunities for improved nutrition and poverty reduction. The vast bulk of the roughly 900 million livestock keepers in sub-Saharan Africa and South Asia work on small, mixed farms.[87] In India, small and marginal farmers own 60 percent of female cattle and buffaloes. Women farmers play a particularly prominent role.[88] Systematic government investment and supportive policies led India to become the world's largest dairy producer, with heavy participation by small farmers.[89] Not only can efficiency gains in developing countries by definition lead to more milk and meat while using fewer resources, but efficiency gains by small farmers will be critical to their continued ability to enhance their incomes through farming.

Figure 11-1 | More efficient milk production reduces greenhouse gas emissions dramatically



Note: Dots represent country averages.
Source: Gerber et al. (2013).

Technical options

The wide range in beef and dairy production efficiencies across production systems and regions indicates that high technical potential exists for improvement. According to FAO data, in 2006, the yield of meat per beef carcass was 166 kg (carcass weight) in developing countries compared to 271 kg in developed countries.[90] The quantity of feed required per kilogram of beef is four times greater in Africa than in Europe.[91] In fact, variations between the most feed-efficient beef systems in Europe and North America and the least efficient systems in Africa and South Asia vary by a factor of 20, and dairy system efficiencies vary by a factor of 10.[92] Land-use requirements are calculated differently by different studies, but as estimated by Herrero et al. (2013), land-use requirements vary by a factor of 100.

GHG emissions generated per kilogram of beef or dairy protein also vary widely—even without counting emissions from land-use change. One study's findings show ranges of a factor of 30 (Figure 11-2).[93] A study by FAO in 2010 found that, on average, GHG emissions per liter of milk produced in Africa were five times those of North America.[94]

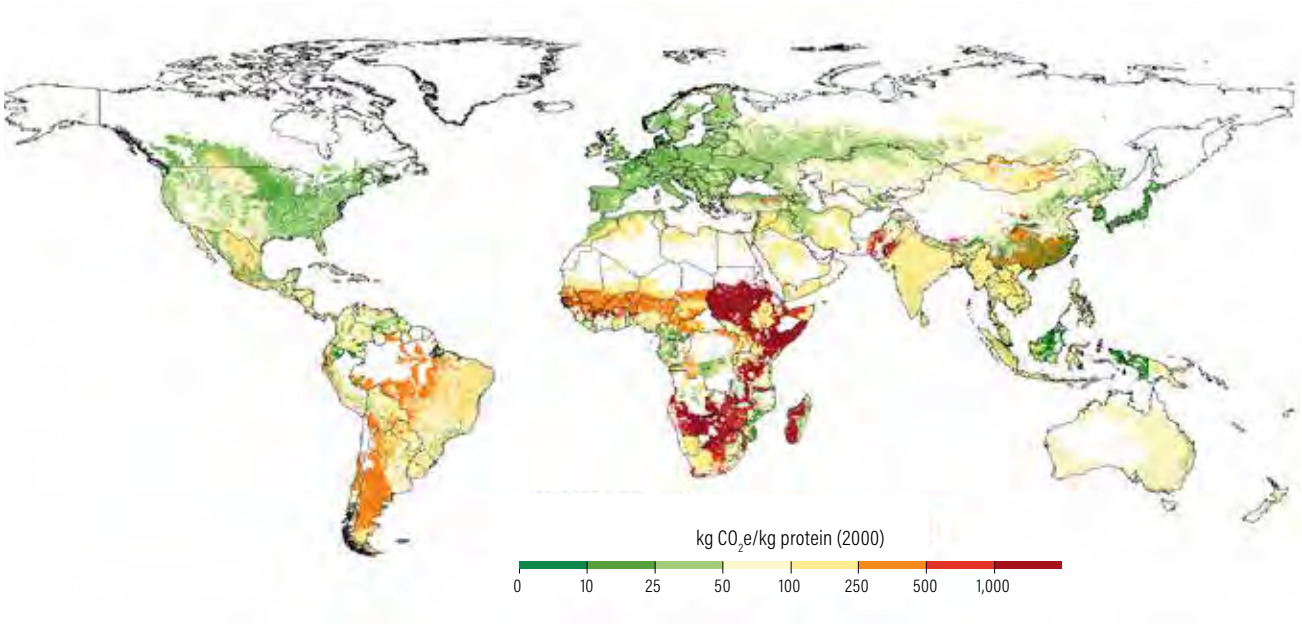
Fortunately, dairy and meat production in the developing world does not need to employ concentrated feedlots to become more efficient. Even today, Indian dairy production emits only half as many GHGs per liter of milk as African dairy production, according to the same 2010 FAO study.[95] The principal opportunities for improvement are well known, and can also build resilience to climate change. They fall into three basic categories: better feeding, better health care and overall animal management, and better breeding.

Better feeding

Improved feeding strategies fall into several categories, including the use of improved forages and better grazing, supplemental feeds, and more digestible crop residues**.**

Improved grasses and use of legumes and trees. Planting pastures with "improved" grasses (grasses bred for higher yields) and using adequate amounts of fertilizer produces larger amounts of more digestible forage. Adding legumes can reduce the need for fertilizer and increase the protein content of forage, but ruminants may selectively graze out the legumes. Rotating animals periodically through different parts of a field, or different

Figure 11-2 | Inefficient beef production systems result in far higher greenhouse gas emissions per unit of meat output



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: Herrero et al. (2013).

fields, often by moving electric fences, also leads animals to consume more of the available forage while it is most nutritious and tends to maximize grass growth by keeping grasses at optimal growing heights. (There is a scientific debate about whether very well-managed, continuous stocking can achieve the same gains.) In some areas, mixing cattle with sheep or goats—animals that graze differently from bovines—improves the efficient use of the whole pasture and can reduce worms and other pest problems.[96] In parts of Africa and Asia where "cut and carry" systems of forage predominate, large potential also exists to improve the production of more digestible and protein-rich forage crops, including both grasses and high-protein shrubs.

Supplemental feeds. Nearly all of the world's grazing lands have seasons when rainfall is too low or temperatures too cold to produce abundant and high-quality grass. Animals can lose much weight in these seasons. The need to keep animal numbers down so that they do not starve results in stocking densities (animals per hectare) that are too low to fully exploit available grass in the rainy season. Supplements can include crops or silage, which is a crop (often maize) harvested with both stovers and grains, chopped up and preserved, or hay harvested and preserved in the wet season.

Some supplemental feeding of animals with feed grains or oilseed cakes, which are highly digestible and some of which have high protein content, typically leads to substantial production gains and reductions in emissions per kilogram of milk or meat.[97] Industrial by-products like brewers' yeast and the leaves of some shrubs (such as *Leucaena* and *Calliandra*) can also provide highly nutritious supplements.

At very high levels of use, reliance on crops will often continue to increase production, but it may not continue to decrease GHG emissions—at least when compared to intensive pasturing. For example, U.S. dairy production, which relies heavily on grains, produces more milk per cow but has higher production emissions than European dairy.[98] This is because the higher GHG emissions from producing crops (rather than pasture) begin to cancel out the yield benefits of more milk per cow. In fact, factoring in land use can more clearly show the advantages of highly intensive grazing. One study found that soil carbon losses from converting intensive pasture in the Netherlands to maize to supply dairy feed would lead to net increases in atmospheric carbon for at least 60 years, despite the reductions in methane from cow digestion due to the higher-quality feed.[99]

More digestible crop residues. Ruminant animals can only eat so much food at any one time. The more digestible the food, the more energy animals derive from each kilogram of feed; and the more rapidly animals digest this feed, the more they can consume.

Roughly 16–19 percent of the world's beef and dairy feeds are crop residues,[100] but most have low digestibility, and reliance on their use is heavily concentrated in poorer countries. But opportunities exist to introduce crop varieties with more digestible residues. Farmers in India, for example, have adopted such sorghum varieties, which does much to explain why India's higher dairy production is more efficient than Africa's.[101] In contrast, few African farmers have adopted crop varieties with more digestible residues, although doing so should greatly improve both milk output and GHG emissions efficiency.[102] For African farmers to fully exploit this opportunity, grain varieties with more digestible residues will need to be adopted into local breeding programs. Other technical opportunities have long existed to improve stover digestibility by treatment with urea. Agricultural development programs have initiated many pilot efforts, but cumbersome labor requirements or the costs of urea have hindered adoption.[103]

Improved health care and overall animal management

Livestock health problems—from ticks to viral and bacterial infections that reduce growth and milk production—suppress fertility and increase mortality. Basic veterinary services, including vaccines and tick control, therefore would increase production. Other management techniques are also available that enable animals to have babies more frequently, and help the young animals grow better. Timing breeding so that young animals are born before the start of wet, forage-abundant seasons rather than dry, hungry seasons can also have a large impact.[104]

Better breeding

Some livestock breeds grow faster and produce more milk than others. Improved feeding in general should make possible more widespread use of high-yielding breeds, although some native breeds are better able to handle heat stress and do better when feeds are less nutritious. Regardless of breed, farms that keep track of their animals' production and use the highest producing animals to breed new cows can steadily increase their productivity over time.

In the developed world, the opportunities for efficiency gains among ruminants largely depend on new breeding. For decades, the focus of breeding has mostly been production per animal, leading to breeds of animals that can consume vast quantities of feed and put on weight or produce milk in high amounts. Coincidentally, this breeding has led to overall efficiency gains because more of the energy in feed goes into production of meat or milk rather than maintenance of the animal.

An alternative breeding strategy might focus explicitly on breeding animals for their efficiency in converting feed into milk or weight gain. That is, the same or increased meat or milk production would be achieved with little or no increase in feed volumes. The opportunity appears substantial—and should also have benefits in developing countries—because different individual animals appear to have a substantial range of efficiencies. However, the field of breeding deliberately for feed efficiency is in its infancy, and there can be economic trade-offs between maximizing how much milk or meat a single animal produces versus how much milk or meat a kilogram of feed produces, so the potential benefits at this time are uncertain.[105]

Using these different ways of improving efficiency, many farms have shown high potential for efficiency gains in developing countries, even in a changing climate. The following provide some examples:

Silvopastoral systems in Colombia. On roughly 4,000 ha in Colombia, farmers have developed intensive silvopastoral systems that provide a highly productive and environmentally efficient method of producing milk or beef. Farmers plant many separate layers of vegetation: a layer of highly productive grasses dominated by stargrass complemented by three rows of shrubs or trees. According to researchers at the country's Centro de investigación en sistemas sostenibles de producción agropecuaria (Center for Research on Sustainable Agricultural Production Systems),[106] *Leucaena* shrubs play a particularly critical role. These shrubs fix nitrogen, which fertilizes the grasses, and create protein-rich leaves for the animals. The shrubs grow fast, and when cows bend the branches to eat the leaves, the branches do not break but rather bounce back. The tree layer increases humidity under the canopy, which promotes grass growth and provides shade to reduce heat stress on animals.

Compared to extensive grazing, farms adopting intensive silvopastoral systems have generated several times the milk per hectare and better resist drought.[107] Production of milk can even be 70 percent higher than otherwise well-managed and fertilized pasture. Silvopastoral areas also have enhanced carbon stocks and biodiversity, including a reported 71 percent increase in bird abundance and diversity compared to standard extensive grazing.[108] These systems require a high up-front investment and complicated management but have proved highly profitable where developed.[109] Although the Colombian systems represent perhaps the most intensive form of silvopastoralism, a wide range of silvopastoral systems exists across different continents and biomes.[110]

Improved grazing systems in the Cerrado of Brazil. Over the past several decades, Brazil has cleared millions of hectares of the Amazon rainforest, the Atlantic Coastal rainforest, and the diverse, woody savanna known as the Cerrado for grazing. Around two-thirds of the resulting 175 Mha of pasture are planted in *Brachiaria*, an adapted African grass. If supported with lime and fertilizers and other good grazing management, *Brachiaria* has the potential to produce as much as 140 kg of beef per hectare and more than 200 if combined with legumes or some crops in the final months of finishing.[111] But when *Brachiaria* is not fertilized, it becomes increasingly unproductive and productivity can fall below 30 kg of beef per hectare per year, comparable to other common and poorly managed systems.[112]

A variety of forms of improved management can provide increasingly large gains in production and reductions in GHG emissions per kilogram of beef in the Cerrado. In a recent analysis, the combina-

tion of adding fertilizer and lime every 10 years, supplying basic mineral licks, and making efforts to breed more productive cattle more than doubled production per hectare from unmanaged pasture and reduced production emissions by 30 percent per kilogram of beef. The same study found possible a fourfold increase in production per hectare and a 50 percent drop in production emissions per kilogram of beef through addition of legumes in the pasture area, a schedule of fertilizing pasture every five years, additional control of parasites, some crop supplements during animal finishing, and greater attention to the timing of breeding, so that calves are born at the start of the wet season.[113]

Dairy farms in Kenya. In sub-Saharan Africa, mixed crop-livestock systems produce the vast majority of milk and meat. Farmers maintain cows in stalls and feed them mostly a combination of crop residues and forage grasses that are either cut from wild growth or from deliberately raised forage grasses. Historically, milk production has been very low. Overall, production from sub-Saharan African herds is only around 1 liter per cow per day, compared to more than 16 liters per cow from Western European herds.[114]

There are many examples of improvements. One from Heifer International describes a small farmer who boosted production 350 percent through more regular tick control and deworming, increased use of dried napier grass and green maize stalks, and haying of wild grasses during wet seasons to feed during dry seasons.[115] Overall, although many farmers in East Africa have made large gains by adopting napier grass, a highly productive and nutritious grass,[116] great potential exists to expand and improve napier production through more precise matching of grass varieties to environments, improved application of fertilizers, and closer integration into cropping systems.[117] Thousands of farmers in East Africa have also adopted high-protein shrubs, such as *Calliandra*. One study estimated that each kilogram of *Calliandra* leaves fed to cows will increase milk production by roughly one-third of a liter per day.[118] Because this kind of shrub fixes nitrogen, intercropping also boosts yields both by improving soil productivity and by attracting stem borers—a problematic pest—away from maize.[119]

Another analysis in Kenya found that changes in feeding systems led to fivefold differences in methane emissions per liter of milk among seven districts, while a mere 10 percent increase in the digestibility of feed led to emissions reductions of almost 60 percent per liter of milk.[120] Additional research suggests the potential in much of sub-Saharan Africa to improve feed digestibility by roughly 10 percent through a range of measures including more digestible stovers or an increase in the use of concentrated grains to 2 kg per day. This study estimated that either intervention could reduce methane emissions per kilogram of milk or meat by two-thirds or more.[121]

Overall potential for improvement

To entirely avoid any expansion of grazing lands by 2050, assuming no reductions in demand from our baseline, beef production per hectare of grazing land would have to increase by 82 percent instead of the 62 percent in our baseline, dairy production by 67 percent instead of the 53 percent in our baseline, and sheep and goat meat by 106 percent instead of the 71 percent in our baseline. Because we build large increases in productivity into our baseline, we are reluctant to hypothesize much larger increases. However, we imagine scenarios with larger or smaller increases in productivity per ha, achieved through greater increases in the efficiency of feed (the quantity of output per kilogram of feed measured in dry matter). Table 11-1 shows the scenario results. In our increased productivity scenario, pasture expansion falls from 401 to 291 Mha. However, if productivity were to grow at a rate 25 percent slower than in our baseline, pasture expansion would increase from 401 to 523 Mha.

Data and methodological challenges have so far prevented us from developing what we consider to be economically valid projections of livestock improvement potential. Analyses often suggest that improvements should be economical. Henderson et al. (2016), for example, analyzed different farms using the same basic production systems in Africa and found that some farmers could produce twice as much output per dollar of input. Yet no one has come up with a good way of estimating the cost of overcoming the various obstacles that stand in the way of these improvements.

Table 11-1 | Global effects of 2050 livestock efficiency change scenarios on agricultural land use and greenhouse gas emissions

SCENARIO	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	
No change in livestock efficiencies between 2010 and 2050	2,199 (+1,798)	256 (+64)	2,455 (+1,861)	10.6	20.6	31.2	27.2 (+16.1)
2050 BASELINE and Coordinated Effort (pasture output grows by 53–71%[a] between 2010–50)	**401**	**192**	**593**	**9.0**	**6.0**	**15.1**	**11.1**
Less optimistic: 25% slower rate of ruminant feed efficiency gains	523 (+121)	203 (+11)	726 (+132)	9.2	7.1	16.3	12.3 (+1.3)
More optimistic: 25% faster rate of ruminant feed efficiency gains *(Highly Ambitious and Breakthrough Technologies)*	291 (-110)	182 (-10)	473 (-121)	8.8	5.1	13.9	9.9 (-1.1)

Notes: a. Pasture output growth (per hectare) between 2010 and 2050 is 62% for beef, 53% for dairy, and 71% for small ruminants.
"Cropland" includes cropland plus aquaculture ponds. Numbers not summed correctly are due to rounding. Numbers shown in parentheses are changes relative to 2050 baseline. Coordinated Effort scenario assumes same rates of growth as projected in the 2050 baseline.
Source: GlobAgri-WRR model.

One way of appreciating the challenge is to look more closely at Latin America. We project increased production of beef in Latin America between 2010 and 2050 to be 92 percent. That level of production increase would require comparable percentage rate gains in output per hectare of grazing land to avoid additional land conversion to pasture. In fact, our 2050 baseline projects very large-scale intensification in the region, with an increase in beef per hectare of 74 percent in Brazil and 78 percent in the rest of Latin America. But given the gap between demand growth and pasture efficiency, we still project 123 Mha of pasture expansion in Latin America.[122]

What would it take for Latin America to produce these increased volumes of beef and dairy without expanding agricultural land? Of Latin America's roughly 400 Mha of grazing land devoted to beef production (by our calculation), roughly 100 Mha are arid. The arid lands have substantially less potential for intensification without heavy reliance on crop-based feeds. To achieve our estimated 2050 production in Latin America without clearing additional pasture and while intensifying only the 300 Mha of wetter pasture lands, production on those wetter areas would have to more than triple, to around 162 kg/ha. But of these 300 Mha of wetter pasture, some grow native grasses, whose conversion to improved grasses would have adverse consequences for biodiversity—consequences that do not fit our criteria for a sustainable food future.[123] Other hectares are steeply sloped or in remote areas to which supplying inputs is difficult. Assuming intensification occurred on two-thirds of the wetter pastures (200 Mha), production per hectare would have to grow to around 215 kg/ha.[124] According to Cardoso et al. (2016), such increases are possible in the Cerrado, but only under the

most efficient present forms of management on some farms. This most efficient management would include fertilizing, plowing, and replanting grasses every five years, and either some substantial reliance on crops for feed in the last 90 days before slaughter or the successful introduction of legumes into pastures (which is usually challenging because animals selectively graze them).

The suggestion from this Cerrado analysis is that every wetter, feasible, and appropriate hectare of land in Latin America would have to intensify production to a maximum level to meet rising beef needs without expanding into forests and natural savannas.

Recommended Strategies

Improvements in pasture receive a fraction of the global attention directed to improvements in cropland, but a sustainable food future will require a new level of global commitment. We offer four recommendations to address the most serious obstacles facing livestock farmers.

Establish national and international goals for livestock efficiency gains—particularly ruminant systems—and develop technical programs to implement them. Because the importance of sustainable livestock intensification is underappreciated, the establishment of specific national and international goals could help focus efforts. Efficiency can be measured by all the basic metrics discussed in this section: output per animal, per ha, and per kilogram of feed. But output per kilogram of GHG emissions does an excellent job of reflecting them all. Efficiency goals should reflect the carbon costs of land-use change and should recognize that different groups of farmers start from different levels of efficiency; targets should encourage improvement of each group.

Develop analytical systems to track and plan ruminant efficiency gains. Data about different farms and their intensification potential are limited in most countries, particularly those using diverse feeds. Modeling systems at the national or international level today are probably meaningful enough to identify large-scale potential for improvement. However, they must make a large number of assumptions because of the lack of data, and such models cannot be used to plan improvements at the level of individual farms or groups of farms.

To pursue efficiency goals, countries should develop data and monitoring systems that characterize their livestock production systems, estimate their productivity and emissions, and examine opportunities for improvement. Such systems should work at the farm level and scale up to the national level, and easily incorporate new information. Governments should institutionalize them in policymaking and nurture their development with the involvement of private research organizations.

Data and monitoring systems should also guide research with an enhanced commitment to filling in the many gaps in knowledge about livestock systems. For example, even though *Leucaena* shrubs achieved a breakthrough in Colombia's intensive silvopastoral systems by providing a fast-growing, flexible source of protein and soil nitrogen, *Leucaena* does not grow well in highly acidic soils. For Colombia's silvopastoral system to work in these soils, *Leucaena* will need to be adapted, or an alternative legume must be bred to perform the same functions. In much of Africa and Asia, livestock improvements rely on improved production of cut-and-carry forage grasses, and enormous potential exists to improve understanding of how these grasses are produced today and how they can be improved. In more advanced systems, advances in GPS technology make it easier to better analyze the management and consumption of existing natural grasslands[125] so forage can be exploited at the optimum state of maturity.[126]

Protect natural landscapes. Even though pasture intensification will be economical in many locations, without efforts to protect natural landscapes, expansion of pasture will still occur wherever it is cheaper than intensification. Analysis by Embrapa, the Brazilian agricultural research agency, has shown that expanding pasture into forest can be cheaper than rehabilitating pasture.[127] One study in the early 2000s showed that a modest form of intensification, fertilizing degraded pasture, was cost-effective in the western Amazon but that a more intensive form, using some supplemental feeds, was not.[128] Another more recent study in the state of Mato Grosso estimated that intensive cattle raising in itself is not profitable unless it is particularly well-managed.[129] A modeling analysis of Brazilian pasture intensification published in 2015 found that intensification was strongly tied to higher land prices and lower transportation costs,

themselves related to market centers, and that on average, the intensification options were more expensive than expansion options by $80 per ha.[130] Not surprisingly, Brazil has tended to intensify cattle production in some locations while expanding cattle pastures in others. Between 2000 and 2006, for example, even as cattle density in the Brazilian Amazon greatly increased, the pasture area there still increased by roughly 25 percent.[131]

There are compelling ecological reasons to protect natural landscapes. In addition, intensification strategies may prove economically beneficial for a country in the long run because they stimulate the development of more sophisticated agricultural support services and because they may allow governments to better target regional infrastructure and support services. Intensely managed livestock also require more employment to substitute labor for land. But in the short run, some individual ranchers will still tend to prefer pasture expansion if it is allowed and if they are not required to pay the environmental costs of converting forests.

Countries with natural forests or other natural ecosystems that could be converted to grazing lands will need to enact policies to protect that land from conversion. Likewise, companies seeking the same outcome will need to incorporate avoided deforestation considerations into their purchasing decisions. Such actions must make the political, legal, market, and/or reputational cost of conversion higher than the near-term financial benefit of conversion. We discuss how this can be done in more detail in the final section of this report, "Cross-Cutting Policies for a Sustainable Food Future."

Integrate programs to support intensification with a greater focus on feed quality. Livestock farmers face many obstacles to taking full advantage of intensification opportunities, including lack of formal and secure tenure over land, high cost of inputs, and limited access to relevant technical information.[132] The evidence shows that market access also has a major impact on intensification. For example, farmers have little incentive to increase milk production beyond subsistence levels if they cannot easily sell their milk.[133]

The potential interventions to address these challenges are known, and include programs to strengthen tenure, create cooperative marketing efforts, improve transportation or retail networks to lower input costs, introduce social insurance to reduce food security risks, enhance education services provided by extension agents, create farmer-to-farmer networks, and form cooperatives. We discuss these issues in "Cross-Cutting Policies for a Sustainable Food Future." Many countries have programs targeting one or more of these issues, though they are often inadequately funded.

Often, however, farmers will need to overcome all these challenges simultaneously to be able to intensify. One option would be to create systems that target a variety of programs for a group of farmers committed to working together for sustainable intensification. In areas where forests or other natural ecosystems are at risk of conversion, or where grazing land has little intensification potential but could be restored as forests, these programs could support efforts to combine intensification with forest protection or restoration. For example, governments might allow these groups of farmers to compete against each other with initial proposals for improvement and commit resources to the most promising groups with the most ambitious forest protection commitments. Combining such efforts into programs that generate measurable reductions in emissions per kilogram of beef or milk and spare natural ecosystems should also increase the capacity of such projects to attract international funding as "climate-smart agriculture."

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CHAPTER 12

MENU ITEM: IMPROVE CROP BREEDING TO BOOST YIELDS

Because crop breeding has driven much of the world's previous yield gains, this menu item involves advancing crop breeding. Great promise exists both in boosting regular efforts to "incrementally" breed better crops, and in taking advantage of rapid progress in techniques of molecular biology.

The Challenge

Breeding new crop varieties can increase yields in a number of ways. Breeding can result in plants that grow more densely, that direct more of their energy into the edible portions of plants, or that more efficiently use water and nutrients. New crop varieties can better exploit local day lengths and soil conditions, resist disease or pests, or cope with dry periods and other stresses. Breeding can increase the maximum yield that crops achieve under ideal, fully watered conditions, which is called the "yield potential." Breeding can also help farmers achieve yields that are closer to the potential in real-world conditions, thanks to characteristics that better resist disease, periods of drought or flooding, or other sources of stress.

Although farmers increase crop yields in part by using better seeds and in part through better management (especially increased fertilizer use), disentangling the contribution of each is difficult. Green Revolution crops, for example, produced higher yields mainly when combined with fertilizer application and irrigation. Despite this challenge, typical estimates claim that, since the Green Revolution, breeding has been responsible for roughly half of all crop yield gains.[134] In the future, crop breeding will probably have to bear more of the burden because, as discussed, except in sub-Saharan Africa agriculture has already exploited most of the "easy" potential ways of increasing yields: adding more water, using chemical inputs, and introducing basic machinery.[135]

To provide continuing yield gains, breeding will need to become more nuanced. In the past, much yield gain in the major cereals wheat and rice resulted from shifting biomass from vegetative parts to seeds and shortening and stiffening the stems so they could support more grain (resulting from higher fertilizer application) without falling over. These traits, which were largely responsible for the Green Revolution, are in some cases reaching their biological limits; crops can only grow so close to one another before they have no more space, and crops can only direct so much of their growth into edible portions before they will no longer stand upright. These limits, plus the need to boost crop yields even faster than in historical trends, present the crop breeding challenge.

The Opportunity

Four major related opportunities exist to increase crop yields through improved breeding: speeding up crop breeding cycles, marker-assisted and genomics-assisted breeding, improvement of "orphan" crops, and genetic modification.

Speeding up "incremental" breeding cycles in developing countries

Although there is a continuum of breeding efforts, it is helpful to think of breeding as focused on big "step-changes" in varieties, achieved through major changes in traits, on the one hand, and small continuous improvements, on the other. Major step changes in yield, disease resistance, or stress tolerance are often the result of incorporating rare genes with large and visible effects, or of changing from open-pollinated to hybrid crops. Such major changes involve concentrated efforts by researchers to develop new varieties. Famous historical examples include the creation of successful hybrid maize seeds in the United States in the 1930s; dwarf wheat and rice in the 1960s, which allowed crops to produce more seeds without stems breaking under the weight; and new breeds of *Brachiaria*—an African grass—developed in the 1980s and 1990s, which allowed the pasture grass to thrive in Brazil's highly acidic soils. By contrast, continuous incremental improvements result from the steady accumulation of thousands of favorable genes with small effects. Incremental improvements result from a continuous process of selecting higher-yielding individual crops and breeding them.

Commercial breeding of maize in the United States sets the standard for the continuous incremental improvement that results from modern crop breeding. A few major seed companies follow a series of steps to regularly improve their varieties.[136] They create new in-bred lines of maize to assure genetic consistency, cross-breed these new lines to create new "hybrid" varieties (crosses of two lines), test the new results for performance and select new commercial varieties from the best performers, set out test strips widely across the corn (maize) belt of the United States every year, examine yields and other characteristics and select desirable performers, and finally leverage an extensive seed network so farmers quickly adopt the new commercial varieties.

Faced with competitive pressures, these seed companies have new breeding cycles that require only four to five years from one generation of products (hybrids) to the next. This timeline contrasts with public breeding programs in developing countries, which often take 10 years or more to develop a new generation of seeds, plus many more years to disseminate them. By overlapping their efforts, U.S. seed companies are releasing improved varieties of major cereals every two or three years. As a result, studies find that the average hybrid maize seed used in the United States is only 3 years old, compared to 17 years for maize in Kenya, and 13 years for wheat, and 28 years for rainfed rice in India.[137]

A variety of techniques are available to speed up breeding. For example, breeding outside of the main crop-growing season (such as the winter or dry season) can double rates of improvement and in some tropical countries requires irrigation only of test fields.[138] Doubled haploid breeding can accelerate the breeding process by inducing plants to produce identically matching chromosomes in each pair within only two seasons, a process that normally takes six or seven generations. This technique makes it possible to purify strains of plants with desirable traits, which can then either be released as true-breeding varieties (in rice or wheat, for example) or crossed with other, similarly purified plants to form hybrids (as is common with maize).[139]

Virtually every country in the world has some basic set of institutions for national crop breeding that receives financial support from the national government and technical support from international networks. But funding levels often vary from year to year. Breeding is a multiyear effort and requires well-trained breeders who develop knowledge over years of experience. Ultimately, funding that is both adequate and consistent is the key to successful crop breeding.

It is also difficult to get improved seed varieties rapidly into circulation. Although many analyses assume that farmers in developing countries reuse their own seeds from year to year, in many cases smallholder farmers purchase a significant proportion of their seeds from local markets or from fellow farmers.[140] Yet only about 2.4 percent are "certified seeds" from private sector companies. Commercial farmers who have the funding to buy private sector seeds and can evaluate them are far more likely to buy these seeds more frequently, and to test new varieties offered by their seed supplier. Competition among seed companies in the United States and Europe also fosters sales efforts that lead to more rapid adoption. Government seed companies often lack these incentives. Because purchasing commercially provided seeds creates markets for more rapid variety development (by providing seed companies with a steady revenue stream), there are synergistic benefits between fostering improved distribution systems and more rapid adoption rates.

The potential of marker-assisted and genomics-assisted breeding

Crop breeding has primarily improved crops by crossing different individual members of the same plant species, different varieties of the same plant species, or sometimes assisting self-pollination by the same plant to achieve consistent traits. To generate new genetic diversity with which to experiment, breeders occasionally have used mechanisms such as radiation to create new plant mutations. They then test to determine whether any mutations are favorable and, if so, spread them through conventional cross-breeding.

Until recently, breeders primarily bred new crops by crossing two individual members of the same species, which they select for breeding based on how those crop varieties performed in the field—while occasionally using estimates of whether they contained certain gene types (alleles). Breeders then repeatedly select offspring with the most desired traits for dissemination or for subsequent crossing. Even with the advent of genetic modification discussed below, conventional breeding has driven yield gains in part because most traits that lead to higher crop yields result from many genes and their interactions with environmental factors.[141] Conventional breeding provides the means by which breeders can affect large numbers of genes (even without knowing precisely which genes or their genetic codes).

Even as breeding has continued in this way, molecular biologists have developed dramatically faster and cheaper methods of analyzing deoxyribonucleic acid (DNA), providing new mechanisms to accelerate and enhance crop breeding. One mechanism, called marker-assisted breeding, allows breeders to map and label portions of DNA associated with agronomically useful traits.

With these techniques, even without growing crops, breeders can identify those seedlings from among a large population that are most promising for further breeding. This approach reduces the time required to develop new crop varieties because breeders need not sow millions of plants or wait for individual plants to grow to determine which individuals to cross.[142] Thus, while "low-tech" conventional breeding may require a minimum of 7 to 17 generations of crops to produce a new cultivar, marker-assisted breeding can cut this breeding cycle down to just a few generations.[143] The International Rice Research Institute (IRRI) demonstrated the potential of this approach in 2009 by introducing a rice variety that could survive submersion under water for up to two weeks. IRRI developed this variety in just three years after it identified the relevant genetic marker for flood tolerance, a trait found in a traditional variety grown in a flood-prone part of India. Since then, IRRI has delivered 10 additional varieties that are resistant to flash flooding in South and Southeast Asia.[144]

Like genetic engineering, marker-assisted breeding by itself is primarily of value for simple traits determined by a single gene. But within the past decade, improvements in "genomics" have created opportunities to increase and accelerate yield improvements by analyzing groups of genes. Genomics applies DNA sequencing methods and genetic mapping to analyze the function and structure of whole (or large portions of) genomes—the complete set of DNA within a single cell of an organism.[145] Genomics also includes the evaluation of the large portions of DNA that do not "code" for new proteins but rather play critical roles by determining when genes are turned on and off.[146] A breeder that desires to breed-in many traits now may be able to predict through a combination of a DNA map and statistical analysis whether or not individual plants have all the genes needed to yield the desired traits.[147]

Genomics has the potential to make conventional breeding not only faster but also better. Conventional approaches require that breeders use indirect methods to identify seeds with the favorable underlying genes, which they can confirm only once those genes express themselves in beneficial traits in actual plants. The new genomics-assisted techniques allow breeders to identify and breed for promising gene combinations that are predicted to occur when parents with complementary traits are crossed. Breeders can then test for the presence of these genes in offspring and push these combina-



tions forward through continued breeding even if the first generations of offspring do not themselves express favorable traits. That may occur, for example, because the trait, such as yield, only becomes evident in large field plots and cannot be accurately measured in single plants in a greenhouse.

In general, large commercial seed companies have extensively incorporated genomic techniques into their breeding programs.[148] Much crop breeding is undertaken by the public sector, however, and the achievements of these techniques are still limited for several reasons, in part because they are new and in part because the facilities to use such techniques are less available in developing countries.[149]

Although genomics is already speeding up plant breeding, the extent to which genomics will enable major new improvements remains unclear. Breeding for complex traits that depend on many genes and their relation to the local environment is inherently complicated. Although identifying genes is becoming easier, knowing what these genes do and how they respond to a variety of environmental settings is hard, time-consuming, and complicated. For complex traits, the size of the crop population under study must be large, the assessment of traits should be reliable and replicable, and the population of crops studied must be of the same variety.

Fortunately, technological advances are creating new capacities in techniques known as "high throughput phenotyping." They include using sensing devices to monitor attributes of plant growth in the field and robotic platforms that can make reliable measurements of traits that have been difficult to quantify, such as water use, photosynthetic capacity, root architecture, and biomass production.

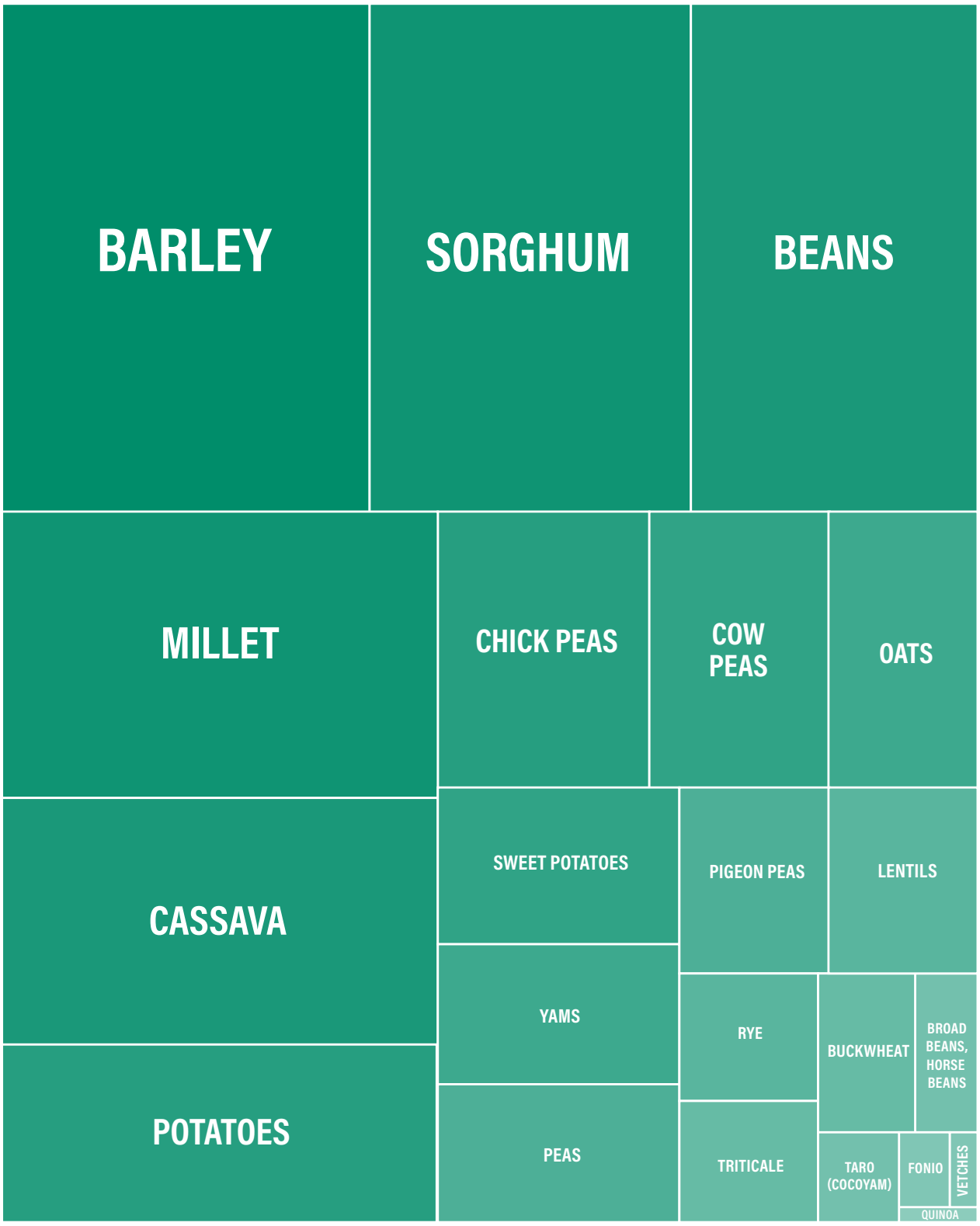
The information gathered will be cumulative. As scientists identify the molecular functions of different strands of DNA and their relationship to traits, they gain increasing ability to predict what combinations of DNA are optimal for specific crop types and environments. In addition, breeding institutions can share different responsibilities. Globally oriented research institutions can engage in "pre-breeding" that uses some of these new techniques to develop promising plant material while local institutions can incorporate promising germplasms into local varieties. This kind of division of responsibilities is occurring in partnerships between U.S. and European universities, the CGIAR system, and national organizations.[150]

Improvement of orphan crops

The advances in marker-assisted breeding and genomics create additional potential to breed improvements into orphan crops.[151] The term *orphan crops* generally refers to crops that have received relatively little research attention, often because they are little traded on global markets. Yet they are important for food security in many regions.[152] Orphan crops include sorghum, millet, potatoes, peas, cassava, and beans. By one definition, 22 orphan crops occupied almost 300 Mha in 2017 (Figure 12-1). Because of their importance to poor smallholder farmers, improving orphan crop yields to even half of their maximum potential would have greater benefits for food security in regions such as sub-Saharan Africa than improvements in any other crops.[153]

Marker-assisted selection and genomics should make it easier to achieve quick yield improvements in these less-studied crops in two ways. First, these technologies can increase the pace of breeding programs. Second, these technologies may in the future enable breeders to understand the gene combinations that have already led to yield gains in more intensely studied crops, and then select for them in orphan crops.

Figure 12-1 | Orphan crops occupy nearly 300 million hectares



Note: Total harvested area of these 22 crops was 296 million hectares in 2017.
Source: FAO (2019a) using definitions of ***orphan crops*** from Naylor et al. (2004), except teff, for which data on area under cultivation are not available from FAO (2019a).

Genetic Modification

Genetic modification (GM) typically refers to inserting specific genes—often from a different species—into the genome of a target plant. This approach differs from conventional plant breeding, which selects individual plants with desired traits and sexually crosses whole genomes from the same or very closely related species to produce offspring with random mixes of genes from the parent plants. To date, most GM crop traits have been inserted into just four high-value crops: maize, soybeans, canola, and cotton. Of the 190 Mha annually planted in GM crops—approximately 12 percent of global cropland[154]—the vast majority are in the United States, Canada, Brazil, Argentina, India, and China.[155]

GM crops overwhelmingly employ one of two basic traits. The first conveys absolute resistance to the herbicide glyphosate. This allows farmers to spray glyphosate—originally effective against virtually all weeds—directly over crops that the herbicide would otherwise kill. This trait is most used for soybeans and maize. The second trait is the production of a natural insecticide from the bacterium *Bacillus thuringiensis* (Bt), which is particularly effective against insect larvae such as those of the corn rootworm and the corn borer. Bt traits are used predominantly in maize and cotton.

Genetically modified crops: the debate so far

Genetic modification has potential to improve crop breeding and increase yields, but it is the subject of by far the most contentious public policy debate surrounding plant breeding. We believe that the merits of GM technologies lie primarily with traits other than glyphosate resistance or Bt, as we discuss below. But because the public debate about GM crops has focused so heavily on these two traits, we summarize the debate here. The debate also encompasses extending the use of these crops to Africa.

The debate focuses on four issues: food safety and human health, environmental toxicity and pest resistance, crop yield effects, and economic effects on farmers, particularly a shift of profit and control to major corporations. We draw heavily on a 2016 study by the National Academies of Sciences, Engineering, and Medicine, which, based on our own independent review of the evidence, does a careful job of presenting the evidence.

Food safety and human health

Fear that GM crops are not safe for human consumption drives much of the public opposition to genetically modified organisms (GMOs). At this time, there is no evidence that GM crops have harmed human health.[156] The vast majority of studies have found no adverse health effects.[157] Even GM critics argue that they oppose GM crops mainly because the risks have been insufficiently studied.[158]

Much attention has focused on possible links between glyphosate and cancer. Significantly, this debate is not about whether the genetic modification itself causes cancer, but on the toxicity of glyphosate, whose use is enabled by breeding glyphosate resistance into crops. Most studies have found little to no evidence of glyphosate causing cancer in humans.[159] One of the most alarming studies of GM crops claimed to find a large increase in cancers in lab rats. However, the sample involved only 10 rats of each gender, and food safety institutes criticized it for a high likelihood of random error.[160] Over the objections of the authors, the *Journal of Food and Chemical Toxicology* retracted the study.[161] A subsequent review of the study by the U.S. National Academies of Science, Engineering, and Medicine was less critical of the study's method but still did not find that it showed statistically significant evidence of concern.[162] In its 2016 assessment, the U.S. National Academies of Science, Engineering, and Medicine found no differences in cancer rate trends of different cancers in the United States and Europe, despite the U.S. embrace of these crops and Europe's resistance.

Although the evidence as a whole does not show health effects, that does not mean glyphosate itself is harmless. Many studies of glyphosate, whether epidemiological or using animals, have suggested pathways through which glyphosate or the chemicals that occur as it is broken down by microorganisms in the environment could cause health effects, possibly even including cancer.[163] One concern is a potential link between high exposure to glyphosate, generally in farmworkers, and a higher rate of non-Hodgkins lymphoma.[164] As another example, even though the U.S. Environmental Protection Agency found that glyphosate is not an endocrine disrupter through traditional pathways, other researchers identified possible effects through more unusual pathways.[165]

The evidence on Bt crops suggests that health effects have probably been positive overall because Bt crops, so far, have enabled many farmers to reduce significantly their overall use of insecticides. These insecticides, particularly those used in China and India, are generally more toxic than Bt.[166] That is true even though in some areas Bt crops have led to an increase in "secondary" pests—pests not controlled by Bt—and reducing the secondary pests can, in turn, require more pesticide use. However, several studies show that Bt crops can also contribute to reductions in secondary pests[167] and, thanks to reduced overall use of insecticides, can even promote beneficial insects that reduce pests on neighboring maize, peanut, and soybean fields.[168] Bt crops have also reduced use of insecticides on non-Bt crops by reducing the presence of major pests, such as corn stem borer.[169]

Although neither glyphosate nor Bt is without health concerns, the human health evaluation of Bt and glyphosate-resistant crops depends not on their absolute health risks but on their health risks relative to the alternatives. For most farmers, the alternative means use of other pesticides that raise more concerns than glyphosate and Bt. The scope and increase in use of both glyphosate and Bt crops warrant continued health studies, but the evidence to date is that these GM crops have not increased health risks compared to the alternatives and, in the case of Bt, may be contributing some health benefits.[170]

Environmental toxicity and pest resistance

Much of the environmental criticism of glyphosate-resistant and BT crops acknowledges the advantages of reduced toxicity in the short term but argues that they may lead to greater toxicity in the long term.

Any increased reliance on specific pesticides can lead to more rapid development of resistance to those pesticides in weeds or invertebrate pests so, over a longer period, use of these GM crops could lead to the loss of benefits from the lower toxicity of glyphosate and Bt. There have been examples of crop infestations by insects that are resistant to some Bt proteins. Resistance to the effective proteins in fall armyworm emerged within three years of introducing multiple types of Bt in Brazil.[171] In South Africa, the one sub-Saharan African country to use Bt maize, a variety was introduced in 1998 but some resistance evolved in stem borers by 2006. That form of Bt maize was withdrawn from the market in 2013 and replaced by a new variety, to which insects have also started to develop resistance.[172] A 2016 study reported 16 separate cases of Bt resistance, each of which took an average of only five years to evolve.[173]

One strategy to reduce the evolution of resistance has been, where feasible, to introduce crops with multiple Bt proteins. Bt crops can generate a variety of proteins that harm insects, and the types of proteins and level of harm vary. Breeding multiple Bt proteins into crops may reduce the likelihood of resistance developing because even genetic mutations that lead to resistance to one Bt protein will not give pests an advantage if they remain vulnerable to the other Bt proteins.[174] But forms of cross-resistance to multiple Bt proteins can also evolve, although the science is complicated and depends on the proteins.[175] Stacking of Bt proteins may help reduce the rate of evolution of resistance, but it will probably not stop it entirely.

Growing herbicide resistance is a significant concern for glyphosate-resistant crops. Twenty-four weeds in the United States have become resistant, including several that are major problems, particularly for soybean production.[176] Large seed companies have responded by introducing varieties of

soybeans that are also resistant to older herbicides, such as 2,4-Dichlorophenoxyacetic acid (2,4–D) and dicamba. Relative to insecticides, these chemicals (like other herbicides) have lower human toxicity concerns. But these older herbicides pose significant environmental concerns as they are far more toxic to broad-leaved plants and more likely to "drift" on winds from farm fields to adjacent lands and damage nontarget plants.[177]

A key strategy to reduce the evolution of pest resistance is for farmers to continue to plant crops without the GM traits on some of their fields, creating pest "refuges" where non-Bt or non-glyphosate-resistant crops can be grown. In these areas, weeds and insects without resistant genes would continue to survive. They can then breed with insects that evolve resistance after exposure to GM crops in other fields and the offspring will die when exposed to Bt plants or glyphosate (so long as whatever resistant gene evolves is recessive). The effectiveness of this pest refuge approach varies with the toxicity of the Bt plant and the size of the refuge, among other factors. In general, countries with larger refuges and well-managed farms tend to delay emergence of resistance, and in some cases have prevented resistance from appearing for roughly 20 years.[178] But farmers do not always follow the practice. Small farmers in particular struggle to set aside and maintain refuges, refuge area requirements are sometimes too small, and resistance can evolve anyway.

The emergence of resistant weeds is one reason why glyphosate-resistant traits have not always led to a reduction in the aggregate use of herbicides. Usage depends on the crop. The total application of herbicide active ingredients to U.S. maize crops declined by 18 percent from 1991 through 1994 even as herbicide use shifted toward glyphosate, a safer product.[179] Yet the overall herbicide application to soybeans in the United States grew by 70 percent over the same period , both because the application rate for glyphosate increased and because glyphosate use did not significantly reduce the application of other herbicides by volume.[180]

In addition to risks that glyphosate-resistant crops may not ultimately reduce use of other pesticides, increased application of glyphosate is also a concern. Even if it is less toxic to humans and less likely to drift than some other pesticides, glyphosate still likely has adverse effects on some other organisms. The greatest risk is probably to some aquatic species.[181] At least one study raises concern that glyphosate may be harming honey bees,[182] whose hive collapses in the United States have posed major challenges to pollination and agriculture itself. As with other pesticides, these environmental effects are seriously understudied. Because the global use of glyphosate is high and continues to expand, continued research into both human and environmental effects of glyphosate remains appropriate.

Crop yield effects

Whether glyphosate-resistant and Bt crops have led to yield gains is open to some debate. Neither trait by itself was designed to boost the yield *potential* of these crops, as opponents of GMOs point out. In addition, the introduction of a new gene often leads to "yield drag" because conventional versions of those crops continue to improve during the time it takes breeders to integrate the new gene into local crops. Yields eventually catch up for a particular GM gene,[183] but the insertion of new genes will repeat the drag effect in the future, although more rapid breeding techniques generally should reduce this drag.

Yields improve not only when maximum yield potential increases but also when farmers are better able to control stresses, such as pests, on their crops. Easier weed management enabled by use of glyphosate-resistant crops, or greater control of insects that attack crop roots enabled by Bt, could in theory boost yields. In addition, greater profitability thanks to reduced losses caused by pests could lead farmers to make other investments that improve overall yields. Therefore, the question is what net effects on yields GM crops have produced in the real world.



A huge number of studies, using almost as many different approaches, have tried to answer this question. They have offered a range of answers, but fundamental methodological challenges make it difficult to get a definitive answer. Studies that compare test plots of well-managed GMOs with well-managed alternative plots often find little or no effect on yields, particularly from glyphosate-resistant crops.[184] However, their methods make them less likely to recognize the potential for real-world gains from the greater ease of pest management that GM crops may allow because, for example, Bt reduces the need to apply pesticides at all and it is easier to apply glyphosate on top of crops rather than carefully around them. Conversely, comparisons of real-world yields obtained by farmers who adopt and farmers who do not adopt GM crops are confounded by the fact that early adopters tend to be farmers already achieving higher yields. Also, farmers who pay more for GM seeds are likely to plant them on better fields and pay more attention to them.[185] Similarly, studies based on country comparisons tend to ignore the fact that countries adopting GM crops already had high and rising yields.[186]

In 2016, the National Academies of Science, Engineering, and Medicine produced a particularly careful review of the evidence from the United States, building on a report by the National Research Council in 2010. The bulk of the evidence shows different results for glyphosate-resistant crops and Bt crops.

The net effect on yields of glyphosate-resistant crops has probably been either zero or very small.[187] There are wide differences in study results, and substantial uncertainties because of methodological differences between studies, but this is the most reasonable conclusion that can be drawn from the evidence to date. By contrast, the evidence tends to show some yield gains from Bt crops. The 2010 study concluded that Bt had led to 5–10 percent yield gains for cotton[188] and perhaps smaller gains for maize.[189] The 2016 study found repeated evidence of gains of this size in both maize and cotton, based on studies of direct plot comparisons; some studies showed larger gains.[190] Yet the 2016 report found that despite this evidence from farm-level studies, U.S. yields in the major GM crops had not grown any more rapidly after the introduction of

GM varieties than they had before. The authors also found no reason to believe that yields might not have grown as fast without the advent of GM crops. The report plausibly concluded, "Although the sum of experimental evidence indicates that GE [genetic engineering] traits are contributing to actual yield increases, there is no evidence from USDA data that they have substantially increased the rate at which U.S. agriculture is increasing yields."[191]

In developing countries, the evidence for yield gain is stronger and intuitively more likely, both because many farmers will have less access to other pesticides and because pests tend to flourish more in warmer environments, which are more common in developing countries. Most of the studies have focused in particular on Bt cotton and have found increases in yields.[192] The largest apparent success occurred in India, which experienced yield gains in cotton of 56 percent between 2002 and 2011, which corresponded to the introduction of Bt cotton. Doubters properly point out that nearly all of this rise occurred from 2002 to 2005, when official Bt cotton adoption rates were only 6 percent.[193] Yet other researchers noted that even in this period, some farmers were unofficially adopting the seeds, suggesting that the 6 percent adoption rate was an underestimate and pointing to a significant role of Bt cotton in yield gains.[194] Although improved management of cotton overall probably played an even larger role, the evidence tends to justify claims that Bt cotton helped significantly increase yields, particularly in locations where pests addressed by Bt were most prevalent.[195]

Overall, the weight of the evidence supports the proposition that GMOs to date have led to meaningful but not large yield gains on average for Bt crops. Nonetheless, precise data are lacking.

Effects on costs, labor productivity, and equity

A fourth concern with genetic engineering is the expense and control of GM crops. Most farmers need to buy new seeds annually and GM seeds cost more than traditional varieties. The concern is that private seed companies will extract more of the income generated by farming, leaving farmers with less.

Although seeds cost more, they also bring economic benefits. In addition to yield gains, particularly for Bt crops, both major types of GM crops reduce the work and expense of pest control. Studies have generally found sizable savings from reduced labor and, in the case of Bt, from the costs of alternative insecticides, which explains the high rates of adoption of these seeds in countries like Brazil, the United States, and Argentina.[196]

The question is whether these economic benefits outweigh the higher seed costs and improve overall profitability. The answer is largely determined by the pricing policies of companies, which naturally seek to profit to the extent they can from their seeds, and from the level of competition among companies. But farmers generally will not buy the seeds unless they make their farms more profitable. Not surprisingly, studies have generally found that those farmers who purchased seeds found them profitable.[197] The evidence suggests that GM seeds may not be profitable in years or locations with low pest pressures.

The evidence has been more mixed where small farmers are concerned, although many studies have found substantial benefits for small farmers.[198] There are prominent examples of farmers in parts of India and West Africa beginning then abandoning the use of Bt cotton.[199] Higher seed costs, even if more than compensated for by increased yields, can be more of a burden for small farmers than large farmers because they are often less able to raise the initial capital needed to purchase seeds and other inputs. Higher input costs also increase the risks associated with bad weather and crop failure. Small farmers may be less able to balance these added losses in bad years with the greater benefits in good and average years. This is the case even though small farms can be as productive as large farms, or more so, in many farming systems.[200] The availability of credit to small farmers is one important determinant of whether they can benefit from GM crops.

Despite this mixed record, the evidence that GM crops could enable small farmers to farm better is strong. The impediment appears to be the price. If good seeds could be provided at low cost or without a premium, the benefits could be compelling. For example, maize farmers in Africa face substantial challenges from insects such as stem borers that can be controlled with Bt.[201] They are also facing substantial losses from the fall armyworm, recently arrived from the Americas. With support from

USAID and the Bill & Melinda Gates Foundation, public breeding institutions are working to provide Bt maize in Africa that works against such pests without the price premium normally paid elsewhere.

Outstanding challenges to introducing GM crops more widely in Africa are thus both technical—for example, whether a Bt variety can be developed to kill fall armyworm and other threats to maize in Africa without quickly leading to resistance—and economic. Most small farmers in Africa do not purchase seeds annually, either because they cannot afford hybrid seeds or because higher-priced seeds are too risky given weather variations. Introducing genetically engineered crops without addressing these issues is unlikely to contribute to yield increases or socioeconomic development.

Some conclusions regarding the debate over major GM crops

Although claims both for and against GM technology have often been overstated, the best evidence is that GM technology has already provided some yield gains from Bt crops and has probably reduced toxicity both to humans and the environment, relative to the use of alternative crop varieties that require more pesticide use. For many farmers, both crop traits have led to increased profitability and reduced labor requirements, although the experience of small farmers has been has varied. Less positively, both glyphosate itself and Bt, like other pesticides, pose concerns. The big, unknown question is whether or how long these traits can remain functional before being overwhelmed by resistance, and what would replace them if and when resistance undermines their utility.

Although the controversy over today's dominant GM crops has led us to provide this summary, we do not believe that debate over these particular GM traits should dictate policy about the entire technology of genetic engineering. The case for using this technology is compelling when the full range of potential gains and costs is taken into consideration.

Regarding health effects, there is a scientific consensus that food safety does not justify rejecting genetic modification in general. That is the view of such entities as the U.S. National Research Council, the European Joint Research Centre, the American Medical Association, the American Academy for the Advancement of Science, and the combined National Academies of Sciences, Engineering, and Medicine.[202] There is also a general consensus that while GM technology enables a range of crop modifications, some of which should appropriately require significant safety testing, the basis for regulation should generally be the types of changes in a crop rather than the method for generating them.[203] Even conventional breeding techniques can include such methods as using radiation to generate more mutations.[204] GM technology is probably more capable of altering plants in ways that raise new risks, but many uses of GM technology are unlikely to pose any more significant risk than conventional crop breeding.[205]

In addition, while the market power granted by patents to private companies can raise equity and even efficiency concerns in any industry, patents play an important role in the seed industry that is broader than their application to GM technology. And GM technology does not always involve private patents. The public sector can also be a source of GM innovation, with the technology then licensed freely.

Use of genetic modification to resist diseases

One important reason not to allow the debate over Bt and glyphosate-resistant crops to dictate GM policy is the potential uses of GM technology to breed pest-resistant traits into crops under serious pest attack. In Hawaii, for example, papayas would probably have been wiped out without the benefits of GM technology. Hawaiian papayas faced a virulent virus but were protected by insertion of genes from the virus itself into the papaya, generating a kind of plant immune response.[206] Because of public resistance to GMOs, this variety has not spread much to the developing world.[207] Likewise, current work demonstrates the potential for controlling potato late blight worldwide with GM technology.[208] Transgenic potato varieties under trial in Uganda are unaffected by this pathogen.[209] GM soybeans with resistance to Asian soy rust are under development by a major seed company: this disease causes annual losses of around $2 billion in Brazil, and the chemical sprays used for disease control are losing their efficacy.[210] GM tomatoes have demonstrated resistance to bacterial spot in successive years of field trials in Florida, where the disease has been

the number one endemic disease problem affecting tomatoes for over 40 years.[211]

Although data sets are incomplete,[212] studies estimate that various diseases, animals, and weeds cause yield losses of 20 percent to 40 percent of global agricultural production.[213] Crop diseases can originate from many different sources, including viruses, bacteria, fungi, oomycetes, nematodes, and parasitic plants. Scientists have started to understand that, like animals, plants can respond to and defend themselves against infections and parasites. Although plants, unlike animals, do not have mobile defender cells such as antibodies, each cell relies on its own immunity and responds to systemic signals emanating from infection sites.[214] The plant has proteins that detect pathogens and trigger immunity responses, including signals for a cell to die to prevent further spread of the disease.[215]

When selecting for disease-resistant crop varieties, breeders are essentially selecting for genes that will code more effective detector chemicals.[216] But using conventional breeding takes time, and pathogens are often able to overcome resistance conferred by a single, major gene.[217] By identifying the genes that promote pathogen susceptibility and removing them, or by identifying the genes that promote pathogen immunity and adding them, GM plant breeding can limit plant vulnerabilities and enhance resilience.

The world's crops are likely to become increasingly exposed to a greater variety of diseases because the expansion of trade and travel makes it easier for disease pathogens to move around and because warmer, wetter weather overall makes it easier for pests to thrive. In addition, any yield breakthroughs by particular crop varieties encourage other farmers to use the same varieties. Broad adoption of the same or similar varieties increases resistance development in the disease organism, and major crops may become more susceptible to global diseases.[218] Genetic techniques do not displace conventional breeding but allow for more varied and faster responses to diseases in some cases.

Emerging new techniques of genetic identification and modification

When deliberate genetic modification of DNA to improve seeds first began, the primary technique involved a kind of "gun" that injected hundreds of copies of a gene into a cell in the hope that the gene would attach itself somewhere and express itself. Only by growing the offspring could scientists determine whether the new genes were doing anything. The technique was essentially a time-consuming form of trial and error, which greatly favored large companies because only they could afford the scale of effort. Over time, biologists have developed a variety of alternative techniques that could deliver genes more precisely, in less time-consuming and expensive ways.

In 2013, scientists reported dramatic progress with gene editing using an evolving method, called CRISPR-Cas9 (CRISPR). Although some of what this method allows can be achieved by other methods,[219] CRISPR is far more agile, inexpensive, and quick. CRISPR allows biologists to precisely target genes at any location in strands of DNA to turn genes on and off at will. It also allows them to cut and insert new genetic material of their design in precise locations.[220] Scientists can also insert genetic switches into plants that will activate genes only if they are exposed to certain chemicals or light. Each year since 2013, scientists have been announcing new variations on the technique that offer a range of new options. For example, scientists can now edit individual "base pairs" of DNA rather than entire genes. Among the other opportunities provided by CRISPR, scientists can study and modify the 98 percent of DNA that does not produce proteins but much of which has other important, though little understood, functions.

CRISPR is so new that no one can confidently predict which advances it will ultimately generate in crop breeding. Breeders caution that at this time there is limited knowledge of what the different parts of plant genomes do. In addition, most crop yield gains result from multiple gene interactions, so the process of conventionally breeding desired plants with each other is likely to continue to drive the majority of yield gains for the foreseeable future. Yet CRISPR offers many new opportunities:

- The process enables gene editing to occur with less yield drag. This drag results from taking one crop variety with a desired special trait but not necessarily other high-yielding qualities and cross-breeding it multiple times with elite, high-yielding varieties to generate a high-yielding variety with that same special trait. CRISPR enables breeders to introduce specific traits directly into elite varieties, circumventing the need for cross-breeding multiple times.

- CRISPR makes it easier for plant breeders to turn genes off, breed a variety, and then quickly obtain information about what the gene does. Over time, knowledge of the functions of different parts of the genome should accumulate and enable more deliberate breeding.

- CRISPR enables gene editing to achieve more complex results because sequentially using CRISPR makes it easier for researchers to alter multiple genes in a plant as well as to influence noncoding DNA, which regulates whether genes are expressed.

Combined with improved genomic information, the new potential to deliberately and intelligently edit DNA seems likely to offer high potential for crop yield improvement. The new techniques also make it possible for much smaller research teams to use genetic modification techniques. This could reduce the likelihood that genetic modification will be dominated by a few, large companies. But it is also possible that small companies will help develop new traits then sell them to larger companies to get the new traits through expensive regulatory processes. In addition, CRISPR is unlikely to alter the fact that large companies dominate sales of some crop seeds, such as maize; the result could be to give large companies ultimate control over the seeds even if traits are developed elsewhere.

At the same time, the ease of the new technique also raises issues of health and environmental safety because the technique is likely to become widespread. Even talented high school students can now learn to do genetic modifications. How the world will manage these new techniques raises questions that go far beyond crop breeding.

Recommended Strategies

The combination of the great need for yield gains and new technologies to map or edit DNA makes a strong case for increased dedication to crop breeding. We offer four recommendations:

Boost breeding budgets

Substantial investments by a wide range of institutions will be required to improve breeding where it is now slow and take advantage of new technologies.[221] The challenge is particularly acute in developing countries, where these innovative approaches to plant breeding are still essentially out of reach for most public-sector researchers. Developing countries need more scientists trained in modern breeding technologies, more transfer of these technologies from developed countries, and new data management systems and computational tools to support market-assisted and genomics-assisted breeding. Reports of agricultural research spending do not separate out crop breeding and are incomplete, but, overall, the world probably devotes only around 1.4–1.7 percent of agricultural GDP to agricultural research and development (R&D), which is less than the rate of total research spending relative to the total global economy (2.1 percent).[222]

Limited R&D funding is compounded by the high volatility of funding in the world's poorest countries, which in part depend on—and therefore respond to—the interests of international donors.[223] But crop breeding requires stable funding because breeding is inherently a gradual and cumulative process. A good example is the funding for the CGIAR network of agricultural research institutions, which were set up in the 1960s as part of the Green Revolution effort. After many years of stagnation, CGIAR's budget grew rapidly after the food crises in 2008–11, from $707 million in 2011 to $1,067 million in 2014. However, its budget declined again to $848 million in 2017.[224] The need for increased and consistent agricultural R&D is discussed in more detail in the final section of this report, "Cross-Cutting Policies for a Sustainable Food Future."

Share genomic advances

Public and private sector researchers can accelerate yield enhancements by developing and publicizing basic genomic data and methods. The Genomes Online Database (GOLD)[225] is designed for such a purpose. Likewise, Mars Incorporated paid for the genetic sequencing of a common variety of cocoa and then publicly released it without patent in 2010 to speed up research on improving yields for the plant.[226] In general, mapped genomes of major row crops are now being shared. Going forward, sharing information as it is discovered about what different DNA sequences actually do will be equally important.

Leverage new technologies

Crop breeding programs should take full advantage of advances in new technologies. This lesson means that conventional breeding should embrace marker-assisted and genomics-assisted breeding, supported by better data management, sensors, and other tools to more quickly and cheaply identify the functions of different genes.

Whatever the debate about Bt and glyphosate-resistant crops, they represent only a few of GM technology's potential uses. Breeding disease-resistant traits into crops under serious threat is a problem to which genetic engineering may, in some cases, be the only solution if the crop is to be saved. CRISPR opens up a wide range of additional possibilities to increase yields in subtle ways, sometimes by adding new genes, and sometimes by influencing when genes turn on and off. These techniques also hold out promise for improving the environmental performance of crops, as we discuss in Chapters 27 and 28, by reducing emissions from nitrogen fertilizer use and rice cultivation. Although new regulatory systems will be needed to address the broad ease-of-use of these technologies (with implications that go far beyond crop breeding), the techniques offer too much opportunity for crop breeding to ignore them.

Increase research on orphan crops

Researchers at universities, agriculture agencies, and agricultural companies should broaden their scope beyond the most intensely researched crops—maize, wheat, rice, and soybeans—to give increased attention and funding to orphan crops. Advanced plant breeding tools like CRISPR may help quickly improve orphan crops, which often have intractable breeding improvement challenges. Sorghum is a good example, with many quality and productivity problems, especially in the numerous varieties cultivated in Africa. As genes of interest are identified and linked to important phenotypes, in a wide variety of ways CRISPR holds potential to improve orphan crops more quickly, and breeders are already reporting a variety of rapid improvements.[227]

Some movement in this direction is under way. In 2003, CGIAR launched its 10-year Generation Challenge Programme to improve crops in drought-prone and harsh environments through genetic diversity and advanced plant science. From 2009 to 2014, the program focused on drought tolerance for nine crops, six of which are orphans: beans, cassava, chickpeas, cowpeas, groundnuts, and sorghum.[228] In addition, CGIAR has launched a research partnership initiative on grain legumes. Furthermore, the African Orphan Crops Consortium[229]—consisting of companies, nongovernmental organizations, and international institutes—is undertaking an effort to sequence the genomes of 100 little-studied food crops in Africa. Although promising, the research dollars involved are still small. By 2014, the consortium had raised $40 million per year from developed countries, with a promise of $100 million more from African countries.[230] Nevertheless, more efforts to improve orphan crops and research funding are needed.

For more detail about this menu item, see "Crop Breeding: Renewing the Global Commitment," a working paper supporting this World Resources Report available at www.SustainableFoodFuture.org.



CHAPTER 13

MENU ITEM: IMPROVE SOIL AND WATER MANAGEMENT

Many agricultural soils are degraded, and degradation is particularly acute in many areas where yield gains are most needed for food security. This menu item explores the potential to boost yields by restoring these degraded lands through practices such as agroforestry, water harvesting, and fertilizer microdosing.

The Challenge

Although reliable data are lacking, FAO estimates that 25 percent of all cropland suffers from significant soil degradation.[231] Sources of degradation include water and wind erosion, salinization, nutrient depletion (of nitrogen, phosphorus, and potassium), and loss of soil organic carbon.[232] Although protecting and rebuilding agricultural soils is the foundation of agricultural "conservation," and although many projects have focused on such efforts in Africa, soils there continue to degrade.

Land degradation is of special concern in the world's more arid croplands, often called "drylands," although we are not referring here to grazing areas too dry for growing crops.[233] Drylands cover 41 percent of the earth's surface and account for approximately 44 percent of global food production.[234] About 43 percent of Africa is drylands[235] and we focus in this chapter on sub-Saharan Africa. One challenge facing drylands is that rainfall levels often do not permit agricultural production to grow to match high rates of population increase, which can lead to overuse. A 2016 World Bank analysis examined the challenges in African drylands, highlighting population growth as a central stressor. While sub-Saharan drylands are expected to expand by 20 percent in some scenarios, the population in these areas is expected to grow by 58–74 percent by 2030, leading to overuse and land degradation, as well as possible social conflict.[236]

Loss of soil organic carbon is a particular challenge. Organic carbon helps soils hold moisture and provides the kinds of chemical bonding that allow nutrients to be stored but also easily exchanged with plants. Soil organic carbon originates from decomposed plants. Because microorganisms in nearly all soils constantly break down soil organic matter and release the carbon into the atmosphere, maintaining soil organic carbon requires continual replenishment. In the case of cropland, replenishment comes from the decomposition of plant roots and residues, or from the addition of material such as manure. Loss of soil organic carbon is also problematic because organic matter contains virtually all of the potentially plant-available nitrogen and 20–80 percent of the phosphorus in soils.[237] In fact, if cropping removes more nitrogen than it adds through fertilizer or nitrogen fixation, soil organic carbon will decline because the nitrogen must come from the breakdown of existing organic matter.

African soils are not only low in organic matter but have long been losing carbon and nutrients.[238] These losses probably result in part from insufficient replenishment of carbon and in part from insufficient addition of nitrogen.[239] The problem has been exacerbated in sub-Saharan Africa by adverse conditions for carbon and nutrient retention. The combination of old soils and high temperatures creates conditions where thriving microorganisms are able to consume, respire, and therefore transfer the carbon in soils into the air year-round.[240] Organic matter's ability to retain water is particularly important in this region because of the highly variable rainfall.[241] The growing season is also often short, and a relatively small percentage of rainfall is actually used by growing crops.[242] Multiple studies have now documented that low organic matter reduces crop response to fertilizer application and makes fertilizer application uneconomical for vast areas of farmland.[243]

Overall, the low levels of organic matter in African soils create a vicious circle because they lead to low yields, which in turn lead to less replenishment of soil carbon by crop roots and residues, and thus further losses in soil organic matter. But where crop yields are high, carbon levels not only can be maintained but even increased. Several papers have estimated that this is the case in China.[244]

The Opportunity

A range of soil and water management practices has evolved over the past several decades to address low levels of soil organic matter, as well as nutrient depletion and moisture stress.[245] Many are obvious and fundamental practices of agriculture: adding fertilizers, irrigating, and plowing crop residues and animal manure back into soils. The challenge is to come up with practical and economical solutions for many poor farmers who cannot afford fertilizers, lack access to large irrigation systems, have little access to mechanization, start with low crop yields, and must choose between competing demands for crop residues, such as animal feed or domestic fuel.

We start by exploring three techniques that have shown particular promise in dryland areas of Africa: some forms of agroforestry, rainwater harvesting, and fertilizer microdosing. We then summarize the debate around "conservation agriculture," and some ideas for new or revised approaches based on that debate.

Agroforestry

Agroforestry is any form of farming in which farmers deliberately integrate woody plants—trees and shrubs—with crops or livestock on the same tract of land. The term is broad and can refer to any form of agriculture that uses woody plants, including rubber, fruit production, and cocoa. Here we focus on the incorporation of trees into production systems for row crop agriculture.

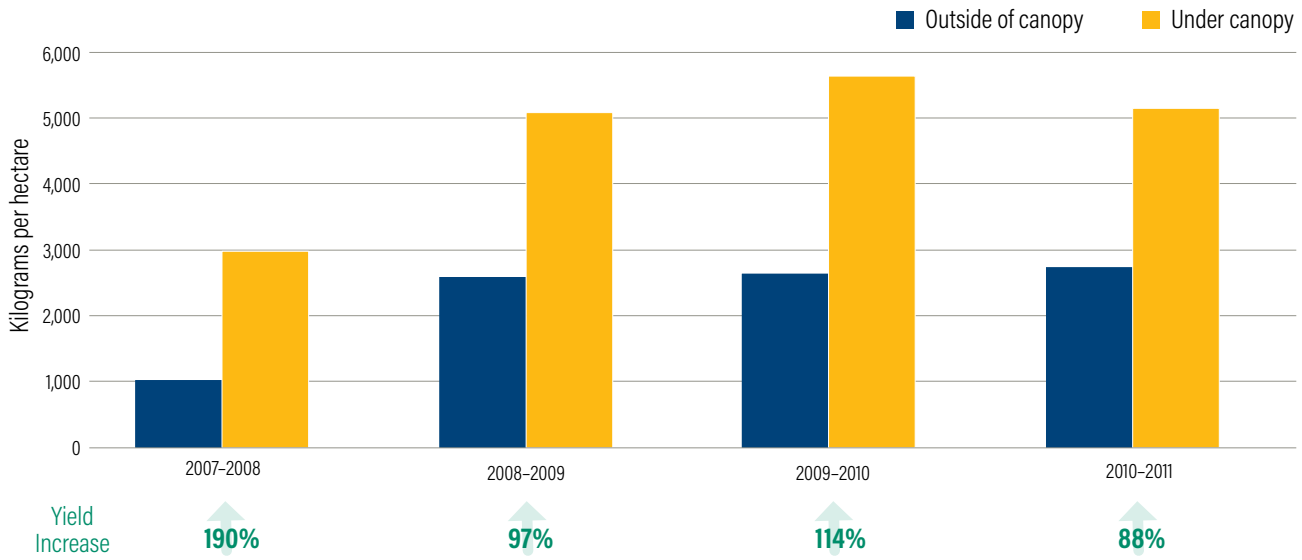
A major success has occurred with the rejuvenation of agroforestry parklands in the Sahel. Since the mid-1980s, farmers have assisted in the regeneration of trees across more than 5 million ha, particularly in Niger but also in Burkina Faso, Mali, Senegal, and Ethiopia.[246]

Although farmers have used a variety of trees, the species *Faidherbia albida* highlights the potential to use trees to restore soil fertility. Because it fixes nitrogen, its roots fertilize the surrounding soil, and because the tree's leaves drop during the growing season, they avoid shading out crops while also adding more nitrogen and mulch. A number of studies have shown an increase in yields in the areas around these trees. In the Kantché district of southern Niger, a region with high levels of on-farm tree densities, a 2012 study found that farmers had produced grain surpluses every year since 2007, even in the below-average rainfall year of 2011.[247]

In addition to the Sahel, farms in Kenya, Zambia, and Malawi have also adopted *Faidherbia*, and studies have shown yield gains there too. For example, in Zambia, trial sites under *Faidherbia albida* canopies yielded 88–190 percent more maize than sites outside of canopies (Figure 13-1).

Well-managed agroforestry systems can generate benefits in addition to enhanced crop yields.[248] For example, depending on the species, trees might provide fruit, nuts, medicines, and fiber—all important for direct human use. Large branches can be cut to make poles for home construction or to sell in local markets for additional income. Branch trimmings can be used for firewood. For example, *Leucaena leucocephala* trees, which grow at a rate of 3–5 m/year and supply wood at a rate of 20–60 m^3/ha/year, are efficient producers of firewood.[249] Seed pods and leaves can serve as fodder or forage for livestock; *Leucaena* hedgerows provide 2–6 tons of high-protein forage per hectare per year.[250] Leaves can be sold in markets; leaves of one mature baobab in Niger's Mirriah district vary in value from US$28–US$70, an amount sufficient to buy at least 70 kg of grain in the market.[251] Among other benefits, agroforestry systems help farmers in drylands build some economic resilience to drought and climate change. When the crops fail, the trees continue to produce.

Figure 13-1 | Maize yields are higher under *Faidherbia* trees in Zambia



Note: Average maize grain yields from trial sites under and outside canopies of mature *Faidherbia albida* trees across regions in Zambia.
Source: Shitumbanuma (2012).

Rainwater Harvesting

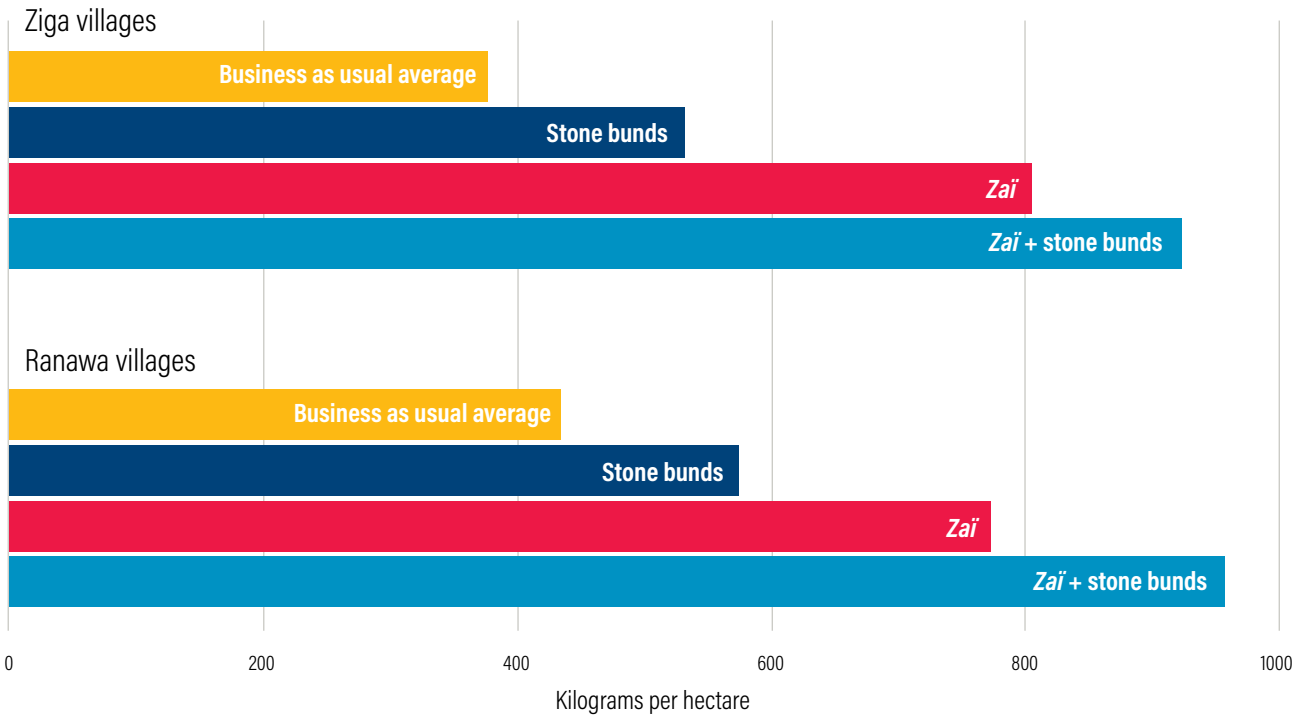
Without attention to soil and water conservation, the loss of rainwater due to runoff from denuded fields can be significant. In Mali, for instance, 70–80 percent of rainwater falling early in the rainy season is lost to runoff, and rainfall runoff takes away about 40 percent of the nutrients applied to the soil through organic and mineral sources of fertilizer.[252] A variety of simple, low-cost water management practices can effectively capture and collect rainfall before it runs off farm fields.[253] By slowing water runoff, such practices help farmers adjust to fluctuations in rainfall. These "rainwater harvesting" practices include:

- Planting pits ("zaï")
- Half-moon-shaped, raised earthen barriers ("demi-lunes")
- Lines of stone placed along contours ("bunds")
- Earthen barriers or trenches along contours ("ridge tillage")

Yield improvements from rainwater harvesting can vary from 500 to 1,000 kg/ha, depending on other factors such as soil fertility management.[254] Farmers in Burkina Faso using rainwater harvesting techniques such as stone bunds and *zaï* to capture rainfall and reduce runoff have increased their yields from 400 kg to more than 900 kg/ha in some studies.[255] And combining techniques on the same farm can increase yields more than one technique on its own (Figure 13-2).[256]

Multiple studies indicate that rainwater harvesting can help buffer farmers from the effects of erratic and reduced rainfall and increase crop yields.[257] In Mali, for instance, the practice of ridge tillage reduces rainfall runoff and helps to capture scarce rainfall in a dry year. The practice has resulted in soil moisture increases of 17–39 percent. Ridge tillage allows earlier sowing and prolongs vegetative growth by as much as 20 days, thereby increasing millet yields by 40–50 percent. Ridge tillage also has resulted in an increase of 12–26 percent in soil carbon, and an increase of 30 percent in fertilizer-use efficiency.[258]

Figure 13-2 | A combination of rainwater harvesting practices is more effective at increasing grain yields than one practice (Burkina Faso)



Note: These two groups of villages are located on the northern central plateau of Burkina Faso.
Source: Sawadogo (2006).

Fertilizer Microdosing

Microdosing fertilizer is a complementary practice that involves applying often just a capful of fertilizer directly to crop seeds or young shoots at planting time or when the rains fall.[259] Microdosing enables expensive fertilizer to go as far as possible with the least amount of waste. Approximately 473,000 smallholder farmers in Mali, Burkina Faso, and Niger have used the technique and have experienced increases in sorghum and millet yields of 44–120 percent, along with increases in family incomes of 50–130 percent.[260]

Field results indicate that combining agroforestry, water harvesting, and microdosing has significant promise.[261] Agroforestry increases soil nitrogen, organic matter, and moisture. Water harvesting helps improve soil moisture and recharge groundwater. Fertilizer microdosing adds phosphorus and potassium where soils lack these elements. When conducted in tandem, agroforestry and water harvesting prepare the soil for the fertilizer, maximizing fertilizer-use efficiency.[262]

Conservation Agriculture

Conservation agriculture is typically defined as farming that involves three basic practices:

- Minimizing soil disturbance by reducing the amount of tillage: seeds may be planted into small excavated basins rather than into tilled soil, or seeds are drilled into fields ("no-tillage" planting).
- Retaining vegetation on fields after harvest: farmers leave crop residues on the field (the dominant practice in developed countries), mulch from trees or other plants is applied, and/or a cover crop is maintained during the dry season or winter.
- Rotating different crops on the same land: rotation is used particularly to include more legumes and thereby to build soil nitrogen, to the benefit of all crops in the rotation.[263]

Together, the goal of these techniques is to reduce soil erosion, increase soil organic matter and moisture content, add nitrogen, and help control pests.

In theory, these practices should be available even to farmers who cannot afford expensive agricultural inputs. Development projects in Africa have often pushed these conservation agriculture methods, and farmers practicing them with the aid of such projects have often increased their yields significantly and been able to make more efficient use of fertilizer and water.[264] The International Fertilizer Development Center, a U.S.-based NGO, has been encouraging these kinds of efforts in conjunction with some increased use of conventional fertilizers, and has reported large yield increases by farmers participating in its projects.[265] Of course, even without external encouragement, farmers in Africa have historically intercropped nitrogen-fixing beans and rotated in soil-enhancing crops.

Yet, despite the promise of conservation agriculture, adoption rates have been modest, and many farmers abandon efforts after development projects end. In Zambia, for instance, official government policy has strongly encouraged conservation agriculture since the 1980s.[266] Yet FAO studies examining practices in 2008 of two key traits—minimum soil disturbance and planting basins—found not only extremely low adoption rates of 5 percent nationwide, but also that 95 percent of farmers nationwide who had previously used these practices had abandoned them.[267]

Although studies of participants in development projects have often found large yield gains from conservation agriculture,[268] more recent studies have argued that this favorable literature "is subject to (i) data from experimental plots, (ii) small data sets from a non-representative group of farmers, or (iii) selection or other endogeneity problems."[269] In a study of conservation agriculture in practice in Zambia, FAO found no consistent yield gains from changed tillage or maintenance of residues with the exception of farms in the drier, eastern part of the country, where the practices probably helped to preserve soil moisture.[270] This FAO study also found that yield gains from virtually all practices evaluated were often wiped out by unexpected periods of drought. Other analyses of conservation agriculture also find a lack of yield gains when they analyze farms that are not part of experiments directed by researchers.[271]

These experiences have led many researchers to challenge conservation agriculture, even scientists who specialize in nitrogen-fixing crops or soil carbon.[272] In doing so, they have highlighted many practical obstacles to adoption of conservation agriculture practices:

- **Labor.** Without mechanization and access to herbicides, large reductions in tillage require a great deal more work. Tillage has traditionally been the main way of dealing with weeds, and lack of tillage necessitates either more use of herbicides or laborious hand-weeding. Caring for trees offsite and then mulching them and adding them to soils is also time-consuming. In the absence of mechanization, smallholder farming already requires massive labor efforts, and farmers tend not to have the time or desire to add to these efforts.
- **Caloric needs and agronomic challenges with legumes.** Legumes such as beans provide protein and flavor to diets, but they produce fewer calories than maize, cassava, or yams per ha. Farmers who are already short on calories have less potential to add beans. In much of Africa, beans also face disease problems or various challenges with soil fertility.[273]
- **Competition for residues.** Crop residues are major sources of animal feed, and even farmers who do not have livestock often allow other farmers with livestock to graze their fields.[274]
- **Uncertain yield effects.** At a minimum, uncertain yield effects make investments of both funds and labor risky.

- **Short-term decreases in yield.** Even if and when practices add organic matter to soils, the added carbon tends to absorb and immobilize nitrogen. Unless farmers have increased access to nitrogen fertilizer, soil carbon practices will often lower yields in the short term, and in fact, building soil carbon will require additional nitrogen.[275]

These challenges do not mean that adding soil carbon by retaining residues or reducing tillage through conservation agriculture practices could not have advantages. Rather, these challenges mean that effects are complex, and merely urging farmers to incorporate these practices into their existing farming systems will often be unsuccessful.

New approaches?

The technical potential to restore soils is not at issue. For many years, researchers have developed promising strategies for revitalizing African soils that tend to work both in research plots and often for the duration of aid projects with participating farmers.[276] For example, researchers explored "enhanced fallows," which involve planting trees or shrubs on farm fields for two or more years, and then plowing the biomass into the soils.[277] Related efforts plant trees along field borders or in small plots and bring the biomass generated to the crop field.[278] Research studies have demonstrated potential for large yield gains from these kinds of efforts.[279]

The challenge is that these approaches tend to require more labor and costs for inputs, and the practice may involve at least a temporary loss of income. As a result, African farmers have not adopted soil conservation practices enough even to stabilize, let alone reverse, current levels of soil degradation. The lack of wide-scale adoption suggests the need for new approaches. We believe two strategies may hold promise.

One approach is to focus more on the changes in farm practices and agronomic factors that would make soil-building strategies more profitable and practicable. They include mechanization to reduce labor demands, development of quality fodder grasses that can grow well in land areas other than typical cropland, timely access to fertilizer, and reductions in the diseases that heavily affect bean production.[280]

A second approach involves working incrementally on a farm to restore one small piece of land at a time. Incremental restoration reduces labor requirements and takes less farmland out of production at any one time. By concentrating resources, including labor, nitrogen, and available carbon, the hope would be to restore a small area quickly to the point where it will generate large yield gains, thus providing economic return soon enough to justify farmer efforts. With enough yield gains and use of nitrogen-fixing crops, such areas could potentially enter a "virtuous cycle" whereby soil carbon continues to build over time.

Another possible option involves various ways of converting residues or household wastes into biochar, a residue of pyrolysis similar to charcoal. Although there continues to be scientific debate and uncertainty, biochar appears to provide at least a more stable form of concentrated carbon to soils that can also provide other agronomic benefits.[281] Those benefits appear to include, at least for some soils, enhanced nutrient effectiveness, probably through enhanced cation exchange. Many tropical soils are acidic, and biochar can also benefit yields by reducing that acidity. The key challenge is finding an economical and practical mechanism for increasing the production and use of biochar. Again, the incremental approach to farm fields might provide a viable approach.

Recommended Strategies

Experiences in sub-Saharan Africa and elsewhere underscore the importance of several strategies for scaling-up improved soil and water management practices. Four strategies hold particular promise:

Strengthen understanding

Evidence of which practices truly work for farmers and help to restore productivity is weak in much of Africa. Data about the costs and benefits are mostly lacking for both technical and social outcomes and obstacles. One way to improve understanding is for donor agencies to build this kind of technical and socioeconomic analysis into their project budgets for monitoring and evaluation. Agroforestry seems to have particular potential, but no good system exists for systematically evaluating where and why farmers find agroforestry successful. A promising start is that the World Agroforestry Center has built a website for agroforestry in Africa to organize information in a systematic way. Further progress will require expanded funding to support stronger evaluations of agroforestry projects and use of this website to organize that information systematically.

Increase communication and outreach

Practical methods exist to spread knowledge of conservation management.

Amplify the voice of champions. Champions of improved soil and water management practices should be identified and their voices amplified. Champions can come from the public or private sectors. Some of the most effective champions are farmers who have already adopted these practices.

Facilitate peer-to-peer learning. Farmers can learn from other farmers working under similar agroecological conditions. Over the past two decades, farmer-to-farmer visits for knowledge sharing have become increasingly common.

Use technology to directly communicate with farmers. Mobile phones are becoming a widespread tool for information sharing. The Web Alliance for Re-greening in Africa[282] has developed a "Web of Voices" that links the use of mobile phones with radio stations and the internet. Likewise, radio stations can air programs in which experienced farmers share their knowledge. In southern Tunisia, for instance, a regional radio station had a special weekly program during which farmer innovators shared their experiences and answered questions.



Support institutional and policy reforms

Accelerating the spread of improved soil and water management practices requires enabling policies and legislation. Specific recommendations include the following:

Reform outdated and counterproductive forestry legislation. Despite repeated attempts to enact reforms, the forest codes in Senegal, Mali, Burkina Faso, and other countries still contain many provisions that allow forest service agents to impose fines or to otherwise discourage farmers from investing in protecting or regenerating trees in agroforestry systems. Reforming these laws is difficult when it involves changes to provisions related to the taxes, fines, and permitting requirements that some forest agents exploit to supplement their meager incomes. These forest codes are intended to conserve remaining areas of natural forests and woodlands but, because they lack specific provisions governing the management of multipurpose trees in farming systems, they are liable to have a perverse effect that contributes to reducing tree cover in agricultural landscapes.[283]

Establish more secure land tenure and management rights over trees. Smallholder farmers will only adopt these improved soil and water management practices when they feel they can reap the benefits of the improved practices. This means that land tenure and forestry legislation need to eliminate ambiguities and ensure that farmers have secure rights to their land and the resources flowing from that land. These resources should include trees on cropland that have been protected, regenerated, or planted by farmers. And farmers should be allowed to freely harvest and market the full suite of products from their farming systems, including wood and nontimber forest products from agroforestry systems.

Strengthen local institutions to improve natural resource governance. Experience underscores the critical importance of developing the capacity of local institutions—such as traditional or modern village development committees—to negotiate and locally enforce rules governing access to and use of natural resources, particularly the protection and management of on-farm trees and of natural vegetation. This requires locally enforceable rules to sanction illegal cutting of trees, limit damage caused by livestock to on-farm trees, and control bush fires.[284]

Pursue new models for increasing soil carbon in depleted croplands

Aid agencies and governments need to pursue new approaches for rebuilding soils, and we suggest considering the two strategies we discuss above. One involves working on the impediments to soil conservation measures (such as bean diseases) and boosting production of high-quality forage grasses as a substitute for crop residues. The other involves projects that focus on incrementally restoring fertility to small portions of farms, perhaps as small as one-tenth of a hectare, through comprehensive programs that bring together all of the components needed. They would include financial assistance to allow farmers to forgo the food production involved and adequate fertilizers to feed the microorganisms necessary to turn plant carbon into stable soil carbon. One advantage of such an incremental approach is that it would allow programs to assist many farmers within the same budget.

For more detail about this menu item, see "Improving Land and Water Management," a working paper supporting this World Resources Report available at www.SustainableFoodFuture.org.



CHAPTER 14

MENU ITEM: PLANT EXISTING CROPLAND MORE FREQUENTLY

One way to produce more food on existing cropland is to plant and harvest crops on that land more frequently. The ratio of the quantity of crop harvests in a year—the harvested area—to the quantity of arable land is known as the "cropping intensity." Globally, FAO estimates cropping intensity at only 0.82 because much cropland is kept fallow. This chapter explores the practical potential for increasing cropping intensity and finds limited information.

The Challenge

Two factors influence global cropping intensity in different directions. The first is the amount of fallow land—cropland that is not harvested in a given year. The identification of land as fallow implies that cropland is being rested, which results in a cropping intensity of less than one. The second factor is the number of crop harvests per year. In some warm climates with irrigation or sufficient rainfall throughout the year, farmers plant and harvest two cycles of crops—and in a few locations three—each year on the same tract of land. Multicropping creates a cropping intensity greater than one. In Bangladesh, for example, farmers on average achieve 1.56 crop harvests each year per hectare of cropland.[285]

The need to increase food production and avoid expansion of agricultural land means that it is generally desirable to increase cropping intensity. In principle, if land is cropped once per year or once every several years, cropping it twice per year will produce more food, save land, and reduce GHG emissions. There are, however, three significant challenges.

One challenge is economic. Using a simple global crop model, IIASA has estimated that the potential for increasing double-cropping—even on rainfed lands—is large and that half of all land suitable for growing cereals could technically support two crops per year.[286] "Suitable land" counts both existing cropland and potential cropland, including forests. However, this estimate includes any land capable of producing any crop with up to 10 percent of global average yields. According to FAO global estimates, approximately half of all double-cropped land is irrigated, and farmers probably plant two crops a year on only 6 percent of rainfed area.[287] Unless farmers are missing opportunities, the realistic economic prospects for expanding double-cropping on rainfed lands must therefore be far more limited than those projected by IIASA.

Second, the prospect of increasing double-cropping through irrigation is limited at best, and even present levels may not be sustainable. For example, cropping intensity across India is already at 140 percent, with Punjab ranking highest among Indian states at 190 percent.[288] However, because much of India is experiencing increasing water shortages and falling groundwater reserves,[289] it is not clear whether existing levels of double-cropping can even be maintained.

Third, some efforts to reduce fallow lands would come with large costs in carbon and habitat values, particularly in areas that practice long-term shifting cultivation. Under shifting cultivation practices, land is allowed to regrow natural vegetation, typically trees, to rebuild soil fertility. Both the root growth and eventual clearing and often burning of the trees adds carbon and nutrients to the soil. In the forest part of the cycle, the trees can provide substantial carbon storage and habitat value, creating a landscape with higher values for both on average.

According to a recent estimate, areas of shifting cultivation, both cultivated and fallow, currently cover 280 Mha of land.[290] This same study found that although fallow periods during shifting cultivation are declining, which reduces the share of land that is forested on average in the shifting agricultural landscape, shifting cultivation is persisting as a system. In these areas, a shift to permanent or more regular cultivation is not carbon-free or without loss of habitat.

The Opportunity

Increases in cropping intensity from 85 to 89 percent, based on FAO estimates, are already factored into our baseline projections. According to GlobAgri-WRR, this increase would avoid roughly 70 Mha of land clearing. FAO projects that irrigated lands will provide roughly two-thirds of this cropping intensity gain, presumably from an increase in double-cropping.[291] These estimates are based on the judgments of regional experts, but there is no documentation to evaluate them further.

Recent FAO data appear to suggest a much more rapid increase in cropping intensity than is suggested by its 2050 projection, which we rely on for this report. The data suggest that between 2000 and 2011 alone, increases in cropping intensity provided the equivalent of 101 Mha of cropland farmed each year, and in that way avoided the conversion of 101 Mha of land from forest or other carbon-rich ecosystems.[292] On this basis, some researchers

record a rapid escalation in cropping intensity.[293] Unfortunately, for reasons we discuss in Chapter 10 on the land-use challenge, data on cropland extent submitted to FAOSTAT can be highly unreliable, which means the changes in cropping intensity are also unreliable (Chapter 10).

An alternative way to increase cropping intensity involves leaving land fallow less often. Adjusting for areas that are double-cropped, about 350–400 Mha of cropland were not harvested in 2009 according to FAOSTAT data.[294] (This amount roughly matches the 450 Mha estimate based on 2000 data from a paper by Siebert et al. [2010] that attempted to analyze cropping intensity globally.) Planting this land more frequently would appear to provide a good opportunity to increase production without increasing land area. However, there are several limitations:

- As discussed above, some fraction of this land probably represents land in shifting cultivation, in other words, land with long-term fallows. More frequent planting would entail substantial environmental costs.
- According to maps by Siebert et al. (2010), fallow lands are concentrated in dry areas where rainfall is probably not sufficient to plant crops every year.
- Some fallow lands should actually be considered "abandoned." For example, U.S. cropland includes lands enrolled in the U.S. Conservation Reserve Program, and most of these lands have been planted with grasses or trees for more than five years.[295] Cropland also appears to include large areas of abandoned agricultural land in the former Soviet Union.[296] Unlike truly occasional fallow land, abandoned land reverts to forest or grassland (according to what the soils and climate can support), which sequesters abundant carbon and provides other ecosystem services. One study estimated carbon accumulating at a rate of 2.45 tons of carbon per hectare per year on abandoned land in Russia.[297] Returning this land to productive use may be preferable to plowing up the world's remaining intact ecosystems, but it still comes at an environmental cost.

Notwithstanding the broad uncertainty and potential adverse effects of some increases in cropping intensity, there clearly are opportunities for progress. Brazil, for example, has seen an increase of roughly 9 Mha of maize planted as a second crop between 2001 and 2016.[298] Brazil appears to have substantial potential for more double-cropping, although one study has estimated that climate change will greatly undermine that potential.[299]

Overall, the data limitations bar any confident assessment of the potential or likelihood of increased cropping intensity, or of the environmental implications of such an increase. Increases in double-cropping and reductions in short-term fallow land area probably provide an important mechanism for holding down agriculture-driven land-use change. In some long-term fallow regions, more intense cropping of regularly cropped land might allow long-term fallow areas to permanently regenerate to forests or grasslands. But where and how such intensification of cropping occurs will determine its economic, social, and environmental merits.

We assume that with great effort, cropping intensity might be increased by 5 percent more to 93 percent. This level of increase would reduce cropland demand by roughly 81 Mha and reduce annual emissions from land-use change by 646 Mt CO_2e, relative to baseline.

Recommended Strategies

Analysis of the potential to reduce fallowing or increase double-cropping is so limited that making recommendations is difficult. Nonetheless, one obvious recommendation is for scientists and agronomists to conduct more detailed analysis of realistic, potential increases in cropping intensity. These studies should be detailed and spatially explicit, meaning that they should build in data reflecting small-scale differences in weather and soils by location. They should also account for limitations on irrigation water availability and build in at least some basic economic calculations. Only with this type of analysis can governments and researchers determine which improvements in infrastructure or crop varieties can contribute to making increased cropping intensity economically viable.



CHAPTER 15

ADAPT TO CLIMATE CHANGE

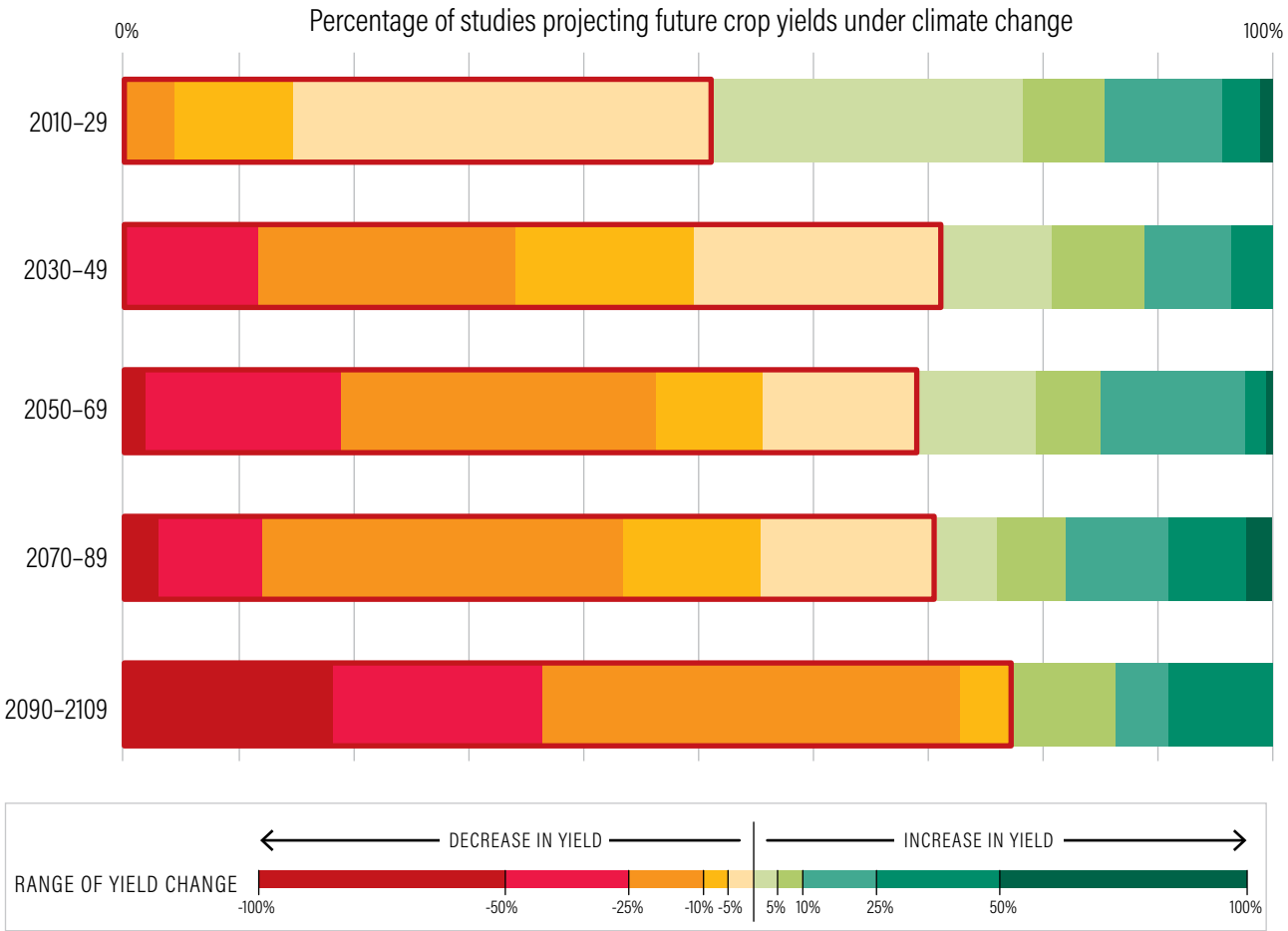
This course has focused on efforts to boost livestock and crop yields on existing agricultural land, but such efforts will not occur in a static world. Technology is changing but so is the world's climate. In this chapter, we explore priorities for agricultural adaptation to climate change. While priority actions sometimes require targeted interventions, they often overlap with and reinforce the need to implement other production-side menu items presented in this report.

The Challenge

Climate change and agriculture are a two-way street: "business as usual" growth in food production adversely affects the climate, but climate change itself poses challenges by adversely affecting food production. FAO's projections of crop yield growth, which we incorporate into our 2050 baseline, make no attempt to account for climate change. Yet the world is on track for warming by 0.5–2 degrees Celsius (°C) or more by 2050 relative to preindustrial conditions and probably greater than 4°C by 2100.[300] In 2007, the Intergovernmental Panel on Climate Change (IPCC) reported that scientists projected, on balance, that climate change would lead to net global yield gains in 2050 due to beneficial conditions for cropping in the temperate zone.[301] But by 2014, new research had convinced the IPCC that, with a warming of 2°C above late-twentieth-century levels, average global crop yields are "more likely than not" to decline by at least 5 percent by 2050—with even steeper yield declines by 2100 (Figure 15-1).[302]

Overall, climate change will adversely affect yields in a few basic ways: through changes in temperature, changes in rainfall patterns, and sea level rise.

Figure 15-1 | Negative impacts of climate change on crop yields are projected to become increasingly likely throughout this century



Note: This figure includes projections for different emission scenarios, for tropical and temperate regions, and for adaptation and no-adaptation cases combined.
Source: Porter et al. (2014), Figure 7-5.

Temperature

Higher temperatures at critical times have direct effects on the growth of some crops. Most studies have focused on maize and wheat, yet tea and Arabica coffee are other clear examples.[303] Much of researchers' increasing pessimism about climate effects on crops results from an increased understanding of the direct consequences of heat.[304] For example, just a few days of exceptionally high temperatures at critical periods of growth, such as vulnerable reproductive stages, will reduce yields.[305]

Warmer temperatures are likely to change the distribution of pests and pathogens and either reduce or cause timing mismatches with pollinators[306] in ways that reduce crop yields. Warmer winters reduce overwintering mortality of some insects and promote their early maturation.[307] This results in earlier predation and an increase in the spread of plant pathogens by insect vectors.[308]

Higher temperatures dry out the atmosphere and soils due to evaporative loss, which, in turn, increases the rate at which plants transpire and therefore lose water.[309] Although warmer temperatures will mean greater rainfall globally somewhere, these conditions will lead to greater water deprivation in other areas. Even in areas that do not dry out on average, this enhanced drying will increase the frequency of days when crops do not have optimal access to water.

Rainfall

In some regions, overall drier conditions will result in shorter growing seasons and increase the risk of large losses or absolute crop failures, although in some colder regions growing seasons will lengthen due to increased frost-free days.[310]

More of the rainfall that occurs will take place in intense storms.[311] Even in relatively "normal" rainfall years, the result will be more days with insufficient soil moisture levels and more problems related to floods and erosion.

Serious droughts and floods will also become more frequent, with the areas affected by drought disasters projected to grow from 15 percent to approximately 44 percent of the planet.[312] Regions facing the greatest increases in instances of drought disaster include southern Africa, the United States, southern Europe, Brazil, and Southeast Asia. One study found that droughts caused annual average losses in global cereal production of 6.7 percent from 1964 to 1984. Losses rose to 13.7 percent between 1985 and 2007.[313] Regional models for sub-Saharan Africa indicate that maize yields could decrease by more than 50 percent in some areas by 2050 due to increased aridity.[314]

Water stress on cropping, already significant in some areas, is likely to increase due to both growing water demand and climate change (see Figure 1-5).



Sea level rise

Sea level rise will result in saltwater inundation of agricultural land and saltwater intrusion into coastal aquifers that irrigate coastal crops. With a 1 meter (m) rise in sea levels, almost 11 percent of South Asia's agricultural land is projected to be vulnerable to flooding.[315]

Climate change will also have some positive effects. First, even as some regions become drier, others will become wetter—which is generally beneficial for crop growth.[316] Second, higher temperatures in some colder, temperate areas will allow for longer growing seasons. Studies in northern China, for example, have projected significant benefits as warming temperatures enable two crops per year.[317] Third, higher atmospheric CO_2 concentrations stimulates plant growth by raising photosynthetic activity in many crops, increasing nitrogen use efficiency, and decreasing water use.[318] Expected benefits from these three effects largely explain why the IPCC as late as 2007 expected positive net effects on global crop yields in the relatively more moderate warming previously expected by 2050.

Over time, however, the weight of the evidence has shifted. Governments funded a series of outdoor experiments in which equipment sprayed out additional CO_2 to test how crops and other plants responded. Although the experiments confirmed much of what indoor trials had shown, researchers found roughly half of the expected yield gain in crops overall, in part because crops funneled a smaller than expected portion of their additional total growth into edible parts.[319] This lower expectation of the benefits of CO_2, combined with increasing evidence of harsh effects of higher temperatures and more variable rainfall, shifted the overall estimate of yield impacts of climate change—even at moderate warming levels—to negative.

The problem of uncertainty

Although the evidence is increasingly pessimistic, estimates of the scale of global impacts are highly uncertain and regional and local impacts are even harder to estimate. Uncertainty results from three core issues.

First, the degree of warming is uncertain because of gaps in our understanding of how the climate changes in response to concentrations of CO_2 that are higher than those prevailing over the past 100,000 years (although this uncertainty about warming has less effect on crop model projections than uncertainty about precipitation changes).

Second, the complexity of regional climate patterns generates great uncertainty in climate models, particularly those that attempt to estimate changes in precipitation as discussed below. Scientists try to overcome differences in model outputs by using suites of models; however, this approach mainly helps to better define the greatest areas of uncertainty and does not necessarily produce more accurate estimates. This uncertainty applies not merely to changes in average conditions but also to variability, which is important to crop responses.

Third, estimates of changes in crop yields due to a changing climate vary because crop models differ.

The high level of uncertainty in projections should actually be a cause for even more serious concern

because we have no assurance that the midrange projections are the most likely. Several studies project far more serious impacts. For example, a 2012 World Bank study estimated that by midcentury, global yields of wheat, maize, and soybeans could decline by 14–25 percent, 19–34 percent, and 15–30 percent, respectively, with a warming of 2.2°C to 3.2°C compared to preindustrial temperatures.[320]

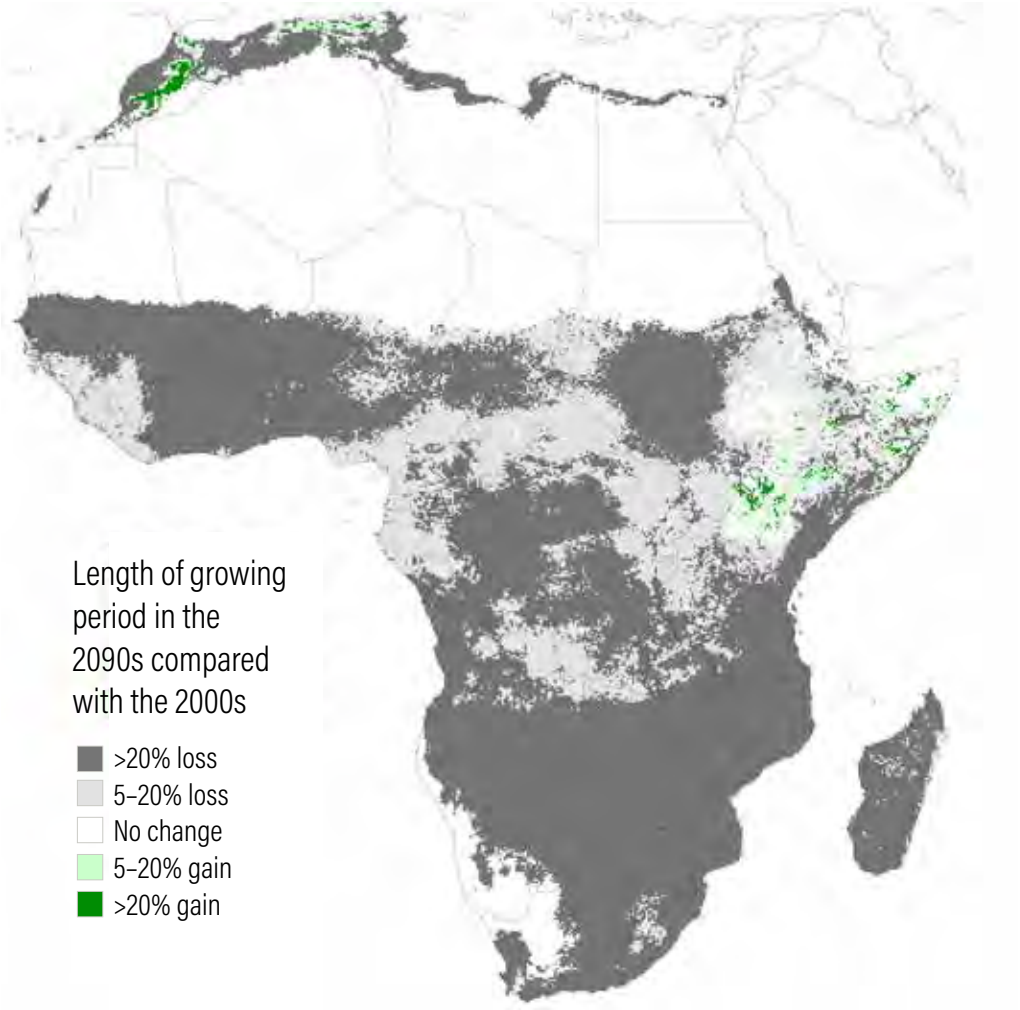
The midrange IPCC projection of yield effects also relies primarily on crop models, whereas analysis using statistical models sometimes projects larger effects. Crop models attempt to simulate dynamic processes of crop growth and their response to variations in soil quality, radiation, rainfall, and temperature. Statistical models mostly relate crop yields to past trends in temperatures and rainfall. One statistical study in 2009 found dramatic effects on yields of maize, soybeans, and cotton in the United States for each cumulative total of 24 hours during the growing season that temperatures rose above 29°C. Using this relationship, the study indicated yield losses of 30–46 percent by 2100 under the most favorable (least warming) climate scenario and by 63–82 percent under the most rapidly warming scenario.[321] Another recent study projected that climate change could eliminate all trend line growth in overall agricultural productivity, or total factor productivity, by 2050.[322]

There is also growing evidence that crop yields have already declined because of climate change.[323] In one analysis, statistical models linking crop yields to weather from 1980 to 2008 showed that declines and increases in soybean and rice yields balanced out on a global scale, they also indicated that climate change depressed the growth in yields of maize by 3.8 percent and of wheat by 5.5 percent.[324] In some countries, according to this analysis, estimated climate change effects were significant enough to freeze yields and thereby cancel out all benefits of improving technology.

Behind the global effects lie more serious regional food security concerns, because a substantial body of evidence indicates that the worst consequences of climate change are likely to be felt in sub-Saharan Africa and South Asia, the two most food-insecure regions of the world.[325] Some crops such as cassava and peanuts might actually increase yields under climate change, although the effect would likely be highly variable across crop varieties and regions.[326] However, cereal yields will most likely decline. One study using a crop model projects wheat declines in sub-Saharan Africa of 23–27 percent by 2050.[327] Some important cash crops—such as coffee and cocoa—will no longer thrive in parts of their present growing areas.[328] Efforts to move these crops to higher elevations will threaten forests in mountain areas, further contributing to GHG emissions.[329]

Shorter growing seasons may be even more of a problem in Africa. Growing seasons measure the periods when temperature and rainfall are adequate to produce crops, and Africa's short growing seasons are already a challenge for agriculture and food security. One study projects greater than 20 percent declines in the length of growing seasons in much of sub-Saharan Africa (Figure 15-2).[330] Combining shorter growing seasons with increased variability in rainfall would make farming substantially riskier.

Figure 15-2 | Climate change could shorten growing seasons in much of sub-Saharan Africa by more than 20 percent by 2100



Source: Verhage et al. (2018), using methods from Jones and Thornton (2015).

All of these changes combine to pose serious risks to food security, particularly by increasing the volatility of food supplies and prices.[331] Studies generally predict that climate change will lead to increased food prices by 2050, with estimated average price increases ranging from 3 percent to 84 percent—a wide range—relative to a world without climate change.[332] Nelson et al. (2009) estimated that, due to climate-related price increases, the number of malnourished children under the age of five could increase by roughly 20 percent by 2050, relative to a world without climate change.[333] Lloyd et al. (2011) estimated increases in moderate stunting of up to 29 percent and in severe stunting of 23 percent to 62 percent by midcentury relative to a world with a stable climate.[334]

The Opportunity

The quantitative estimates of climate change impacts cited above generally assume no adaptation. What potential exists for adaptation and what can the world do now to take advantage of that potential? A number of researchers have used crop models to make quantitative estimates of adaptation potential (Box 15-1), primarily by modeling effects on yields if farmers changed crop varieties or were able to irrigate. These analyses suggest substantial potential to adapt, but the range of estimates remains large, and there are significant reasons to doubt the most comforting estimates. The major practical problem in formulating adaptation plans today is that regional climate models typically make widely varying predictions about changes in regional and local precipitation. For example, models disagree about whether West Africa will be wetter or drier,[335] how rainfall will be distributed between the two monsoons in Sri Lanka,[336] and how changes in climate oscillations such as El Niño will affect intraseasonal extreme rainfall in the contiguous United States.[337] Even where models agree, there is uncertainty. For example, although most models predict that southern Africa will become drier, it actually appears now to be becoming wetter.[338] In some locations, even if rainfall increases, the increased losses of water from soils and plants because of higher temperatures may make conditions for plants effectively drier.[339] Because precipitation plays such a fundamental role in agriculture, these variations—with some exceptions—make it impossible to develop plans that are sufficiently reliable to guide changes in the types of crops farmers in the area should grow.

In part because of this constraint, the most important efforts needed are those improvements in farming that would be valuable regardless of climate impacts—what are known as "no regrets" strategies. For example, if farmers are better able to manage the rainfall variability that exists today, they will be better able to handle the even greater variability that will exist tomorrow. If farmers have greater social security to deal with their risks today, they will be better able to deal with the increased variations in crop production likely to occur in the future.

In addition, in most cases, general improvements in farming will be more important than specific adaptation strategies for the simple reason that the former's scope of impact is potentially larger. For example, if farmers could raise yields by 50 percent using improved management to close a yield gap, an estimated 10 percentage point adverse effect of climate change would generally still leave a net gain of 40 percent in yield.

For these reasons, both researchers and policymakers have been struggling to separate actions that adapt to climate change from more general agricultural development strategies.[340] Despite uncertainties, there are some clear, general patterns of climate change that greatly enhance the importance of resolving an existing agricultural challenge and that therefore merit special focus. Likewise, some climate-related physical changes in specific agricultural locations are sufficiently likely that major adaptation efforts can start—and in some cases have already started. We therefore focus on four adaptation measures that are specific applications of the menu items described in Chapters 12 and 13:

- Enable farmers to select alternative crop varieties
- Cope with rainfall variability
- Breed to overcome highly likely big climate challenges (e.g., extreme temperatures)
- Change land management practices to deal with predictable physical changes

Improve incremental crop breeding and systems for farmers to select alternative crop varieties

One lesson from the adaptation analyses discussed in Box 15-1 is that, as the climate changes, farmers will often be able to lessen effects on yields by switching to alternative crop varieties that already exist somewhere in the world. But for many farmers, selecting new seed varieties is not as simple as picking a different seed each year from a catalog. Researchers are modeling seed traits that exist somewhere but that are not necessarily both adapted and available to each local condition. For farmers to be able to adapt, therefore, they need effective regional breeding systems to adapt varieties to the regions, and they also need to better marketing systems for acquiring seeds.

As Atlin et al. (2016) point out, "The best predictor of the climate in the very near future, (i.e. the next ten years) is the current climate . . . [so] farmers who are at least risk with respect to climate change are [therefore] those who use varieties bred very recently." Therefore, as climate evolves over time, "the most important climate change adaptation tools for crop production are thus breeding and cultivar delivery systems that rapidly and continuously develop new varieties and replace old ones." In general, these incremental breeding systems and seed distribution networks are weakest in sub-Saharan Africa, as discussed in Chapter 12. Climate change enhances the importance of improving them.

Cope with rainfall variability through improved water management

Higher rainfall variability will be a nearly universal phenomenon of climate change. Farmers will face longer periods of droughts, more frequent torrential storms, and a general trend toward more concentrated delivery of regular rainfall.[341] Farmers can adapt somewhat to this variability by shifting planting dates. Greater understanding of climate patterns and improved weather forecasting may help farmers plan their annual cropping decisions appropriately.

Many farmers would also benefit from enhanced irrigation. Unfortunately, for reasons discussed in "The Scope of the Challenge," we do not believe that major new irrigation projects meet our sustainability criteria or will be economically or technically feasible in most locations because of the level of current water shortages and the high share of extractable water already used for irrigation. But small-scale irrigation efforts such as small storage basins,[342] small reservoirs, and direct river and groundwater pumping in locations where abundant water still exists are more environmentally benign. Small farmers in sub-Saharan Africa have particularly undeveloped access to groundwater. One study estimated that small-scale irrigation could be economically expanded by roughly 100 Mha in the region, benefiting between 113 million and 369 million people.[343] In addition, farmers can benefit from the rainwater harvesting techniques described in Chapter 13.

BOX 15-1 | Quantitative estimates of adaptation potential

To provide quantitative estimates of the effects of adaptation, researchers can use "process-based" crop models and estimate how crop yields would change not only under a different climate but if farmers adapted by using different crop varieties or irrigation. Process-based models simulate the different biological processes in plants and how they are influenced by factors such as rainfall, soils, and temperature; they therefore can estimate how plants with different growing seasons or other rainfall or temperature needs would respond. They differ from statistical models, which try to use direct evidence of how crop yields in the real world have varied with weather changes over time. Although different models generate varying results, the majority show a high potential for avoiding many of the worst impacts.

A comprehensive comparison of models has now calculated that adaptation could fully offset expected cereal declines of roughly 20 percent caused by temperature effects.[a] On average, models also estimated that adaptation could offset half of declines due to changes in precipitation. These analyses on the whole suggest enormous potential for adaptation, mostly from the relatively modest effort of selecting alternative crop varieties or changing planting dates.

Looking at these process-based models in more detail, however, leads to more cautious conclusions:

- Even with adaptation, the average projection of these models indicates adverse effects on rainfed crops due to changes in average precipitation.
- Regional effects would still be severe for some crops after adaptation. For example, averaging multiple studies to estimate temperature effects still projects an almost 10 percent decline in maize yield in tropical climates in a world experiencing a 2°C increase over preindustrial average temperatures.[b]
- Just as the overall effects of climate change vary from model to model, so do the benefits of adaptation. Some studies still project adverse effects on global cereal yields of 30 to 40 percent with a temperature increase of 2–3°C.[a] Because models make different predictions, it is natural to focus on some form of "average" results. But no statistical rule applies here to make the average more likely, and it is quite possible that some of the worse results will turn out to be more accurate.

Lobell (2014) summarizes several reasons to believe that these adaptation analyses are overly optimistic. Process-based models often leave out many of the features that climate change may adversely affect, such as temporary temperature extremes and variability in moisture conditions. Some adaptation studies analyze the benefits of adaptation measures without distinguishing whether they are effective in dealing with climate change or just in improving agriculture in general. A new crop variety or irrigation scheme may boost crop yields regardless of climate change. Although implementing such improvements can be important, all measures to boost yields in effect help to compensate and therefore "adapt" in a broad sense to climate change. To analyze the effect of "adaptation" alone, we need to measure only the additional effect a measure would have as a result of a changing climate.

Perhaps most significantly, many studies using statistical models find significant adverse effects from climate change on current crop yields in the United States and Europe already. In these regions, farmers have a wide choice of seed selection, can regularly upgrade their seed varieties, and have detailed information about which varieties perform best in specific localities. If switching crop varieties were enough to offset adverse effects of climate change, these adverse effects should not be occurring.

Overall, the evidence from crop models does suggest significant capacity to adapt. But there is high uncertainty about the extent to which adaptation can offset the adverse effects of climate change, and it is doubtful that currently available forms of adaptation—although significant—can fully offset these adverse effects.

Sources:
a. Challinor et al. (2014).
b. Lobell (2014).

Breed new traits to overcome large, highly likely climate challenges (e.g., extreme temperatures)

This recommendation concerns not simply improving the systems for incremental breeding but deliberately developing new traits. For example, despite many uncertainties, scientists have shown that maize and wheat are extremely sensitive to high temperatures, particularly during grain filling and silking—the reproductive stage during which grains are pollinated. Twenty thousand field trials in Africa have reported large maize yield losses for each 24 hours of temperature above 30°C, which typically occurs wherever average temperature during the growing season is 23°C or more.[344] Rising temperatures are also likely to preclude Arabica coffee production in many midlevel mountain areas currently devoted to this crop.[345] Breeding maize, wheat, and coffee to withstand higher temperatures is therefore urgently needed, but the task will not be easy because, at this time, all existing varieties of these crops exhibit temperature stresses.

Some crop breeding needs for adaptation fall into the category of fundamental crop research, which may have low odds for success but high potential for gains. For example, one study has projected that hotter, drier climates and increasing plant transpiration could lead to water shortages in the U.S. corn (maize) belt, where farmers use limited irrigation.[346] Adaptation could include breeding for a variety of sophisticated changes in metabolic plant processes to reduce transpiration rates.

These kinds of adaptations require innovative genetic tools and breeding systems along with well-trained plant scientists. Breeders need to receive sufficient resources and concentrate efforts to breed greater resilience to the already identified and likely climate change effects. Encouragingly, there are already some modest efforts in this direction.[347]

Change land management practices to deal with likely physical changes (e.g., sea level rise)

Rising sea levels are among the certain impacts of climate change. In recent years, rapid ice melt in Antarctica has surpassed expectations, leading to augmented projections that, if emissions remain high, sea levels would most likely rise 1.5 m and possibly more by 2100.[348] In addition to much larger areas that become vulnerable to occasional flooding, one study indicates that sea level rise of 1 m would inundate roughly 0.4 percent of agricultural land in developing countries (roughly 6 Mha), and a rise of 2 m would inundate about 0.7 percent (roughly 12 Mha).[349] While these global percentages are low, effects would be harsh for farmers and economies at the local level. In Bangladesh, agriculture has already experienced adverse impacts due to saltwater inundation and salinity intrusion, resulting in a conversion of 500 ha of agricultural land per year (in the study area) to saline land and a decline in rice production.[350] The coastal areas of the Mekong Delta in Vietnam are similarly experiencing saltwater intrusion.[351]

In these areas, work to build resilience has already started. In Bangladesh, efforts include coastal afforestation, cultivation of saline-tolerant crops, homestead and floating gardens, embankment cropping, and shifts in livelihoods, including to shrimp farming.[352] In Vietnam, agricultural changes have been mainly driven by national-level policies. Physical infrastructure projects appear to be the favored approach to minimizing the effects of sea level rise, but there has been a combination of adaptation activities, including upstream flow control, agronomic measures, and regeneration of coastal ecosystems.[353] In both Bangladesh and Vietnam, fully inundated areas may require transitions to aquaculture, and the extent of inundation will determine the types of aquaculture that are feasible.

Although not certain, there is also a high risk that some of the drier arable lands in Africa will cross thresholds and become unsuitable for crop production due to decreased rainfall and/or greater rainfall variability. Africa already has highly variable rainfall seasons that result in short crop-growing seasons in many areas. Delays in rainfall, or periods of little or no rainfall during the wet season, can lead to high rates of crop failure. The aggregation of climate change impacts may lead to circumstances in which parts of Africa must abandon crop agriculture and transition to agropastoralism or pastoralism, which is capable of handling both drier and more variable rainfall conditions.[354]

Recommended Strategies

Most needs for adaptation overlap with the menu items we discuss in this report and involve fine-tuning menu item strategies. For example, increasing food production in Africa requires improvements to incremental breeding and seed distribution systems, which would also help crops to evolve with changing climates. Building social welfare systems would allow small farmers to withstand periods of hardship without selling their assets, and the need for resilience will increase with climate change. Many systems that are important today, such as small-scale water-supply systems in Africa and institutional capacity to respond to plant diseases, will only become more important in the future.

In some contexts, information about the future climate is sufficiently clear or local to call for specific new efforts that would otherwise not be justified. Examples include breeding new traits for many crops that enable them to handle high temperatures, and adjusting agricultural production in coastal areas affected by rising sea levels. Over time, as evolving weather patterns become clearer, more of these examples will emerge.

Overall, we believe countries and global organizations should view the need for adaptation as adding urgency to the broader menu for a sustainable food future.



CHAPTER 16

HOW MUCH COULD BOOSTING CROP AND LIVESTOCK PRODUCTIVITY CONTRIBUTE TO CLOSING THE LAND AND GREENHOUSE GAS MITIGATION GAPS?

This chapter uses the GlobAgri-WRR model to explore the combined potential of the measures described so far in this course to limit agricultural land expansion and reduce agricultural GHG emissions, even as the world feeds a growing population.

The menu items in Chapters 12–14 (improve crop breeding, improve soil and water management, and plant existing cropland more frequently) all increase crop production per hectare to meet growing food demand while avoiding further land clearing and associated GHG emissions. What is the combined potential of these menu items? And to what extent might climate change hinder progress if the adaptation measures discussed in Chapter 15 are not pursued? Table 16-1 summarizes the effects of several crop yield change scenarios, based on the GlobAgri-WRR model. All scenarios but the final one in Table 16-1 hold cropping intensity constant from the 2050 baseline level. The final scenario uses the yield growth in our baseline but increases cropping intensity.[355]

Our analysis first shows that differing conceptions of an appropriate "2050 baseline" lead to vastly different amounts of future cropland expansion. A purely theoretical scenario that holds crop yields constant from their 2010 levels, and assumes no change in projected demand, would require cropland expansion of more than 950 Mha between 2010 and 2050 to meet projected food demand and accompanying high land-use-change emissions (more than 12 Gt CO_2e per year during that period). Using FAO's projected growth in yields and cropping intensity (which follows historical trends from 1962 to 2006), as we do in GlobAgri-WRR, expansion is limited to 171 Mha and land-use-change emissions to 6 Gt per year. Using more recent and slower estimates of yield growth from 1989 to 2008 from Ray et al. (2013), cropland area would expand 301 Mha by 2050 relative to 2010, with annual land-use-change emissions of 6.9 Gt.

As discussed in Chapter 15, a changing climate has the potential to depress crop yields, especially in the tropics. We therefore explore a scenario with a 15 percent decline in crop yields across the board relative to our 2050 baseline projection.[356] This scenario in effect would lower average global crop yield growth between 2010 and 2050 from 48 percent to only 28 percent.[357] Thus, a "mere" 15 percent decline in yield would increase the necessary expansion in cropland during this period to 437 Mha, nearly tripling the cropland expansion relative to our 2050 baseline scenario. This large additional expansion would increase the land gap by 45 percent and the GHG mitigation gap by 23 percent, relative to the 2050 baseline.

On a more positive note, we model scenarios of additional increases in crop yields between 2010 and 2050 to simulate large-scale implementation of the crop breeding and soil and water management menu items discussed in Chapters 12 and 13. We model additional increases in crop yields that are 20 percent and 50 percent larger than those in our baseline, which would push global yield increases between 2010 and 2050 from 48 percent under our baseline projection to 56 percent and 69 percent, respectively. Such scenarios would represent enormous agricultural progress, as both would require more substantial yield increases than the historical period 1962 to 2006, which encompassed the Green Revolution, and would be achieved in a period of greater resource scarcity and under a changing climate.

The scenario that increases yields by 56 percent compared to 2010 would bring the amount of necessary cropland expansion between 2010 and 2050 down to 80 Mha. The scenario that increases yields by 69 percent would actually achieve a net reduction in cropland area of 39 Mha. Even this highest yield scenario, however, would only cut the land gap by 35 percent because it would not affect pasture.

Because sub-Saharan Africa is such an important "hotspot" for achieving a sustainable food future, as described in Box 2-4, we also examined scenarios of different levels of yield growth just for that region. Under our baseline scenario, cropland would expand by 102 Mha in sub-Saharan Africa, by far the most of any region.[358] A scenario with 20 percent slower yield growth (relative to baseline) would increase the additional cropland demand in the region to 138 Mha. Going the other direction, 20 percent faster crop yield growth would lower the additional cropland demand in sub-Saharan Africa to 73 Mha.

Finally, although our 2050 baseline raises global cropping intensity from 85 percent in 2010 to 89 percent in 2050, we explore a scenario that increases cropping intensity to 94 percent. That additional increase would reduce cropland expansion from 171 Mha (under our baseline) to only 90 Mha, closing the land gap by 14 percent and the GHG mitigation gap by 6 percent.

At some level, the implications of these different scenarios are all the same: boosting yield growth and cropping intensity (at least for lands that are already regularly cropped) is critical to achieving a sustainable food future.

Table 16-1 | Global effects of 2050 crop productivity change scenarios on agricultural land use and greenhouse gas emissions

SCENARIO	CHANGE IN CROPLAND AREA, 2010–50 (MHA)	ANNUAL GHG EMISSIONS, 2050 ($GT CO_2E$)			GHG MITIGATION GAP ($GT CO_2E$)
		Agricultural production	Land-use change	Total	
No change in crop yields from 2010	952 (+781)	9.6	12.2	21.8	17.8 (+6.8)
2050 BASELINE (crop yields grow 48% between 2010–50)	**171**	**9.0**	**6.0**	**15.1**	**11.1**
Crop yields grow at 1989–2008 rates using Ray et al. (2013)	301 (+130)	9.0	6.9	15.9	11.9 (+0.8)
15% global decrease in crop yields due to climate change with no adaptation	437 (+265)	9.3	8.2	17.6	13.6 (+2.5)
20% additional global increase in crop yields	80 (-92)	8.9	5.3	14.3	10.3 (-0.8)
50% additional global increase in crop yields	-39 (-210)	8.8	4.4	13.2	9.2 (-1.8)
20% decrease in crop yields in sub-Saharan Africa	207 (+35)	9.0	6.3	15.3	11.3 (+0.3)
20% additional increase in crop yields in sub-Saharan Africa	142 (-29)	9.0	5.8	14.8	10.8 (-0.2)
5% additional increase in global cropping intensity	90 (-81)	9.0	5.4	14.4	10.4 (-0.6)

Notes: Numbers not summed correctly are due to rounding. Numbers shown in parentheses are changes relative to 2050 baseline.
Source: GlobAgri-WRR model.

ENDNOTES

1. Mueller et al. (2012).
2. Alexandratos and Bruinsma (2012).
3. Alexandratos and Bruinsma (2012).
4. Evenson and Gollin (2003a).
5. For papers exploring the significance of this shift from draught animals in Austria, see Gingrich et al. (2007); and Gingrich and Krausmann (2018).
6. According to FAOSTAT, East African maize yields were 1.79 t/ha/yr in 2010 and U.S. maize yields were 9.58 t/ha/yr.
7. Burney et al. (2009); Foresight (2011a).
8. Our calculations based on projections from GlobAgri-WRR and using FAOSTAT for historical growth.
9. The summary here is from Schmitz et al. (2014), Figure 1, scenario S1, which is defined as "no climate change and a medium pathway of economic growth and population development."
10. Schmitz et al. (2014), Figure 2.
11. To obtain a slight decrease in cropland area, Bajzelj et al. (2014) estimate a need both for closing most yield gaps and a 50 percent reduction in food loss and waste.
12. Tilman et al. (2011) do not split the agricultural land expansion between cropland and pastures.
13. Schmitz et al. (2014). The summary here is from the Figure 1, scenario S1, which is defined as "no climate change and a medium pathway of economic growth and population development."
14. OECD (2011).
15. Alexandratos and Bruinsma (2012); UNDESA (2017).
16. FAO yield growth rates are somewhat lower than historic global rates of yield growth but somewhat higher on average than regional rates of yield growth. Because it is not clear which rate of yield growth makes more sense to compare with history, we use the phrase "comparable to historical yield growth" as, in effect, an average of the two trend lines.
17. Ausubel et al. (2012).
18. See summary in Grassini et al. (2013).
19. Grassini et al. (2013).
20. Ray et al. (2013).
21. Ray et al. (2012).
22. Sands et al. (2014).
23. The GLOBIOM model runs we cite in this report assume an independent growth rate of crop yields, as well as an "endogenous" growth rate on top of that exogenous growth rate based on demand and price. For a discussion of the GTAP and MIRAGE models, see the supporting information in Searchinger, Edwards, Mulligan, et al. (2015).
24. GlobAgri-WRR model.
25. The basis for this analysis is set forth in Bodirsky et al. (2015).
26. Authors' calculations from FAO (2019a).
27. Lobell et al. (2009); van Ittersum et al. (2013).
28. Lobell et al. (2009).
29. Licker et al. (2010).
30. Lobell et al. (2009).
31. For example, if the top 10 percent of farms define the yield potential, then data errors that exaggerate that potential top 10 percent will result in larger gaps with other performers.
32. See Estes et al. (2013) for a comparison of different categories of crop models.
33. Foley et al. (2011).
34. Fischer et al. (2014).
35. For example, Fritz et al. (2010) shows large discrepancies in cropland maps in Africa from different satellite mapping products. For a discussion of the challenges and inconsistencies between satellite maps and more detailed methods, see Estes, McRitchie, Choi, et al. (2016). See also Li et al. (2010).
36. Hansen et al. (2013).
37. The computer-interpreted analyses from satellite photographs like Landsat at this time are less accurate than human interpretation of closer, aerial photographs. One mechanism for determining the accuracy of satellite interpretation is therefore to verify its projections in a particular location with those derivable from Google Earth photographs using the human eye. In Zeng, Estes, et al. (2018) the authors compared UMD-based projections with thousands of Google Earth photographs in Southeast Asia and found an accuracy of more than 90% for claims of forest-cover loss, and more than 80 percent for claims of nonforest-cover loss, which was much higher than analyses of a range of other land-cover products.
38. In Tyukavina et al. (2018), for example, the authors estimated a loss of 16.6 Mha between 2000 and 2014 in the Congo basin, of which 84 percent was attributed to agriculture, more than 90% of which was "rotational agriculture." In that paper, the authors made clear that while they believed the agriculture would be "rotational," it involved new agricultural expansion that would also be rotational so did involve net forest loss.

39. In Celine et al. (2013), the authors found gross deforestation in the Congo basin of 480,000 ha/yr from 2000 to 2005—twice the rate of the previous decade—and net deforestation of 317,000 ha/yr. The authors attributed some of the additional net deforestation to the reduced length of fallow in rotational agriculture.

40. Zeng, Estes, et al. (2018) shows regional patterns including northern Thailand. Zeng, Gower, et al. (2018) found large-scale deforestation in the Nan province of northern Thailand, 92 percent of which was crop fields.

41. Zeng, Gower, et al. (2016).

42. McNicol et al. (2018) found five times higher rates of deforestation for 2005–10 in the woodlands of southern Africa than in the Hansen data set, which we believe is based on a much lower canopy-cover threshold used to estimate forest in McNicol et al. (2018).

43. Searchinger, Estes, Thornton, et al. (2015) discuss agricultural expansion pressures in the savannas of sub-Saharan Africa; Lambin et al. (2013) discuss other savanna hotspots of conversion that include savannas, such as the Chaco dry forest.

44. The analysis employed by GFW did not distinguish what land that reforested had previously been, but two indicators explain why the substantial majority was likely reforesting from forestry or fire. One is that, unlike agricultural land, clear-cut or burned forest land is not maintained for some other use, and so is likely to reforest. Two, the analysis found that the leading areas with reforestation were Russia, the United States, and Canada, in all of which forest-cover loss is primarily due to forestry and fire.

45. The most important restriction was to count forest gains only when forests achieved 60 percent canopy cover. By contrast, forests are counted as lost if they had 30 percent canopy cover. The 60 percent canopy cover restricts the types of forests that could be counted, but it may also count increasing thickening of forests that already existed but not at 60 percent cover.

46. For example, maps produced by the European Space Agency Climate Change Initiative estimate a gross loss in forest area of only 4.5 Mha per year from 1992 to 2015, with even slower rates after 2000 (Li et al. 2017). Song et al. estimate net gains in forest in this period.

47. The images used in Li et al. (2017) are based on maps that are 9 ha in size, in contrast to the roughly one-tenth of a hectare Landsat maps used by Global Forest Watch. The maps generated by Song et al. (2018) have a pixel size of 2,500 ha and are based on multiple satellite image products, the primary one with pixels representing 121 ha. Many other analyses use Moderate Resolution Imaging Spectroradiometer (MODIS) satellite images, which have a pixel size of 6 ha.

48. Estes et al. (2018) contains a thorough discussion of the challenges in using satellite images with pixels of different sizes and, by comparing them with a high-quality, local spatial data set, finds higher inaccuracies and systematic biases in mapping products based on these images with larger pixel sizes.

49. Estes et al. (2018).

50. FAO (2019a). These data are based on FAO-reported harvested areas for 159 crops, which are all the FAO-reported crop harvested areas except two small-area crops that had no reported data from early years.

51 To avoid bias with any one year, each year reported is actually an average of harvested area that year and in the one preceding and one subsequent year.

52. FAO (2019a). These are data for 2002 through 2016.

53. Foley et al. (2011); Babcock and Iqbal (2014).

54. This calculation is based on background data provided by the authors of Zalles et al. (2019) for Figure S9 of that paper, which is based on Brazilian government reported data on double-cropping.

55. According to FAO (2019a), China reported an increase in harvested area by more than 8.7 Mha between 2001 and 2013, and a decline in "arable" and "permanent" cropland by 4 million ha, for a net gain of nearly 13 Mha, roughly a 10 percent gain in cropping intensity.

56. Qiu et al. (2017).

57. Borchers et al. (2014). United States Department of Agriculture statistics. See Summary Table 3, https://www.ers.usda.gov/data-products/major-land-uses/major-land-uses/#Summary tables.

58. United States Department of Agriculture statistics. See Summary Table 3, https://www.ers.usda.gov/data-products/major-land-uses/major-land-uses/#Summary tables. The difference probably has much to do with a recategorization of land in a category called "cropland pasture."

59. This figure is the decline in land in the Conservation Reserve Program. U.S. Department of Agriculture, Farm Services Agency, "CRP Ending Enrollment by Fiscal Year, 1986–2018," https://www.fsa.usda.gov/programs-and-services/conservation-programs/reports-and-statistics/conservation-reserve-program-statistics/index (last accessed April 2019). Because this land would have been out of production for at least five years, it would not have been considered cropland according to the FAO definition and would therefore qualify as an increase in cropland when cropped.

60. The paper, Zalles et al. (2019), compared its analysis not with FAOSTAT but with cropping data reported by the Brazilian Institute of Geography and Statistics (IBGE) and found that, when deducting double-cropped areas, the discrepancy in cropland reduced to around 10 Mha in 2002 and 5 Mha in 2014. However, IBGE data on cropping are still nearly 20 Mha less than FAOSTAT in 2014, and only 7 Mha of that discrepancy might be explained by its not counting permanent crops, which FAOSTAT does count. That still leaves a 13 Mha gap.

61. Hua et al. (2016); Ahrends et al. (2017).

62. Fetzel et al. (2017).

63. This was the area in effect back-calculated from feed consumption and other sources of animal distribution by the authors of Herrero et al. (2013).

64. Ramankutty et al. (2008).

65. Erb et al. (2007).

66. Stadler et al. (2018).

67. FAO (2019a).

68. A recent summary for all of Latin America is Graesser et al. (2015). Local studies include Barona et al. (2010); Barreto and Silva (2010); Gasparri and Grau (2009); Killeen et al. (2008); and Redo and Millington (2011). Although most studies find that expansion of pasture is the primary driver of forest loss in Latin America, Pendrill and Persson (2017) found conversion to pasture responsible for one-third of forest loss in Latin America from 2000 to 2011.

69. Graesser et al. (2015).

70. The increase in economic output is measured in dollars. As a result, increases in yields and total production of high-value agricultural products, such as milk, meat, fruits, and vegetables, count more in economic terms than increases in yields of cereals and other lower-value products, but this assumes constant prices for the different outputs. In theory, because the relative prices of different agricultural outputs vary, the specific time used to fix those prices could influence these calculations. In reality, the growth of economic output does not vary much by this time frame.

71. Fuglie and Nin-Pratt (2012).

72. Fuglie and Nin-Pratt (2012).

73. FAO (2015b), 30.

74. GlobAgri-WRR model.

75. GlobAgri-WRR model.

76. GlobAgri-WRR model.

77. A major focus of the GlobAgri-WRR analysis was to project a baseline for ruminant livestock efficiency gains. Efficiency gains come in two forms. One is a reduction in the feed (in the form of dry matter) per kilogram of beef or milk. These gains can occur either because of improved animal management or breeds or improvements in feed quality, including more nutritious grasses and some switch to crop-based feeds. The other efficiency gain is in the quantity of feed consumed by animals per hectare. Neither of these figures is directly known historically. FAO estimates quantities of crop-based animal feeds back to 1961, but not grasses and other forages, nor does FAO estimate how much crop-based feeds were eaten by ruminants versus other livestock. We therefore developed a statistical relationship for modern livestock systems between output of milk or meat per animal and output per unit of feed separately using data that went into both Wirsenius et al. (2010) and Herrero et al. (2013). Although these papers had different estimates, the relationship they estimated between efficiency per animal and efficiency per unit of feed was similar. From this relationship, we could estimate a rate of gain in output per unit of feed by 2050 of 20% for beef and 16% for dairy. This rate was global. We also did not believe that historical rates of improvement by region are relevant to future predictions because regions with the highest previous gains now face biological barriers to their rates of improvement. We programmed GlobAgri-WRR to find a resolution that achieves this level of feed efficiency gain within each region by switching livestock production systems to proportionately close gaps between their existing efficiency and the highest global efficiencies. We also assumed a level of yield gap growth in the highest systems of 3%. We also estimated the growth in output of grass per hectare of grazing land by examining global improvements in output per hectare of grazing land based on FAO (2017a) data. We focused on the last 30 years for this trend line in part because knowledge of use of crops before this time is particularly uncertain. This calculation is necessarily imperfect as there were large, but unknown, switches in the quality of grazing land since 1962, and some of the gains were due to these switches rather than to improved management of each hectare of grazing land. However, it leads us to project a 27% rate of increase in forage consumed per hectare of grazing land.

78. Rojas-Downing et al. (2017).

79. AnimalChange (2012), Figure 7. This analysis focused on efficiencies based on protein (kilograms of protein in output, e.g., meat, divided by kilograms of protein in feed). This analysis also noted that feed conversion efficiencies were not widely different in different regions for the reasons we discuss related to backyard systems.

80. Lamb et al. (2016).

81. Erb et al. (2009).

82. Shields and Orme-Evans (2015).

83. GlobAgri-WRR results counting emissions from enteric methane, manure management, and emissions from pasture and paddocks. FAO's GLEAM model estimates ruminant emissions at 80% of global emissions from livestock, although the calculations are not directly comparable because the GLEAM estimate incorporates not only these emissions but also emissions associated with feed production and some postfarm energy and a particular form of land-use change. Gerber et al. (2013), 16, Figure 2.

84. FAO does not directly track or estimate the percentage of feed grains that are provided to different animal types. Herrero et al. (2013) estimated that in 2000, 78% of feed grains were fed to pigs and poultry, with the remainder for ruminants.

85. Herrero et al. (2013), Figure 5. Diagram C shows the emissions per kilogram of milk and the relationship to the digestible portion of the feed in megajoules per kilogram, and Diagram D shows the same for beef. As feed quality improves, there are disproportionate reductions in emissions intensity.

86. The quantity of methane a ruminant will produce from each kilogram of feed will generally be lower for higher-quality feeds, but this relationship turns out to be more complex than previously thought and varies by type of feed and quantities consumed. In contrast, the more digestible the feed, the more meat or milk a ruminant will produce from each kilogram. Because the methane produced for each kilogram of feed declines as digestibility increases, fewer GHG emissions are produced for each kilogram of milk or meat.

87. McDermott et al. (2011), Tables 2 and 3; Pica-Ciamarra et al. (2011).

88. FAO (n.d.); Punjabi (2008).

89. Punjabi (n.d.).

90. Alexandratos and Bruinsma (2012), 132.

91. Wirsenius et al. (2010), Table 4.

92. Herrero et al. (2013), Figure 4. Systems are defined in this paper, and in the so-called Seres-Steinfeld system, by whether they are grazing only, mixed systems of grazing and feeds (a broad category that varies from only 10% feed to 90% feed), or entirely feed-based, and whether they are in arid, temperate, or humid zones.

93. Herrero et al. (2013), Figure S47.

94. Gerber et al. (2010).

95. Gerber et al. (2010).

96. d'Alexis et al. (2012); d'Alexis et al (2013a); d'Alexis et al. (2013b).

97. This analysis appears in Herrero et al. (2013).

98. Gerber et al. (2010), 35, 71.

99. Vellinga and Hoving (2011).

100. Calculated from files provided for the year 2000 as back up materials to Herrero et al. (2013). Beef is 16 percent and dairy is 19 percent.

101. Blummel et al. (2008); Blummel et al. (2009).

102. Thornton and Herrero (2010).

103. Walli (2011).

104. Cardoso et al. (2016).

105. Gerber et al. (2013).

106. Murgueitio et al. (2011); Chara (2012).

107. Murgueitio et. al. (2011).

108. Calle et al. (2013).

109. Calle et al. (2013).

110. Riguero-Rodriguez (2005); Solorio et al. (2016).

111. Cardoso et al. (2016).

112. Boddey et al. (2004); Braz et al. (2013).

113. Cardoso et al. (2016). A separate study, de Figueiredo et al. (2016), found even larger production increases and GHG savings from similar improvements but did not evaluate animals on a "herd basis," which includes both unproductive and productive cows.

114. Gerber et al. (2010), 71. Calculations on a herd basis are lower than calculations that focus only on the milk-producing cow because they count milk-producing cows when they are not lactating, plus all young animals. Comparisons on a herd basis are more meaningful because one way dairy becomes more efficient is by increasing the percentage of cows in the total herd that are producing milk. This can be done by increasing fertility rates, reducing mortality, and reducing the time between lactations of milk-producing cows.

115. Ooko (2014).

116. Bryan et al. (2011).

117. Orodho (2006).

118. Place et al. (2009).

119. Hassanali et al. (2008).

120. Herrero et al. (2011).

121. Thornton and Herrero (2010).

122. GlobAgri-WRR model.

123. Strassburg (2012) estimated that roughly one-third of the potentially improvable grazing land in Brazil was in native vegetation that should not be improved.

124. Authors' calculations.

125. Dixon and Coates (2009); Decruyenaere et al. (2009); Swain et al. (2011).

126. Boval and Dixon (2012); Boval et al. (2007); Fanchone et al. (2012).

127. See the discussion of economic findings by Embrapa studies in Searchinger and Amaral (2009).

128. Rueda et al. (2003).

129. Strassburg (2012).

130. Cohn et al. (2014).

131. Barona et al. (2010). The increase in cattle per hectare was roughly 50%.

132. Herrero and Thornton (2013); IFAD (2009); Department of Agriculture, Forestry, and Fisheries (2012).

133. To cite just two study examples, Cohn et al. (2014) and Henderson et al. (2016) found strong linkages between transportation time and market access and levels of intensification in livestock production in Brazil and sub-Saharan Africa, respectively.

134. Evenson (2003a); Tischer et al. (2014).

135. Alexandratos and Bruinsma (2012); Searchinger, Hanson, Ranganathan, et al. (2013); Foley et al. (2011).

136. Atlin et al. (2017).

137. Atlin et al. (2017).

138. O'Connor et al. (2013).

139. Prigge et al. (2012).

140. Access to Seeds Foundation (n.d.).

141. Hall and Richards (2012).

142. Hall and Richards (2012); Jannink and Lorenz (2010); Nakaya and Isobe (2012).

143. Shimelis (2012).

144. Information about the IRRI monsoon-resistant rice variety was gathered from Higgins (2014).

145. National Human Genome Research Institute (2015).

146. Chen and Rajewsky (2007).

147. Griffiths et al. (2000); Primrose (1995).

148. Personal communication with Gary Atlin, program officer, Bill and Melinda Gates Foundation (June 2017). Periodic announcements are also made in the press by various seed companies; e.g., "NRGene and Syngenta Expand Genomics Collaboration in Key Crops," https://www.businesswire.com/news/home/20190110005053/en/NRGene-Syngenta-Expand-Genomics-Collaboration-Key-Crops.

149. Varshney et al. (2012).

150. Varshney et al. (2012).

151. Varshney et al. (2012).

152. Naylor et al. (2004) use the word *orphan* to describe crops that "receive little scientific focus or funding relative to their importance for food security in the world's poorest regions." They use *minor* to describe crops other than the major food crops of wheat, rice, maize, and soybeans. However, Varshney et al. (2012) associate the word *orphan* with both the extent of research and commercial value. They write, "As they are not extensively traded and receive little attention from researchers compared to the main crops, these important crops for marginal environments of Africa, Asia and South America are often referred to as 'orphan crops.'"

153. Nelson et al. (2014).

154. CFS (2014).

155. Editors of *Nature* (2013); FAO (2012b).

156. NRC (2004).

157. Snell et al. (2012).

158. Greenpeace International has long been a leading opponent of genetic engineering. Its website expresses concerns about the potential consequences of genetic engineering on human health but cites no claims of actual harm to human health to date from an engineered crop. See http://www.greenpeace.org/international/en/campaigns/agriculture/problem/genetic-engineering/failings-of-ge/.

159. The evidence is summarized in NAS (2016).

160. Séralini et al. (2011).

161. Séralini et al. (2014).

162. NAS (2016).

163. Myers et al. (2016) provide a thorough summary of evidence from all sources of potential effects on human health.

164. Zhang et al. (2019).

165. de Souza et al. (2017).

166. NRC (2010).

167. Krishna and Qaim (2012).

168. Wang et al. (2009) found large reductions in the use of pesticides in China despite occasional problems with increased growth of secondary insects. A later article also found reductions, but smaller (Zhao et al. 2011). Other evidence showed an increase in beneficial predators in fields that used Bt cotton (Lu et al. 2012).

169. NAS (2016).

170. NAS (2016).

171. Porterfield (2017).

172. Visser (2018).

173. Tabashnik and Carrière (2017).

174. NRC (2010).

175. Tabashnik and Carrière (2017).

176. NAS (2016).

177. Schütte et al. (2017).

178. Tabashnik and Carrière (2017); NAS (2016).

179. Benbrook (2016), supplemental tables worksheet S1.

180. Benbrook (2016), supplemental tables worksheet S2, S3.

181. Myers et al. (2016).

182. Hoopman et al. (2018).

183. NRC (2010).

184. E.g., Shi et al. (2011).

185. Stone (2012) provides a summary of the wide volume of literature on the yield effects of Bt cotton in India, and Smale et al. (2009) provide summaries of the literature on the broader economics, including yield, of Bt crops in many developing countries.

186. Sexton and Zilberman (2011) provide an example of the challenge. They found enormous yield gains through GM crops by regressing the yield growth in countries that have broadly adopted GM crops against that in countries that have not. Yet countries that have adopted these crops, such as Brazil, Argentina, China, and the United States, have also made other large investments in agriculture, so it is difficult to segregate the consequences of GM crops.

187. NRC (2010); NAS (2016), 127–33.

188. NRC (2010).

189. Fernandez-Cornejo and Wechsler (2012).

190. NAS (2016).

191. NAS (2016), 15.

192. NAS (2016), 111–14.

193. Stone (2012).

194. Gruere and Sun (2012).

195. Supporting this judgment that Bt cotton has boosted yields is the fact that studies that have tried to control for selection bias or use methods that should not reflect selection bias still find significant yield gains despite finding higher benefits from management changes (Crost et al. 2007; Kathage and Quaim 2012; Gruere and Sun 2012), and the fact that the overwhelming majority of peer-reviewed studies, biased or not, do find yield gains.

196. NAS (2016).

197. NAS (2016).

198. Kathage and Quaim (2012); Smale et al. (2009).

199. NAS (2016).

200. Wiggins (2009) provides a good summary of the debate about the productivity and advantages and disadvantages of small versus larger farms in developing countries.

201. Tefera et al. (2016).

202. NRC (2004); NRC (2010); EU Joint Research Centre (2008); AMA (2012); AAAS (2012); NAS (2016).

203. NAS (2016).

204. Ronald (2011) gives an example.

205. NRC (2004).

206. Gonsalves et al. (2007).

207. Davidson (2007); Witty et al. (2013).

208. McGrath (2014).

209. Descriptions of the potato story and the other crop advances described in this paragraph can be found on the website of the 2Blades Foundation, 2blades.org (accessed March 2019).

210. 2blades.org.

211. http://2blades.org/projects-and-technology/projects/resistance-to-bacterial-diseases-in-tomato/.

212. Strange and Scott (2005).

213. Teng and Krupa (1980); Teng (1987); Oerke et al. (1994); Oerke (2006).

214. Jones and Dangl (2006).

215. Jones and Dangl (2006).

216. Jones (2017).

217. NAS (2016).

218. Gepts (2006).

219. Barrangou and Doudna (2016).

220. For a summary, see Ledford (2016).

221. Nelson et al. (2014).

222. The world devoted 2.23 percent of total GDP to R&D in all sectors in 2015 (World Bank 2017e), and a strong case can be made for increasing research funding across all sectors generally (Griffith 2000). By contrast, world agricultural GDP was $3.62 trillion in 2014 according to the World Bank (2017f). If agricultural R&D were still $52 billion, the percentage would be roughly 1.4 percent ($50 / $3,620 = 0.014). Assuming from partial data described below that it has grown by 20 percent, then this percentage would have grown to 1.7 percent.

223. Beintema et al. (2012).

224. CGIAR (2017).

225. Mukherjee et al. (2018).

226. Nieburg (2013); Motamayor et al. (2013).

227. Jaganathan et al. (2018) describe recent breeding progress in a variety of crops enabled by CRISPR-CAS, and Lemmon et al. (2018) describe how breeders used CRISPR-CAS to make rapid improvements in plant architecture, flower production, and fruit size of groundcherry and tomatoes.

228. See GCP (2014).

229. AOCC partners include Beijing Genomics Institute; Biosciences Eastern and Central Africa; The iPlant Collaborative; Life Technologies; Mars Incorporated; New Partnership for Africa's Development (NEPAD); University of California, Davis; World Wildlife Fund; and World Agroforestry Centre.

230. Howard Shapiro, personal communication, May 15, 2014. Shapiro was a founder of the consortium.

231. FAO (2011b). Preliminary results from the Global Land Degradation Information System (GLADIS) assessment.

232. Place et al. (2013).

233. Cervigni and Morris (2016). By "drylands," we refer to the zones classified on the basis of an aridity index of 0.05 to 0.65, and encompassing the dry subhumid, semiarid, and arid zones. We are not referring to the hyperarid zone with an aridity index of less than 0.05 and which does not support crop and livestock production and is very sparsely populated. According to recent analysis by the World Bank, the drylands including these three zones cover some 1.3 billion ha, or nearly 55% of sub-Saharan Africa, and are home to about 390 million people, or roughly 48% of the region's population. The dominant farming systems in the drylands of sub-Saharan Africa are "agro-pastoral" and "maize mixed."

234. Johnson et al. (2006).

235. Koohafkan and Stewart (2008).

236. Cervigni and Morris (2016).

237. Allison (1973).

238. Stoorvogel et al. (1993); Liu et al. (2010).

239. Powlson et al. (2016).

240. Marenya and Barrett (2009a).

241. Rockström et al. (2003).

242. Bationo et al. (2006). As these authors note, "Soil moisture stress is perhaps the overriding constraint to food production in much of Africa. Moisture stress is not only a function of the low and erratic precipitation but also of the ability of the soil to hold and release moisture. About 10% of the soils in Africa have high to very high available water-holding capacities. . . . Most African soils are inherently low in organic carbon (<20 to 30 mg/kg) and consequently have low capacity to retain soil moisture. . . . The development of conservation agriculture technologies with permanent soil cover will be of importance for the conservation of soil moisture as shown in various FAO projects."

243. Marenya and Barrett (2009b). Several studies are cited in Titonell and Giller (2013).

244. Xie et al. (2007); Yu et al. (2009).

245. WOCAT (2015).

246. Reij et al. (2009); Stevens et al. (2014); Reij and Winterbottom (2015).

247. This information is from work by two researchers from the University of Niamey (Boubacar and Sambo), who undertook a quick study in five villages in the Kantché department (Southern Zinder) to look at regreening and food security. A blog about this work is accessible at http://africa-regreening.blogspot.com/2012_03_01_archive.html.

248. Reij et al. (2005); Botoni and Reij (2009); Reij et al. (2009).

249. Tropical Forages (2012).

250. Tropical Forages (2012).

251. Yamba and Sambo (2012).

252. Rockström et al. (2003).

253. Mekdaschi and Liniger (2013); Critchley and Gowing (2012).

254. Hassane et al. (2000).

255. Sawadogo (2006).

256. Hassane et al. (2000) show that yield improvements from water harvesting can vary from 500 to 1,000 kg/ha, depending on other factors such as soil fertility. Sawadogo (2013) found that farms in Burkina Faso using water harvesting techniques increased yields 50–100% when compared with adjacent cultivated land not using harvesting techniques. An increasing number of farmers in the Sahel have used water harvesting techniques to reclaim lands that had been out of production for generations. In areas close to Tahoua, Niger, they were able to convert very low potential lands into productive lands (as measured not only by yields but by land prices). Mazvimavi et al. (2008) found that water harvesting, combined with conservation agriculture, increased yields per hectare by 50% on average across nine districts in Zimbabwe.

257. Doumbia (2010).

258. Doumbia (2010); Feed the Future (2012).

259. Hayashi et al. (2008); Tabo et al. (2007); Sanginga and Woomer (2009); ICRISAT (2009).

260. Aune and Bationo (2008); Vanlauwe et al. (2010).

261. Sawadogo (2013).

262. Sanders and Ouendeba (2012).

263. FAO (2012b).

264. Williams and Fritschel (2012); Bunderson (2012); Pretty et al. (2006); Branca et al. (2011).

265. According to IFDC (2011), in West Africa, the adoption of integrated soil fertility management practices by farmers on 236,200 ha between 2006 and 2010 resulted in yield increases for cassava, cowpeas, groundnuts, and maize—including a 58% yield increase for groundnuts, as well as revenue increases of 179% for maize and slightly more than 50% for cassava and cowpeas.

266. Arslan et al. (2013); Arslan et al. (2014). "Conservation Farming package as promoted in Zambia consists of following practices: (1) reduced tillage on no more than 15% of the field area without soil inversion, (2) precise digging of permanent planting basins or ripping of soil with a *Magoye ripper* (the latter where draft animals are available), (3) leaving of crop residues on the field (no burning), (4) rotation of cereals with legumes and (5) dry season land preparation."

267. Arslan et al. (2013).

268. Arslan et al. (2015) provides a good summary of these studies.

269. Arslan et al. (2014). An endogeneity problem is one in which a study is unable to distinguish statistically which of two related factors is cause and which effect, or to which degree, or whether both are the result of a third factor.

270. Arslan et al. (2015).

271. Giller et al. (2015).

272. Giller et al. (2015).

273. Beebe (n.d.).

274. Duncan et al. (2016).

275. Powlson et al. (2016).

276. Liniger et al. (2011).

277. Mafongoya (2006).

278. Mafongoya (2006).

279. Marenya and Barrett (2009a).

280. Giller et al. (2015); Williams and Fritschel (2012); Bationo et al. (2007).

281. Liang et al. (2006); Lehmann (2007); Whitman and Lehmann (2009).

282. W4RA (2017).

283. Reij and Garrity (2016).

284. Reij and Winterbottom (2015).

285. FAO (2019a).

286. Modeling using the GAEZ model accessible at http://webarchive.iiasa.ac.at/Research/LUC/GAEZ/results/5_7.htm.

287. Table 4.9 of Alexandratos and Bruinsma (2012) provides cropping intensities in 2006–7 for rainfed and irrigated land separately. Assuming that all irrigated lands are harvested at least every year, around 70 Mha of irrigated land are double-cropped. According to Siebert et al. (2010), 150 Mha are double-cropped in total. Putting these two estimates together, approximately 80 Mha of rainfed land are double-cropped, which according to Table 4.9 is 6% of the 1,335 Mha of rainfed cropland as of 2006–7.

288. Kalaiselvi and Sundar (2011).

289. Shiao et al. (2015). Chapter 28 on rice cultivation discusses declining groundwater in Tamil Nadu and Punjab in more detail.

290. Heinimann et al. (2017).

291. Alexandratos and Bruinsma (2012), Table 4.9.

292. As summarized in Ray and Foley (2013), FAOSTAT data suggest an increase in harvested area of 12.1 Mha per year between 2000 and 2001, and an increase in cropland area of only 2.9 Mha per year during that period, for a difference of 9.2 Mha "saved" per year, which over 11 years, implies 101 Mha of additional harvested area without expansion of cropland.

293. Ray and Foley (2013).

294. To develop an estimate of fallow land, we deduct 80 Mha of cropland from the total estimate of rainfed cropland in Table 4.9 in Alexandratos and Bruinsma (2012) to come up with land that is not double-cropped, and deduct 160 Mha of land from harvested area (reflecting two crops per year on 80 ha of land). The resulting difference between single-cropped cropland and harvested area suggests around 350 Mha of fallow land each year. FAO (2017a) indicates a 251 million hectare difference between total arable land (including land devoted to permanent crops such as trees) and harvested area in 2009. These figures differ somewhat from the 299 Mha presented in Alexandratos and Bruinsma (2012), which adjusted arable land and harvested land in a couple of ways. However, assuming that roughly 150 Mha were double-cropped for reasons discussed above, that means 400 Mha were not harvested at all.

295. For example, FAO reported 158 Mha of U.S. cropland in 2012 (FAO 2019a). However, in 2012 (the most recent year for which USDA is reporting data), it reported 138 Mha of U.S. cropland including planted areas that could not be harvested and summer fallow areas (USDA/ERS 2017). The roughly 20 Mha difference consists roughly equally of two land categories: idled cropland, which is primarily Conservation Reserve Program lands, and cropland used for pasture.

296. Nefedova (2011); Ioffe (2005); Kuemmerle et al. (2010); Kurganova et al. (2007). FAO data for 2009 categorize 44% of arable land in the former Soviet Union as unharvested. The region abandoned croplands in vast numbers after the fall of the Soviet Union, and this figure suggests that it includes some or much of that land. But this land has been reforesting and otherwise sequestering carbon.

297. Kurganova et al. (2010).

298. Good et al. (2016).

299. Pires et al. (2016).

300. Relative to 1986–2005. Collins et al. (2013).

301. Easterling et al. (2007).

302. Porter et al. (2014).

303. Craparo et al. (2015); Eitzinger et al. (2011); Ortiz et al. (2008); Teixeira et al. (2013).

304. For increasing scientific evidence of the role of direct heat stress on crops, see Asseng et al. (2011), Lobell et al. (2012), and Shah et al. (2011).

305. IPCC (2014); Semenov et al. (2012); Teixeira et al. (2013).

306. As just one example, Giannini et al. (2017) project a 13% decline in availability of pollinators by 2050 in Brazil.

307. Zhou et al. (1995).

308. Harrington et al. (2007).

309. Lobell and Field (2007).

310. Jones and Thornton (2013).

311. For evidence of adverse impacts of climate change on crops and the disruptive consequences of more likely extreme events, see Battisti and Naylor (2009); Lobell and Field (2007); Schlenker and Roberts (2009). For increased evidence of likely adverse effects in Africa, see Schlenker and Lobell (2010). For recent assessments suggesting the more likely adverse consequences of climate change in colder regions, see Semenov et al. (2012).

312. World Bank (2014).

313. Lesk et al. (2016).

314. Dale et al. (2017).

315. World Bank (2014).

316. Porter et al. (2014).

317. Liu, Xu, Zhuang, et al. (2013).

318. Leakey et al. (2009).

319. Long et al. (2006).

320. World Bank (2014).

321. Schlenker and Roberts (2009).

322. Liang et al. (2017).

323. Craparo et al. (2015); Peng et al. (2004); Rao et al. (2014).

324. Lobell et al. (2011).

325. World Bank (2014); Lobell et al. (2008).

326. IPCC (2014).

327. Nelson et al. (2009), as cited in IPCC (2014).

328. Laderach et al. (2010); Eitzinger et al. (2011); Bunn et al. (2015).

329. Bunn et al. (2015).

330. Jones and Thornton (2015).

331. Porter et al. (2014).

332. Porter et al. (2014), summarizing Hertel et al. (2010); Calzadilla et al. (2013); Lobell et al. (2013); and Nelson et al. (2013).

333. Nelson et al. (2009).

334. Lloyd et al. (2011).

335. Hewitson and Crane (2006).

336. Vermeulen et al. (2013).

337. Gershunov and Barnett (1998).

338. Estes et al. (2013).

339. Thornton et al. (2011).

340. Sherman et al. (2016).

341. Dore (2005); Wetherald and Manabe (2002).

342. For example, this is the irrigation focus of Sri Lanka's climate strategy; Vermeulen et al. (2013).

343. Xie et al. (2014).

344. Thornton and Cramer (2012); Lobell et al. (2011).

345. Watts (2016).

346. Urban et al. (2012).

347. Bolaños and Edmeades (1996); Cooper et al. (2014); World Coffee Research (2015).

348. Kopp et al. (2017); DeConto and Pollard (2016).

349. Dasgupta et al. (2009).

350. Islam et al. (2015).

351. Renaud et al. (2015).

352. Islam et al. (2015).

353. Renaud et al. (2015).

354. Jones and Thornton (2009).

355. We do not show these higher yield gains as reducing the food (crop calorie) gap because we assume that the alternative to these higher yield gains would be "baseline" levels of yield gain that would result in the same number of crop calories produced, but with additional expansion of agricultural land. Our food gap closure menu items therefore focus on the demand-reduction techniques in Course 1, which by limiting the gap can reduce the amount of additional food production necessary between 2010 and 2050 and increase the likelihood that the land and GHG mitigation gaps can be closed while adequately feeding everyone in 2050.

356. This global 15% decline in crop yields (actually an average decline of 15.48%) is drawn from the LPJmL scenario without CO_2 fertilization described in Müller and Robertson (2014).

357. GlobAgri-WRR model. If crop yields were equal across crops, purely reducing yields from 1.48 (a 48% growth above 2010 levels) by 15.48% would lead to 25% growth above 2010 levels (1.48 * 0.8452 = 1.25). Because all crops have different yields, and there are varying amounts of each crop grown in the world, the actual overall growth (across all crops) ends up being 28%, as calculated by GlobAgri-WRR.

358. GlobAgri-WRR model. Asia (outside of China and India) is next at "only" 35 Mha of cropland expansion between 2010 and 2050 under our baseline scenario.

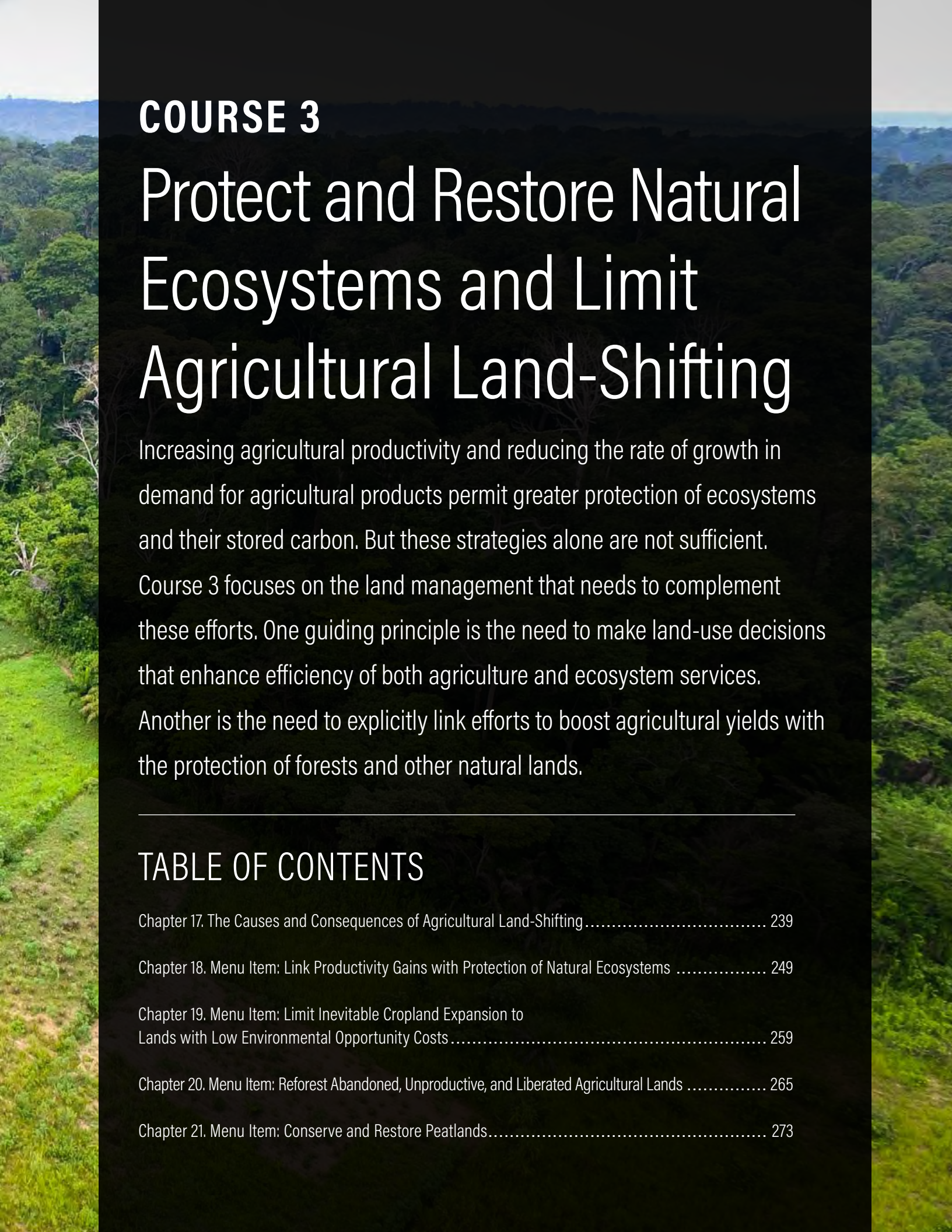
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COURSE 3

Protect and Restore Natural Ecosystems and Limit Agricultural Land-Shifting

Increasing agricultural productivity and reducing the rate of growth in demand for agricultural products permit greater protection of ecosystems and their stored carbon. But these strategies alone are not sufficient. Course 3 focuses on the land management that needs to complement these efforts. One guiding principle is the need to make land-use decisions that enhance efficiency of both agriculture and ecosystem services. Another is the need to explicitly link efforts to boost agricultural yields with the protection of forests and other natural lands.

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Introduction

Holding down growth in food demand (Course 1) and boosting agricultural yields (Course 2) could prevent expansion of the net global area of agricultural land. In the case of our more ambitious scenarios, these two strategies could even lead to a decline in agricultural land area. But our calculations are based on the net need for agricultural land. Our model assumes that every hectare of land that is not converted because of reduced growth in demand (or increased yields on existing hectares) saves the carbon that would otherwise be released by converting that additional hectare. Unfortunately, the land-use challenge is more complicated than that. Even if net expansion of agriculture is eliminated, agricultural production will continue to shift from one place to another. These shifts often involve conversion of biologically diverse and carbon-rich habitats, which immediately releases long-stored carbon and harms biodiversity.

Although necessary to hold down net expansion of agricultural land, yield growth for some crops in tropical countries could even accelerate these shifts, by making farming more profitable and giving farmers an incentive to clear new land. Translating yield gains into full benefits in the real world therefore requires land management efforts that are designed to minimize gross—not just net—agricultural expansion and reduce the environmental costs of any expansion that does occur.

To achieve climate and ecosystem goals, some active restoration efforts are also required. Agricultural land that is abandoned—whether as a result of agriculture shifting to other locations or net declines in agricultural land area—tends to naturally regenerate into forests and other native habitats. However, active restoration could enhance benefits for carbon storage and other ecosystem services. Today, a limited amount of agricultural land is so marginal that it is incapable of generating higher yields in practice and warrants restoration right away. Little-used drained peatlands release so much carbon dioxide that they also deserve priority action.





CHAPTER 17

THE CAUSES AND CONSEQUENCES OF AGRICULTURAL LAND-SHIFTING

Agricultural land is not only expanding overall but also shifting its locations among and within regions and countries, which imposes environmental costs. This shifting is not to be confused with what is sometimes called "shifting" or "swidden" agriculture, in which farmers with few inputs engage in multiyear crop rotations, allowing exhausted fields to reforest before clearing them again.

Global and Regional Shifts in Locations of Agricultural Land

At the global level, agriculture is generally shifting from the North toward the South. Between 1961 and 2013, cropland declined by 126 million hectares (Mha) in Europe and North America but expanded by 331 Mha in Africa, Asia, Latin America, and Oceania.[1] As discussed in Chapter 10, pasture area is also shifting, declining by 66 Mha in Australia and New Zealand between 1994 and 2014 while expanding in Latin America.[2]

This trend is likely to continue because population and demand for food will increase more rapidly in developing countries. For example, using older UN population growth projections, the UN Food and Agriculture Organization (FAO) projected that cropland area would decline by 38 Mha in developed countries between 2006 and 2050 even as it expands by another 107 Mha in developing countries.[3] Using the GlobAgri-WRR model, we also project a shift in the global share of agricultural land. Because future trade is so difficult to estimate, we assume that the percentage of each food imported or exported will remain at the same levels as in 2010, which means the model does not allow a higher percentage of food consumed in developing countries to come from developed countries in the future. Even so, the model estimates that agricultural land will expand by an additional 474 Mha in developing countries but by only 119 Mha in developed countries (Table 17-1).[4] We believe that even this relatively small role for developed countries may be an overestimate because our baseline scenario probably does not fully capture the effects of increasing land-use competition in developed countries.

Table 17-1 | Projected change in agricultural land use by region, 2010–50 (baseline scenario)

REGION	CHANGE IN CROPLAND AREA (MHA)	CHANGE IN PASTURELAND AREA (MHA)	TOTAL CHANGE IN AGRICULTURAL AREA (MHA)
Asia (excluding China and India)	42	61	103
Brazil	2	34	37
China	-25	-1	-26
European Union	-17	8	-8
Former Soviet Union	0	-33	-33
India	32	2	34
Latin America (excluding Brazil)	12	68	80
Middle East and North Africa	8	10	18
OECD (other)	5	52	57
Sub-Saharan Africa	104	158	262
United States and Canada	27	43	70
Total	**192**	**401**	**593**

Note: Figures may not sum correctly due to rounding.
Source: GlobAgri-WRR model.

Gross versus net agricultural expansion

Many years of satellite image studies show that locations of agricultural land also shift substantially within regions.[5] Figure 17-1 shows an analysis by FAO based on satellite imagery of forest losses and gains by continent from 1990 to 2005. Although both Africa and South America had net losses of forest, these were substantially smaller than gross losses, which implies that agricultural land expansion in some places is outpacing reversion to forests on abandoned agricultural land elsewhere.[6] Asia, too, had large gross losses, particularly of native wet tropical forests. The continent experienced a net forest gain overall (nearly 50 Mha between 1990 and 2010), but this gain was largely due to establishment of tree plantations, particularly in China.[7]

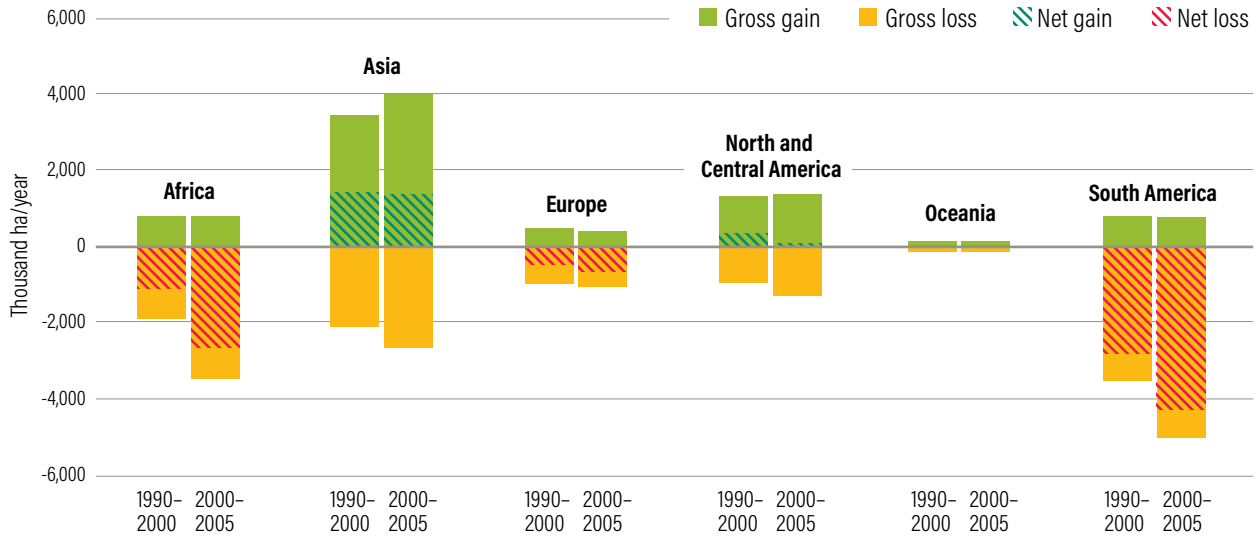
A separate study of deforestation in Latin America from 2001 to 2010 found that gross forest loss exceeded net forest loss by three to one (Figure 17-2). In the United States, 3 Mha were converted to cropland between 2008 and 2012, even as 1.8 Mha of cropland elsewhere in the country were abandoned or otherwise taken out of food production.[8] In Europe, one study found 1.6 Mha of agricultural expansion from 1990 to 2006, but 2.1 Mha of other agricultural land reverted to some kind of forest or other more natural vegetation.[9]

Although these shifts in the locations of agriculture permit some abandoned lands to regenerate, the trade-off tends to be poor from the perspective of biodiversity and carbon storage. New cropland is being established primarily in the tropics and subtropics, where biodiversity is much higher.[10] Many newly converted lands were formerly natural or relatively natural forests and grasslands,[11] whose biodiversity is often irreplaceable.[12]

Because conversion in the tropics often occurs on relatively intact native ecosystems, the carbon losses are often higher per hectare than conversion of agriculture in other parts of the world. It is at least as important to note that tropical yields also tend to be lower. As a result, the carbon storage lost per ton of crops produced is higher in the tropics than in the temperate and boreal zones.[13] Time also matters. The losses of carbon during land conversion mostly occur immediately, while restoring carbon in vegetation and soils occurs gradually over longer time periods.[14]

In addition, farmers tend to abandon land that is dry and at higher elevations, whereas they tend to clear wetter and more productive ecosystems, which tend to be richer in carbon and biodiversity.[15] Overall, gross land conversion caused by shifting locations of agricultural land presents a major environmental challenge that has received insufficient global attention.

Figure 17-1 | Gross forest losses are far greater than net forest losses because locations of agricultural lands are shifting



Source: FAO (2012a).

Figure 17-2 | While forests recovered in some areas of Latin America from 2001 to 2010, even larger areas were cleared elsewhere for agriculture



Source: Aide et al. (2012).

Drivers of Agricultural Land Expansion and Location Shifting

Several powerful forces are driving shifts in location of agricultural land, and they are likely to continue pushing expansion in many locations even if the total, global demand for agricultural land stabilizes. One important driver is high growth in demand for food in specific regions. Another is rising demand for specific food types that are best grown in the tropics. A third is the advance of roads and other infrastructure across the global South that is opening up new, financially cheap but environmentally expensive lands for agriculture.

Some regions face high growth in demand for food

In some countries or regions, the growth in food demand is likely to be so great that it will prove extremely difficult, if not impossible, to prevent some expansion of agricultural area.

Sub-Saharan Africa poses the greatest challenge, as explored in Box 2-4, because the likely growth in domestic food demand will make some expansion of agricultural land inevitable. Although we use FAO's predictions of robust yield growth in the region of roughly 250 percent between 2006 and 2050,[16] our baseline projection is that the region's cropland will nevertheless still expand between 2010 and 2050 by roughly 100 Mha. If we use less optimistic yield trends based on 1989–2008 rates—our "alternative baseline"—we project cropland expansion of 241 Mha.[17] These projections assume that the region continues to rely heavily on other countries for its staple foods, importing roughly 20 percent of meat and milk and 18 percent of cereals.[18]

Other analyses come to similar conclusions. One study found that even if countries in West Africa were able to more than double their rates of cereal yield gain between 2001 and 2014 (and triple their rates of maize yield growth) out to 2050, their imports of cereals would still have to grow from 21 percent to 45 percent by midcentury if they did not expand their cropland.[19] Actual self-sufficiency in maize would require yield growth of roughly 144 kilograms (kg) per hectare per year, which is five times the rates of yield gain from 2001 to 2014 in Africa and roughly 3.5 times the global average rate of yield growth. Some estimates indicate that for sub-Saharan Africa to become self-sufficient in crop calories, cereal yields would have to increase four-fold between 2007 and 2050. Using FAO 2050 yield estimates, crop area would have to grow by 140 Mha from 2006 to 2050 just to maintain roughly present levels of imports.[20]

Some regions will meet high international growth in demand for vegetable oil and animal feeds

The growing demand for vegetable oil and high-protein animal feeds, and the ability of tropical and subtropical countries to meet this demand well by producing palm oil and soybeans, represents another driver of gross land expansion in some countries and a likely shift of agricultural production to their lands.

Soybeans are inputs to both vegetable oils and animal feeds. Globally, soybeans were grown on 84 Mha in 2003 and 111 Mha in 2013,[21] a 33 percent increase over one decade despite advances in breeding and management of this heavily researched commodity crop. Other researchers have projected that even with yield gains, the global area dedicated to soybeans will need to increase by another 30 Mha by 2050 or even by 2030 to meet estimated demand.[22] Latin America is a good region for growing soybeans, with Brazil and Argentina already being two of the world's three principal producers. Even in Africa, where soybean yields to date have been low, vast areas have relatively high growth potential.[23] The economics of rising demand, relatively lower land costs in emerging and developing countries, and good yield potential will continue to drive expansion of soybean planting in these areas.

Continued growth in demand for palm oil will also place enormous pressures on tropical rain forests, which provide the best conditions for growing oil palm trees. With an average global yield of 3.7 tons of oil per hectare, oil palm generates seven times the oil yield per hectare of soybeans.[24] In 2015, oil palm provided 31 percent of the world's vegetable oil production by tonnage, even beating out soybeans (at 24 percent) as the world's dominant vegetable oil crop.[25] The 13 Mha of oil palm plantations around the world in 2011[26] are heavily concentrated in Indonesia and Malaysia, which together accounted for 85 percent of global palm oil supply in 2015.[27] But the industry is making inroads into West Africa, Central Africa, and South America.[28] Despite

some efforts to curtail the use of palm oil,[29] experts predict that palm oil will meet an even larger share of future vegetable oil demand because of its high productivity and low cost. One estimate projects a need for at least an additional 12 Mha of oil palm plantations globally from 2009 through 2050 to meet worldwide demand—and potentially more.[30] And if palm oil production does not expand but vegetable oil demand continues to grow as projected, even more hectares of land would be converted to grow lower-yielding vegetable crops to meet projected demand.

The global South is developing its roads and other infrastructure

Agriculture is also expanding in many areas because of new roadbuilding. Studies have shown that new or improved roads into forests typically lead to large areas of deforestation and agriculture expansion along those roads.[31] In the Brazilian Amazon, for example, 95 percent of deforestation has occurred within 5.5 kilometers (km) of a road.[32] Not only do roads provide economic access to new areas but, over time, economic activity starts to grow, especially extractive and agricultural activities. Vested interests in further clearing and roadbuilding emerge. Large roads tend to lead to serial networks of smaller roads.

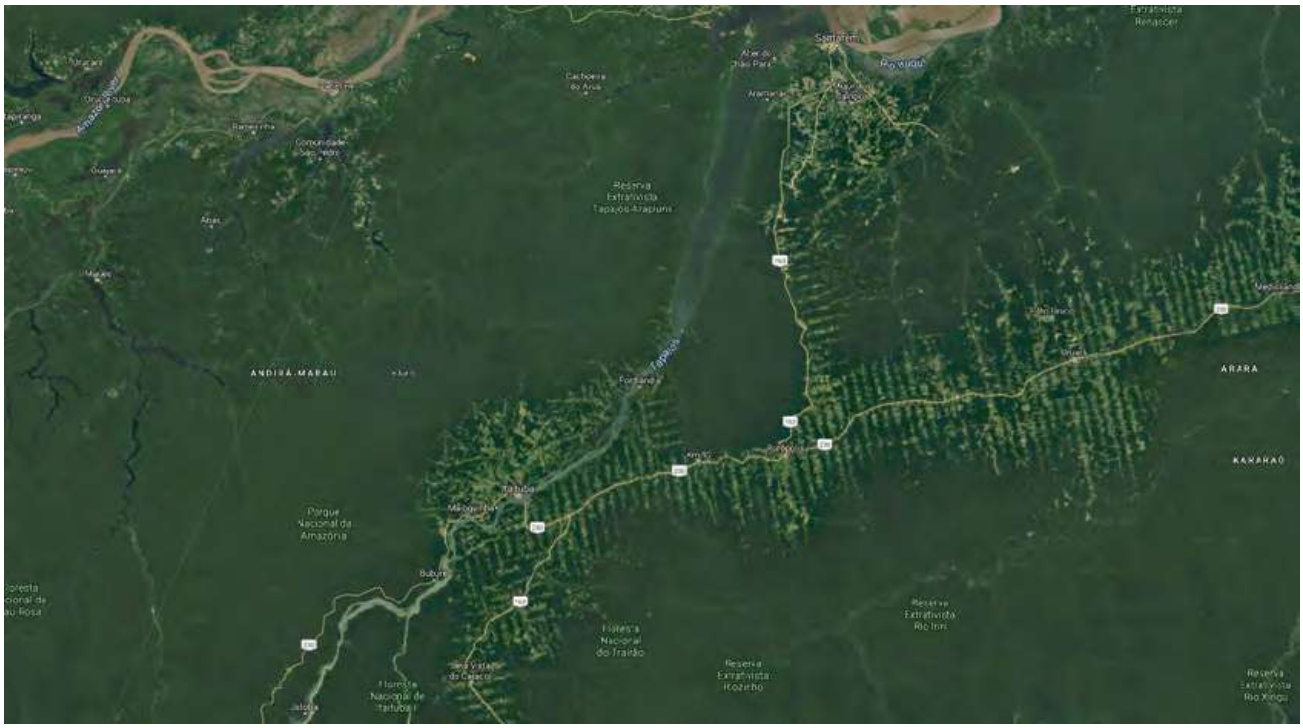
The environmental effects of roads go beyond direct land-clearing. Roads allow people to hunt wildlife and harvest timber illegally and create paths for invasive species.[33] Vehicles on roads kill large numbers of animals and pose particular problems for species that migrate over large areas.[34] Roads also encourage logging.[35] New roads are now penetrating many of the world's last remaining forest wildernesses, including the Amazon, Papua New Guinea, Siberia, and the Congo Basin.[36]

New roads present an enormous challenge to forests and other natural areas because roadbuilding also plays a major role in economic development generally and in the improvement of agriculture on existing croplands and pasture.[37] Poor roads increase the costs of inputs, decrease the prices farmers receive for outputs, increase food storage losses, and create significant additional uncertainties for investors. Many studies have shown that boosting yields of milk and of many crops is often not economical in the absence of good market access, which requires acceptable road networks.[38] The rutted, rural roads common in Africa, Latin America, and even much of Asia are therefore major impediments to agricultural improvement.

For these reasons, roads are often built through forests and other natural areas to spur economic development rather than (primarily) to open up new areas for farming. For example, roads may be constructed to connect cities or to increase access to ports: the purpose of a road paved through the Amazon forest from Mato Grosso in the south to Santarém on the Amazon River in the north was to make it less expensive to export soybeans and other crops from Mato Grosso, an already heavily developed agricultural state. But a side effect was to encourage additional deforestation along the road (Figure 17-3).[39]

Governments have extensive plans for roadbuilding, at different stages of realization, all over the world.[40] One study has documented 33 new or growing transportation and development corridors in sub-Saharan Africa, extending over 53,000 km. Ten of these roads are active, nine are proposed for upgrading, and 14 are planned.[41] The study found that the transportation networks (including a few railroads) would bisect 408 protected areas and 574 Mha of protected habitats, and that many would "promote serious and largely irreversible environmental change." Roadbuilding also appears to be getting a boost from international infrastructure funding. The G20 group of wealthy countries committed to double the current value of global infrastructure by 2030 by investing $60–70 trillion worldwide.[42] The addition of the Asian Infrastructure Investment Bank (AIIB) to the global multilateral bank scene in 2016 is likely to accelerate infrastructural investment. AIIB expects to double its lending within the next five years and to fund major infrastructural projects such as gas pipelines, railways, and motorways.[43] Realistically, if roadbuilding follows present plans, large-scale deforestation of intact old-growth forests is all but certain to occur.

Figure 17-3 | Roadbuilding has led to deforestation and agricultural expansion in Pará, Brazil



Source: Imagery © 2019 Landsat/Copernicus, Map data © 2019 Google.

The Potential of Yield Gains to Shift Locations of Agriculture

Because boosting global output per hectare is a mathematically necessary way to meet increases in food demand without land-use change, yield gains are a critical course on our menu. Unfortunately, yield gains can also accelerate shifting and local expansion of agricultural land, particularly in developing countries.[44] Initial studies struggled to explain this phenomenon and some even suggested that yield gains might increase not just local but even global land use for agriculture. But more recent research has pointed out that expansion occurs at the country level when increased yields lead to greater competitiveness and more exports.[45] In effect, yield gains do tend to reduce global agricultural land use if compared to the alternative of growth in demand without yield gains—but yield gains can also lead to increased agricultural area where those yield gains occur. It is important to appreciate why.

The "consumption rebound" effect?

One potential explanation is that boosting yields helps lower prices, and people respond by consuming more food—a consumption "rebound effect." If consumption increases by a larger percentage than yields, agriculture will expand into new lands. We consider this consumption effect to be generally a small and inappropriate concern.

First, the economic evidence is strong that, on balance, global yield gains will save land. For most foods, people only modestly increase their consumption of crops when prices decline.[46] As a result, a 1 percent decrease in price will generally cause substantially less than a 1 percent increase in consumption of crops. In addition, a 1 percent increase in crop yield by itself will cause less than a 1 percent decrease in crop price because land is only one cost of production and decreasing land cost by 1 percent does not decrease total costs by 1 percent. In addition, farmers may achieve higher yields by increasing other inputs, and therefore increasing their costs.[47] Putting these two effects together, although a 1 percent increase in yield by definition

means a 1 percent decrease in land area to produce the same amount of food, it will in general cause less than a 1 percent increase in consumption and will therefore save land overall.

Second, a sustainable food future requires improving food availability for billions of poor people who spend large percentages of their income on food. Lower food prices help to meet their needs, and intentionally seeking higher prices than necessary is not morally acceptable. An alternative past with no Green Revolution would have included more hunger and less food consumption.[48] Increasing the capacity of the poor to consume food, in part by keeping food prices low, is one of the requirements for a sustainable food future.

Such an approach does not preclude use of prices to influence overconsumption by the wealthy, but that influence must occur through taxes. The consumption of the world's wealthy people is little affected by farmgate food prices for two reasons: price increases have less effect on their consumption, and farmgate prices are a small component of the retail food prices that people pay in developed countries.[49] Increases in farmgate food prices would therefore mainly affect the poor, and the only practical way to use prices to target consumption by the rich is through taxes at the retail level.

One exception may be yield gains for beef and other ruminant meats. These yield increases may not increase total food or total meat consumption, but they may cause consumers to consume more beef and less chicken or vegetable sources of protein. These dietary shifts would not benefit nutrition or the poor but would increase land-use demands and greenhouse gas (GHG) emissions. Studies also estimate that prices have a substantially larger effect on meat consumption than on other foods (sometimes with absolute elasticity values around 1, which means that a 10 percent decrease in price would result in a 10 percent increase in consumption).[50] Yield increases therefore do have some realistic potential to increase beef consumption. Increases in pasture yields still play a critical role in our menu for a sustainable food future, and it is hard to imagine a future scenario that freezes agricultural



land expansion without achieving vast increases in pasture yields. But if higher yields lead to lower prices, some compensating measures to avoid increased consumption of ruminant meat may also be necessary.

The "local production rebound" effect

The more important and environmentally challenging problem is what can be called a local production rebound effect.[51] Yield gains—even if they spare land globally—may encourage local conversion of forests, savannas, and other natural ecosystems by lowering local production costs. In other words, yield gains can improve the economics of farming per hectare, giving farmers incentives to put more hectares into production to increase their total profit. This pattern likely underpins expansion of soybeans, maize, and beef in Brazil and Argentina, and of oil palm in Indonesia and Malaysia.

This kind of locational shifting of agricultural lands does not occur because of yield gains per se. If all countries increased their yields in a way that lowered production costs by the same amount, no country would gain a competitive advantage.[52] The shifting occurs when yields increase and production costs decrease in some countries more quickly than in others. Countries where yields grow and costs decline more will be able to produce and export crops or livestock at lower prices and might therefore expand the land area dedicated to those commodities to meet increased internal and external demand.

This challenge does not mean that yield gains should be avoided because they risk encouraging local production rebound effects. In general, yield gains in North America and Europe are unlikely to trigger regional expansion of agricultural land because cropland area has been in long-term decline in these regions due to yield gains and stabilizing populations. If yield gains improve these regions' competitive advantage, that is likely to result only in maintaining more cropland in production. Even so, breeding that enables crops to grow in different locations can still cause land shifting in these regions; for example, breeding and development of crop varieties that can grow in drier, shorter growing seasons is likely a contributor to grassland conversion in the U.S. Great Plains.[53]

Failing to implement measures to boost yields in developing countries would be both morally unacceptable and foolish. It would be morally unacceptable because it would leave too many people dependent on farming at a disadvantage, and because relying on food imports is a risky strategy for poor countries.[54] It would also be foolish, in part, because not all drivers of yield gains will reduce costs of production and encourage local expansion. For example, protecting forests will force farmers to focus more on boosting yields through greater use of labor or technical inputs and will increase rather than decrease costs. More fundamentally, without yield gains poor countries with growing food demand are all but certain to expand their agricultural lands. Unless they increase yields, as African experience has shown, they will expand agricultural land area.[55] In addition, if no countries increase their yields, massive expansion of agricultural land is inevitable. Despite the risks of locational shifts of some agricultural land, failing to boost yields is a sure-lose strategy.

The only solution is both to boost yields and to use government policies where necessary to protect forests (and other natural ecosystems) and avoid shifting of locations of agricultural land. Private sector approaches that try to eliminate deforestation from their supply chains can also contribute. Although yield gains can pose risks, the challenge is to minimize the risks and harness yield gains for their positive outcomes.



CHAPTER 18

MENU ITEM: LINK PRODUCTIVITY GAINS WITH PROTECTION OF NATURAL ECOSYSTEMS

How can the world and farmers achieve the benefits of yield gains while also protecting natural landscapes? The heart of our answer is that efforts to achieve both need to be linked. The two goals of pursuing higher yields and protecting natural landscapes need to be linked by national and local governments, international funders, and private companies.

As part of this linkage, governments also need to develop integrated, spatially explicit, and evolving analytical systems to target roadbuilding and agricultural assistance where it can do the most good and avoid the most harm. This chapter starts by assessing whether governments can protect natural resources and how, then discusses the various methods for linking efforts to improve agricultural productivity with protection of natural landscapes.

How Governments Can Protect Natural Landscapes

Can governments protect natural landscapes? An extensive literature discusses the various available measures. The core lesson is that landscape protection presents great political and governance challenges but that governments have effective measures available to them to protect natural lands if they can mobilize the political will and master the governance.

Stop giving away public land for conversion

The most direct measure governments can use to protect natural landscapes from conversion is to stop giving this land away or selling it. The effects can be significant because, in much of the world, governments own the majority of natural land, and conversion occurs only when they grant the right to convert. In Indonesia, for example, the national government claims ownership of nearly all forest (subject to possible claims by Indigenous Peoples as a result of a Constitutional Court ruling).[56] This land can become available for agricultural development through reclassifications granted by the national forest agency on application by private companies.[57] By refusing to reclassify these lands, the national government can protect forest from agricultural conversion if it so chooses. However, both the national forestry ministry and regional land use authorities derive substantial revenues from land use concessions and transfers, which poses one of several political challenges faced by the government.[58]

In parts of Latin America, the "acquisitive prescription" doctrine has allowed those who clear public forest for farming to acquire ownership after a few years. Even though this claim to public land may be restricted to farms of a certain size, large landowners can subsequently come in and assemble large estates from the original claimants. In Colombia, for example, the principle of acquisitive prescription dates back to the original civil code. A 2002 law shortened the waiting period to acquire ownership from ten to five years after the forest has been converted to agricultural or similar productive use. One of the purposes of this legal doctrine is to prevent the possible injustice of a person abandoning land then returning to claim it after someone else has taken it over and put it to productive use. In Latin America, the principle was usually established to encourage conversion of natural lands to agricultural use. It allows seizure of government land and therefore allows people to claim ownership by clearing government-owned forest.[59] Changing such laws is fundamental to forest protection.

In Costa Rica and Brazil, changing laws on land titling so that people no longer acquire title to land by clearing it has played an important role in reducing deforestation.[60] Land titling laws can be effective in preventing conversion to cropland because such conversion involves substantial investment. If those who illegally convert fear that their claims to land ownership will not be recognized, and their future farm income jeopardized, experiences show that conversions will be reduced.

Unfortunately, although Brazil no longer promises legal title to those who deforest, it has a history of retroactively granting rights to those who illegally did so.[61] This encourages new cycles of illegal land-clearing. While governments can control how and where private parties may claim ownership or rights to develop public lands, in some cases they must attempt to strike a difficult balance between enforcement of land-use restrictions and the needs of impoverished smallholders.[62] Where farmers have clear title to their land, governments can combine enforcement with support for agricultural improvement on existing farmland to build social support.

Implement land-use restrictions

In the case of private lands or lands on which concessions have already been granted, there is no alternative but to pass laws restricting further conversion. Costa Rica, for example, passed a law in 1996 prohibiting further forest conversion. It has been mostly effective, if not perfectly enforced.[63] A study of productive lands in northern Costa Rica

between 1996 and 2010 showed that the deforestation ban in 1996 cut in half the conversion of mature forest to cropland—in this case mostly pineapple and banana plantations.[64] In 2011, Indonesia imposed a moratorium on granting new agriculture and logging concessions in primary forests and peatlands.[65] Following the 2015 fires, the moratorium on opening peatlands was extended to cover areas already licensed but not yet developed.[66]

Establish protected natural areas

Although the mere designation of protected areas does not guarantee protection from deforestation, studies have generally found that such designations typically result in lower levels of deforestation. One global review found that areas of land designated as a protected area (e.g., national park, wilderness area, national monument) were consistently associated with lower levels of deforestation.[67] The study concluded that the efficacy of protected areas was probably a result of the heightened legal protection, remoteness, and/or poor agricultural potential.[68] The latter two features, however, highlight a requirement of future policy. Natural areas that might be good for agriculture are typically not chosen to become protected areas, but in some parts of the tropics it is these lands that are most at risk of deforestation. Going forward, therefore, an important strategy will be to establish a string of protected areas to block the path of agricultural expansion and thereby further encourage boosting yields on existing agricultural lands.

Establish and respect Indigenous Peoples' territories

Establishing protected lands for Indigenous Peoples, and respecting their integrity, in addition to recognizing the legitimate claims of such people to the land, also often leads to low levels of deforestation.[69] The conservation of forests in Indigenous Territories in the Xingu watershed of Brazil is a well-documented case where tribes guard the forests against illegal loggers, miners, and other intruders while forests continue to be cleared outside the territories. Community titling of indigenous lands appears to have significantly reduced both forest clearing and disturbance in the Peruvian Amazon.[70]

Enforce the law

The above measures work well only if they are combined with consistent enforcement.[71] Law enforcement can take the form of fines for illegal clearing, seizure of illegally converted lands, evictions of illegal squatters, and arrests of illegal ranchers. Three features could help make enforcement credible and politically supported over the long term. First, the "stick" of law enforcement should be complemented with the "carrot" of positive economic incentives for those people who might be most affected. Second, law enforcement needs to avoid being unjust or repressive toward marginal communities, either in reality or in perception. Third, law enforcement needs to be fair; it should not selectively go after the poor while letting the rich and politically powerful go untouched.[72]

Increase transparency of land use and land-cover change

All the approaches to protecting natural ecosystems listed above benefit from adequate spatial monitoring which can detect adherence to and violations of the law and land designations. "Radical transparency" made possible by modern-day monitoring technologies (e.g., satellites, drones, cloud computing, the internet) can be a powerful foundation for accountability and enforceability. Global Forest Watch now has several satellite-based monitoring systems on its platform, capable of detecting the felling of trees at high spatial and temporal resolutions and combining those data with maps of protected areas, indigenous reserves, moratorium boundaries, extractive industry concessions, and more.[73] What is needed next are systems that can detect clearing of any form of natural ecosystem vegetation (beyond forests) since it is not just forests that are being converted to agriculture.

Of course, any one of these measures alone will be insufficient; it is the combination that has impact. Brazil illustrates this potential. The country has long had laws restricting the percentage of land on any farm that may be cleared (the "Forest Code"), yet enforcement lagged. Beginning around 2005, however, Brazil moved to enforce these laws, particularly in the Amazon, resulting in large reductions in deforestation rates, all while agricultural production continued to increase. Brazil reorganized its police enforcement and took actions against corrup-

tion. The country started using satellite monitoring (e.g., DETER and PRODES systems) to identify illegal deforestation in the Brazilian Amazon.[74] The country established new protected areas in the "arc of deforestation." Perhaps most creatively, Brazil identified municipalities where deforestation was most acute and put them on a "black list" for receiving public finance and rural agricultural credit (more on this form of "linking" protection and production below).

Linking Productivity Gains and Natural Landscape Protection

Although governments have mechanisms they can use effectively to protect natural landscapes, there are several reasons why explicitly linking such mechanisms with efforts to boost production on existing agricultural land is probably necessary both practically and politically to achieve this protection:

- **Linkage can help ensure that land protection does not undercut food production.** It will be nearly impossible to protect natural areas if yields do not grow on existing agricultural land because the unsatisfied demand for food will push up prices and increase food insecurity.[75] Not only is such a result unacceptable in and of itself, but it also would likely undermine political support for land conservation and increase the incentive for some agricultural interests to circumvent legal protections.

- **Linkage can help equitably share the burden of climate reductions.** Many relatively poor countries are currently significant sources of land-use change emissions but have small overall per capita GHG emissions. At the same time, the economies of many poor countries are heavily dependent on agriculture, and these countries face rising food needs. For them, global equity considerations require the international community to support their agricultural development on existing land in return for protecting their remaining natural landscapes.

- **Linkage can help sustain domestic political support for both goals.** Agricultural sectors that drive deforestation and other land-use change often have substantial political influence. Linking preservation of natural landscapes with strategies to increase agricultural productivity may be politically necessary at the national level to assure both national governments and agricultural sectors that agriculture can continue to prosper.

We propose three approaches to achieving such linkages:

- **Finance:** Structure domestic and international financing to simultaneously support yield gains and natural ecosystem protection and/or restoration.

- **Land-use planning:** Develop and use "living" analytical tools in the form of detailed land-use plans that prioritize areas for agricultural yield enhancement (including "climate-smart" road networks and other public infrastructure) and protect natural ecosystems.

- **Conversion-free supply chains:** Mobilize buyers, traders, and financiers of agricultural commodities to purchase or finance only commodities not linked to deforestation or other ecosystem conversions.

Finance

Domestic and international sources of finance offer avenues for linking yield enhancements with natural ecosystem conservation.

Domestic finance

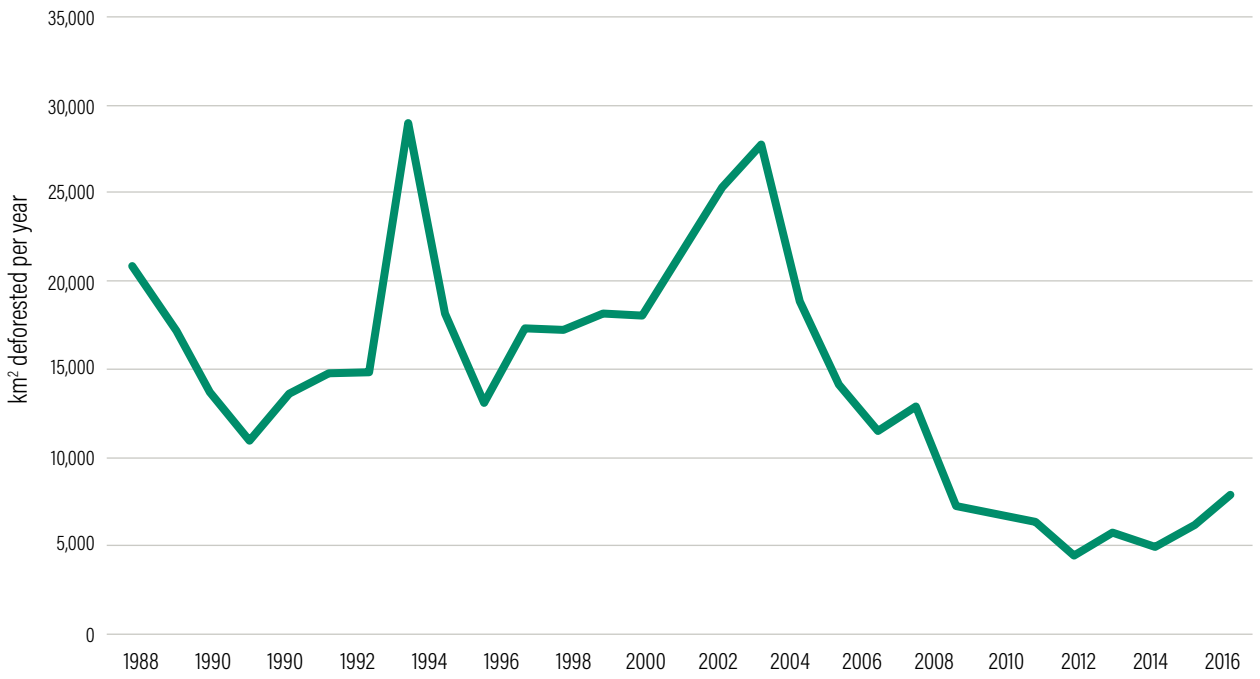
Domestic sources of agricultural finance (e.g., national development banks, private banks) often help farmers and ranchers by providing low interest loans. To make the linkage, these loans could set eligibility conditions that preclude farmers and ranchers from converting forests or other natural ecosystems. Such lending conditions could be retrospective, wherein the bank assesses natural ecosystem clearing on the farmer's or rancher's

land in the past. If there has been clearing after a certain year, the landholder is not eligible for a loan. Alternatively, the conditions could be prospective, wherein the farmer or rancher incurs a penalty (e.g., higher interest rate, hefty fine, loan call back) if he or she clears a natural ecosystem after receipt of the loan. Such conditioned loans would incentivize the landholder to invest in improving yields on his or her existing agricultural fields instead of clearing more land.

The Brazilian Amazon provides a successful illustration.[76] Rural credit supplies about 30 percent of the annual financing of farmers and ranchers in Brazil, and thus can be a powerful lever for behavior change. In 2008, the Brazilian National Monetary Council introduced Resolution 3,545, which conditioned rural credit in the Amazon biome on proof of a farmer's or rancher's compliance with legal and environmental regulations. One of these regulations was a limit on the amount of forest that a landholder could legally clear (20 percent of one's land). As a result, the amount of deforestation declined. According to one estimate, in the absence of the conditioned credit, deforestation rates in the Brazilian Amazon would have been 18 percent higher than actually observed in the 2009 through 2011 period.[77]

This linkage has also been important to maintaining political support for Brazil's forest protection, which has played a key role in reducing deforestation rates from their peak in 2004 (though rates have recently risen again) (Figure 18-1).[78] Work by EMBRAPA, Brazil's national agricultural research institution, helped demonstrate the capacity of Brazilian agriculture to continue to grow by boosting yields without clearing more land.[79] Brazil then explicitly linked its proposals to strengthen forest protection with additional incentives for agricultural intensification, both in its 2004 action plan for forest protection and its follow-up "ABC" climate plan in 2009.[80]

Figure 18-1 | Deforestation in the Brazilian Amazon has receded from historical highs



Source: Brazilian National Space Research Institute (INPE).

International finance

Developed countries have committed to providing billions of dollars to developing countries to help them mitigate and adapt to climate change—although only some of these funds have started to flow. But the funding for forest protection and for agricultural improvement tend to come through different channels. The World Bank, for instance, develops climate or environmental projects to protect forests and separately develops projects to boost agriculture productivity. Some countries provide funds for forest protection under the banner of REDD+ (Reduced Emissions from Deforestation and Forest Degradation in Developing Countries). At the same time, some countries provide funds for agricultural development. The link between agricultural improvement and natural ecosystem protection is rarely drawn.

This should, and can, be rectified. The main reason is to increase the likelihood of meeting both food production and forest protection needs, and preventing the needs of one from undermining the other. Linkages also would offer benefits to the key players. For example, international funders, mainly richer countries, would see their funds advancing two goals—poverty alleviation and climate protection. National governments would be able to make a more powerful case for financial support by achieving multiple objectives at once. And agricultural interests, whether big or small farmers, would improve production on their existing land while avoiding the risks of forest conversion.

Overall, there is a strong global, shared public interest in improving agricultural productivity in developing countries so long as that productivity helps protect forests. If funds are effectively linked, they can make the case for more funding, and they can provide benefits for agricultural interests that might otherwise resist forest protection.

Land-use planning

Land-use planning is a policy tool that governments can use to concentrate agricultural production in certain, high-yielding areas while designating natural areas as protected from conversion. To achieve this goal, land-use plans will need to be specific (geospatially and more), "living," and cover development of road and related infrastructure.

Plans need to be specific

We believe effective land-use planning tools need to have multiple features, including the ability to achieve the following objectives:

- Characterize the location of existing production systems in as much detail as practicable to support technical and economic assessments of their potential for boosting yields.
- Apply at the local level, but aggregate production, emissions and land-use data to the regional and national level to allow assessments of national achievement.
- Identify the technical opportunities for sustainable agriculture intensification on existing agricultural lands.
- Provide analyses of the economic feasibility of improvement options for different types of farms.
- Identify the location of priority areas for sustainable intensification, and areas that must be preserved or restored.
- Identify the location of lower opportunity-cost lands when there is an unavoidable need for agricultural expansion (as discussed in Chapter 19).

Plans at this level of detail could serve many purposes:

- Guide public policies as well as public and private funders on where to invest.
- Reassure agricultural producers of their potential to increase production without clearing new lands.
- Quantify impacts on GHG emissions, including from land-use change, and how they would change with various improvements to agricultural development.
- Provide a technical basis for specific international agreements as well as domestic and international funding.
- Inform private sector and civil society priorities.

Plans need to be "living"

Such comprehensive planning tools will require detailed but evolving technical tools—not merely one-time maps and plans. Any immediate effort to develop these kinds of systems will meet resource constraints and data limitations and rely on models, such as crop models, that are imperfect. If people are to have faith in such efforts, the systems employed must be able to easily incorporate new, improved, and more detailed information as it becomes available. For such planning systems to work, they must therefore be reflected in computer-based programs that are continually updated and modified.

Supporting development of such plans should be a major concern of international institutions focused on either agriculture or climate, such as the World Bank. They should be a particular priority, as we describe in the next chapter, where agricultural expansion is inevitable, and we offer more detailed recommendations for funding such plans in that chapter.

Plans need to address roads and other infrastructure

A key use of such plans should be to identify where to build, rehabilitate, or improve roads and where to place other agriculture-related infrastructure. The only hope for reconciling the need for new roads for agricultural development in developing countries with protection of natural areas is to plan and build "climate-smart" road systems—systems that avoid incursion into remaining natural ecosystems while enhancing the ability of the agricultural sector to access markets.

Climate-smart road systems primarily involve focusing road improvements in existing agricultural areas, particularly where there is high potential for agricultural improvement. A recent study identified some priority areas at the global level for both road-building and avoiding road construction based primarily on climate-smart principles.[81] It and other studies have found, for example, areas of Africa with very poor roads that could reap great benefits from merely improving existing roads (e.g., paving dirt roads), not necessarily adding major new ones.



Such an approach would support high agricultural yields, keep transportation costs low, and contribute greatly to preservation of both carbon stocks and biodiversity.[82]

In general, this planning approach should be undertaken at high resolution at national and subnational levels and then incorporated into government land-use and infrastructure plans. It should be a prerequisite for international funding of road improvements.

Conversion-free supply chains

Buyers, traders, and financiers of agricultural commodities can choose to purchase or finance only commodities not linked to deforestation or conversion of other natural ecosystems. Conversion-free purchasing policies have the potential to persuade farmers, agricultural companies, and even political jurisdictions (e.g., districts, states) to meet growing demand by boosting yields instead of by expanding agricultural area. Otherwise, these farmers, agricultural suppliers, and jurisdictions would risk losing business customers, market access, and finance.

The most notable deforestation-free supply chain commitment is that of the Consumer Goods Forum (CGF). The CGF now comprises 400 of the world's leading consumer goods manufacturers and retailers from 70 countries, with combined annual sales of €2.5 trillion (about $2.8 trillion). In 2010, the board of the CGF committed to achieving zero net deforestation in supply chains for four commodities by 2020 and to curtail procurement from suppliers who do not comply. These commitments cover the agricultural commodities of palm oil, beef, soy, and pulp and paper. The impact of these pledges is trickling upstream. For example, major traders of palm oil have made similar pledges to buy and sell only deforestation-free palm oil. Getting major traders involved could help ensure that the supply chain pressure reaches markets where the CGF may not have as much influence, such as palm oil for home cooking in some Asian countries. As of late 2016, more than half the companies that source palm oil and wood products had made "zero deforestation" commitments, as well as 21 percent of companies that source soy and 12 percent that source beef.[83] The CGF could also reach small to medium-sized farmers or grower companies—which are not publicly visible and do not have robust sustainability commitments—if companies applied their commitment not only to their direct suppliers but also to their suppliers' suppliers.[84]

Financiers of agricultural commodities are taking steps, too. A number of banks have agreed to a Soft Commodities Compact designed to support business customers in their efforts to reduce commodity-driven forest conversion.[85] The compact commits banks to work with consumer goods companies and their supply chains to develop appropriate financing solutions that support the growth of markets producing palm oil, soy, and beef without contributing to deforestation. Twelve banks had adopted the compact as of January 2019.[86]

Voluntary actions by private corporations, in part motivated by civil society campaigns, will have their greatest effect when they reach a scale sufficient to influence an entire industry and motivate national legislators. In the mid-2000s, Greenpeace launched an effort to pressure European companies not to purchase soybeans from Brazil because of deforestation. These pressures helped lead to a commitment by the Brazilian Vegetable Oils Industry Association and the National Grain Exporters Association to establish a moratorium on the production and trade of soybeans grown on lands in the Brazilian Amazon that are deforested after July 24, 2006.[87] International agricultural traders such as Cargill and Bunge played an important role. The moratorium has been quite effective in the Brazilian Amazon. In the two years before the moratorium, 30 percent of soy expansion in the Brazilian Amazon occurred on newly deforested land. Since the moratorium, the share dropped to about 1 percent; almost all of the 1.3 Mha of new soy plantings from 2006 to 2013 in the region were on previously cleared lands.[88] One study showed that the moratorium is protecting lands that could otherwise be legally converted.[89]

At the same time, the moratorium did not undermine Brazil's soybean industry. Since implementation, soy production has continued to grow, mostly through intensification.[90] Nonetheless, some expansion of soybean area has occurred in the Brazilian Cerrado and the Bolivian Amazon. This leakage indicates that private efforts will be most useful only when they reach a scale large enough to motivate government policies as well.

To realize its potential, the conversion-free supply chain model needs more companies and financial institutions to make conversion-free supply chain commitments so that together they account for a significant share of market demand (or financing) of each agricultural commodity. Otherwise there is a risk of sizeable market "leakage," whereby suppliers merely divert deforestation-linked agricultural commodities to a large market of buyers that have not made commitments. Companies and banks also need to follow through on their commitments. And follow-through requires monitoring and accountability mechanisms.[91] Given that commitments for 2020 will likely not be met, how the CGF and other industry players respond and adjust their strategies will be critical to the future success of this approach.

"Jurisdictional" approaches

A potentially potent way of implementing these three approaches is to operate at the jurisdictional scale. The "jurisdictional approach" refers to a comprehensive approach to land-use governance, decision-making, and zoning across a legally defined jurisdiction (e.g., state, district) or territory.[92] Part of the theory of change is that those jurisdictions that succeed in implementing these approaches—and thus succeed in decoupling agriculture from ecosystem conversion—would start to receive preferential investment by companies and financial institutions. For example, they could be considered "low-risk" sources of supply or safe places for investment for companies making forest protection commitments. Other jurisdictions might observe these benefits and start to shift themselves. Examples are beginning to emerge. Launched at the Conference of the Parties (COP) 21 climate conference in Paris in 2015, the Brazilian state of Mato Grosso's "Produce, Conserve, and Include" strategy and plan aims to promote sustainable agriculture, eliminate illegal deforestation, and reduce GHG emissions—all at the same time. Responding to concerns about losing access to international soybean markets, it has 21 performance targets and involves 40 partner organizations. Currently, deforestation remains relatively low while the agriculture sector in Mato Grosso, led by soybeans, thrives.[93]

Produce, protect, and prosper

The underlying strategy of this chapter can be summarized as one of "produce, protect, and prosper." To achieve a sustainable food future, protection of forests and other ecosystems must occur at the same time as enhancements in crop and livestock yields. In addition to linking production and protection, people will need to "prosper" through the growth of their local economies; increased security of food, feed, and fiber; and reductions in poverty through job and income growth. Without such benefits, political support for sustainable intensification and for conserving natural areas might be lost over time.



CHAPTER 19

MENU ITEM: LIMIT INEVITABLE CROPLAND EXPANSION TO LANDS WITH LOW ENVIRONMENTAL OPPORTUNITY COSTS

Although the goal should be to avoid all agricultural expansion, in some locations agricultural expansion is inevitable. As discussed in Chapter 17, agricultural land will expand for local food production in much of Africa, for example, and oil palm plantations will expand in Southeast Asia. In these situations, the land-use plans we described in Chapter 18 need to guide where this expansion should go. How should they do so?

The Challenge

How should we define low opportunity-cost lands?

We begin by focusing on our disagreements with some previous analyses which claim that many broad categories of land should be viewed as either "free" to use or involve little carbon cost, typically because they are not existing cropland or dense forest, or because they are forests that have recently been cut. The errors generally track those discussed in Chapter 7 regarding bioenergy, which similarly assume that these categories of land are available to grow biomass crops at no or little cost in carbon storage or food production and with low or no social opportunity costs. Examples include *abandoned agricultural land*, which is not free because it would typically regenerate to forest or other natural vegetation; *pasture land*, which both stores carbon and produces food; *woody savannas*, which store abundant carbon and tend to have high biodiversity; and *cut-over forests*, which also regenerate if left alone or replanted.

A surprising number of studies refer to the potential to expand bioenergy or crop production onto lands they term "marginal" or "degraded."[94] Unfortunately, as well summarized by Gibbs and Salmon (2015), these terms have no precise meaning. Studies that use them offer multiple definitions but none that identify unused categories of land. These terms are frequently applied to lands that are considered marginal for cropping—but this quality does not make them marginal for purposes such as carbon storage or pasture.[95] Quite often, the terms are applied to lands already in agricultural use but typically experiencing some form of soil degradation. Their reclamation can and should be part of the effort to increase crop and pasture yields. They cannot provide lower opportunity-cost lands for agricultural expansion for the obvious reason that they are already in agricultural production. Even lands that are so unproductive that they store little carbon and produce low yields—and therefore are not good candidates for expanding agriculture anyway—are often extensively used by the poor.[96] The problem in each case is failing to recognize that virtually all land has some kind of opportunity cost.

The opportunity

The goal is to find lands with relatively low environmental and other opportunity costs but with good productive potential on which to expand agriculture. Several principles guide the search:

- Because these opportunities are a matter of degree, a proper analysis requires far more subtle evaluation than simply assessing broadly defined land-use categories and incorporating potential food yields.

- To reflect carbon effects, the analysis must account not just for existing carbon but also for likely future carbon sequestration (e.g., from regrowing forests on abandoned agricultural land or in forest areas that have been recently harvested for wood). Each year globally, regeneration replenishes most of all annual carbon losses from forest clearing and therefore plays a fundamental role in slowing climate change.[97]

- The analysis must focus not just on the loss of carbon per hectare but also on the loss of carbon per ton of crop that would likely be produced, which in turn depends on the likely yields.[98] Land may store little carbon, but if it will also produce few crops, farmers will need to clear more land and release more total carbon to produce the same amount of food.

Several studies support the hypothesis that targeting specific lands can meet food needs with lower environmental costs than using other lands. In Tanzania, one study looked at multiple criteria in addition to potential yield when considering areas for agricultural investment. Ideal areas for agricultural expansion varied depending upon whether the criteria included social capital, forest conservation, and farm management. Sometimes the use of different criteria led to conflicting answers.[99]

A second study focusing on Zambia found good results from a "compromise" approach giving equal weight to maximizing potential yield, minimizing transportation costs, minimizing carbon releases, and minimizing impacts on biodiversity. Such an approach reduced the potential transportation,

carbon, and biodiversity costs by 80 percent while reducing the average potential yield of each new hectare by only 6 percent, compared to a strategy that focused on yield-enhancement alone.[100] This same paper showed that the "farm blocks" of land formally designated for agricultural expansion by the government were poor choices to achieve any of these four objectives.

Studies of this type recognize that land has different potentials. In general, wetter lands are more productive and better at producing crops, but they also store more carbon and support more biodiversity. Yet the relationship is not perfect. Rainfall patterns and soil types may reduce the productivity of crops more than of trees and therefore forests. Access to transportation and other infrastructure may make it more profitable to farm in one location than in another with higher, raw crop potential. Both carbon storage and biodiversity are undermined on lands with a history of human alteration. The biodiversity of any one hectare of land also depends heavily on the lands around it. If the only goal were agricultural profitability or productivity, these environmental considerations would be irrelevant. But if the goal is to achieve a sustainable food future, considering the wider advantages and disadvantages of farming different hectares of land opens up the potential to find options that are still beneficial to agricultural productivity and profitability while reducing environmental effects.

Indonesia has been a major focus of study because expansion of oil palm plantations into forests and peatlands has been occuring rapidly and because growth in global demand for vegetable oil makes some continued expansion of oil palm inevitable. One study estimated that optimal location of new oil palm plantations to double Indonesia palm oil production between 2010 and 2020 could avoid all primary and secondary forest loss. This outcome could avoid all biodiversity effects analyzed in the study, cut land-use change emissions by 30 percent, and reduce loss of other food production by two-thirds compared to the most likely "business-as-usual" scenario.[101] Ideally, farming would expand only into areas that have truly low environmental and social opportunity costs yet could still be productive croplands. To the extent that such lands exist, they will generally be lands that receive enough rainfall to be productive but face some kind of biological and physical barrier to significant natural regeneration.

One category of such low opportunity-cost, potentially productive land includes areas in Southeast Asia that were once logged or farmed then abandoned, and overrun by *Imperata* grasses. *Imperata* grasses store only modest quantities of carbon and will sequester little future carbon so long as they remain subject to frequent fire.[102] They also support far less biodiversity than forests[103] and are of poor quality for livestock, which leaves them with limited economic benefits. And the return on investment from establishing oil palm on converted *Imperata* grasslands can be favorable even when compared with the return on investment of establishing oil palm on recently cleared forests.[104] These lands are not truly free of opportunity costs: many occur in mosaics with some tree cover and some agriculture by smallholders. This is probably why they are burned. Even the densest *Imperata* stands could be replanted as forests but their use for oil palm would be appropriate because the alternative would likely be clearing of valuable primary or secondary forests. Although no one really knows how much *Imperata* grassland there is, estimates include 3.5 Mha[105] in Kalimantan and 8 Mha in all of Indonesia.[106] In theory, this area could provide most if not all of the additional expansion needed in Indonesia for another decade.[107]

In the real world, other factors also play an important role, including transportation access and social and legal acceptance (Box 19-1). These barriers are at least potentially subject to change with appropriate investments, zoning changes, incentives, and community outreach.

BOX 19-1 | Mapping lands suitable for sustainable oil palm expansion in Indonesia

Over the past several years, WRI has been working with Indonesian partners from government, industry, nongovernmental organizations, and research organizations to identify lands with lower environmental opportunity costs that have the potential to support sustainable oil palm plantation expansion in Indonesia.

In this mapping effort, we use an environmental suitability screen to filter out lands that, if converted to crops, would have large environmental costs in terms of carbon and/or biodiversity. In particular, it screens out all primary and secondary forests, swamps, peat soils of any depth, conservation lands and bodies of water, and their buffer zones. It also screens out human settlements, some agricultural lands,[a] aquaculture ponds, airports, and other large infrastructure. Figure 19-1 (left) shows the results of applying this screen to Kalimantan, Indonesia (on the island of Borneo).

Because not all the lands that pass the initial screening will be suitable for oil palm, the method layers on additional screens. The economic viability screen identifies those areas with appropriate elevation, slope, rainfall, soil depth, soil type, soil drainage, and soil acidity for an oil palm plantation to be profitable. Areas not meeting these criteria are eliminated from the map. Figure 19-1 (center) shows the results of layering in the economic screen.

The method then layers on a legal availability screen that factors in land-use zoning and community rights. Lands located in areas not zoned for agriculture can be difficult, but not impossible,[b] to convert into oil palm or other crops. Figure 19-1 (right) shows the results of layering on the legal availability screen for Indonesia.

Finally, for the areas that remain, a social acceptability screen discerns—via field-based stakeholder engagement and workshops—the interest and willingness of communities that live in and around a candidate site to have oil palm developed there. WRI's experience is that some communities support oil palm development while others do not.

As is evident from these figures, although the area of opportunity may seem large at first; the amount of land that remains practically possible for conversion to crops (in this case oil palm) is smaller after incorporating important parameters such as economic, legal, and social factors.

The lands that meet environmental criteria are not necessarily low-cost: most of these lands would reforest if not used by people, and human uses may produce a range of small-scale agricultural products. In the face of the world's fast-growing demand for vegetable oil, however, focusing oil palm expansion on these lands constitutes a vast improvement over alternatives that directly convert valuable natural forests.

For more details about this method, see Gingold et al. (2012).

Notes:

a. The method screens out existing plantations and intensively used agricultural areas according to Ministry of Forestry land cover data. To more precisely fit the definition of lands with low environmental opportunity costs suitable for cropland ***expansion***, the method should screen out ***all*** active cropping areas, which must be determined via field surveys.

b. It would require having the relevant zoning agency (or agencies) rezone the tract of land into a class that allows for agriculture.

Figure 19-1 | Screening out lands that do not meet environmental, economic, and legal criteria reduces the area of land suitable for oil palm expansion in Kalimantan, Indonesia



Source: Gingold et al. (2012).

Recommended Strategies

Where agricultural land expansion is inevitable, selecting areas for expansion that have relatively low environmental opportunity costs is one part of the effort we describe in this course to link yield improvements and protection of natural areas. But how can governments best identify such expansion areas?

Our main additional recommendation in this menu item is for governments to develop the kinds of land-use modeling tools we describe in studies for Indonesia, Tanzania, and Zambia to identify where inevitable land expansion should take place. Such tools will have to assess yield potential, likely costs of production, and carbon and biodiversity effects. International institutions such as the World Bank should help fund them. Several aspects of this challenge merit emphasis.

Quick results. Because different stakeholders have different interests, a tool must quickly show the results of different compromises. Individuals and groups are more likely to find common ground if they can see outcomes and decide whether they are acceptable. The Zambia model discussed above has this kind of feature to allow stakeholders to see easily the consequences of assigning different levels of importance to different goals.

Intuitive presentation of outcomes. Planning tools must overcome many technical challenges. There are many data limitations, and some goals are difficult to measure because they are so complex. Biodiversity will always remain a challenge to express in one simple unit because it may be valued in many different ways. For example, analyses may focus on the total number of species using an area of land, or they may focus only on threatened species, or on different taxa (such as vertebrates or categories of vertebrates), or they may identify areas based on loss of similar habitat types. Quantitatively, each objective can be measured using different units (e.g., units of carbon, biodiversity, and profitability), which are not directly comparable. Different methods of quantification will have different results, such as ranking areas by percentile or by absolute quantities. A useful planning tool needs to present outcomes for each scenario in units that make intuitive sense to people as far as is practicable, for example, in tons of crops per hectare, dollars of profit (if economic analysis is included in the model), and tons of carbon released. Not all modeling approaches are equally good.

Adequate funding. To develop and maintain a proper land-planning tool, dedicated resources are required. To focus on just one important input, estimating potential crop yield requires use of some kind of crop model. Good crop modeling requires a great deal of data, such as detailed soil data, which is typically not available broadly for all locations, and some of which may not be completely available in any location. Funds needed to be spent to make the data as accurate as possible.

Monitoring and updating. Resources must also be dedicated to determine whether predictions prove accurate, to reprogram the tools as necessary, and to update results as the world changes. Monitoring, recalibrating, and updating are not a one-time exercise but must be continued over time to ensure that predictions remain accurate.

Policymakers tend to be in a rush and often want results with limited resources. Because modelers can always make broad assumptions if necessary, they can generate models that look misleadingly convincing but that lack the rigor necessary to justify their use for important decisions. These kinds of mapping enterprises at the national level will require ongoing budgets in the low millions, not hundreds of thousands, of dollars. These efforts are not easy, but there is also no alternative if the goal is to achieve reasonable outcomes. International institutions that focus on climate or development need to support these efforts and use them before funding major new roads or other infrastructure investments.

For more detail, see "Limiting Cropland Expansion to Lands with Low Environmental Opportunity Costs," a working paper supporting this World Resources Report available at www.SustainableFoodFuture.org.



CHAPTER 20

MENU ITEM: REFOREST ABANDONED, UNPRODUCTIVE, AND LIBERATED AGRICULTURAL LANDS

Some agriculture will inevitably shift from one location to another. Reforestation of abandoned agricultural land or restoration to some other natural vegetation will be required just to maintain net forest and savanna area. However, the potential for global reforestation is sometimes overestimated. Large-scale reforestation to mitigate climate change will be possible only if enough agricultural land is "liberated" through highly successful efforts to slow growth in food demand and boost agricultural productivity.

The Challenge

Many climate mitigation strategies involve sequestering carbon by restoring land now in agricultural use to forest or other natural vegetation. "Forest landscape restoration" typically means the process of restoring ecological functionality by enhancing the number and diversity of trees on the landscape.[108] Restoration can start from completely deforested areas, from degraded forests, or from fragmented forests. It can end up in a variety of land covers and uses, ranging from vast tracts of dense natural forests (which would have the highest standing carbon stocks and biodiversity benefits), to mosaics of wooded areas of land adjacent to agricultural areas, to integrated agroforestry and silvopastoral systems, all the way to mosaics of commercial tree farms and natural forests.

In this chapter, we examine the subset of forest landscape restoration that returns areas of land to dense natural forests, woodlands, and/or woods adjacent to agricultural areas (i.e., reforestation). (Restoration to agroforestry or silvopastoral systems is covered in Chapters 11 and 13.) We focus this chapter still more narrowly on reforestation because forests store more carbon than any other form of terrestrial ecosystem.

Reforestation can occur in one of three ways: spontaneous natural regeneration, in which vegetation regrows without human assistance; assisted natural regeneration, in which land managers reduce obstacles to natural regeneration (e.g., remove fire or grazing animals) and then "let nature take its course"; and active reforestation, in which land managers make significant interventions to reestablish vegetation, such as growing young trees in nurseries and then planting them. Replanting can involve the use of varying mixes of natural species or only one or a few species designed to maximize wood output. But what is the real reforestation opportunity, how should land-planning efforts decide where to reforest, and how can reforestation be advanced?

Many climate studies have found a large potential for reforestation, often in the hundreds of millions of hectares. Examples include broader assessments by the Intergovernmental Panel on Climate Change (IPCC), the "Stern Report" on the costs of climate mitigation, and many original underlying studies.[109] One study even developed a scenario that includes the reforestation of all grazing land that was originally forested before being converted by humans, and would therefore cover large tracts of Europe.[110]

Our analysis is less optimistic, and we explain why we disagree with these high estimates at the end of this chapter (Box 20-1). Ultimately, our analysis is not necessarily at odds with some of the more modest estimates of reforestation potential, but we believe the core condition is that "potentially reforestable" land must not also be needed for ongoing food production. Unless this condition is appreciated and taken into account, reforestation of land in one location will likely lead to more land-clearing in other locations, which undermines its environmental benefit. An alternative poor outcome is that reforestation could lead to reduced food consumption, which undermines its public benefits as well as its long-term political support.

The Opportunity

Using this core criterion, we identify three categories of land that offer real potential for reforestation:

- **Abandoned lands.** Although abandoned agricultural lands will tend to regenerate on their own, there is potential to more actively reforest land that is abandoned as a result of agriculture shifting locations.
- **Agriculturally marginal and unimprovable lands.** These lands generate marginal agricultural output today and have little practical potential for intensification in the future.
- **"Liberated" lands.** These lands occur if demand reduction (Course 1) and productivity improvements (Course 2) result in net reductions in the area of agricultural land.

Improved reforestation of abandoned land

Opportunities exist to enhance the reforestation of agricultural land abandoned as a result of shifting locations of agriculture, even while net deforestation occurs globally. As the satellite image studies discussed in Chapter 17 reveal, abandoned agricultural lands usually regenerate to forest anyway—sometimes naturally and sometimes with the active support of land managers and government. By around 1900, the East Coast of the United

States was largely deforested, but it now is home to extensive areas of forest; the same is true for large parts of western Europe. Although most of this land reforested naturally, the United States actively supported reforestation through the Civilian Conservation Corps during the Great Depression of the 1930s. Between the mid-1950s and 1970, South Korea invested massively in reforestation, raising the country's forest cover levels from 35 percent to 64 percent.[111] The Chinese government reports that since 1991 it has spent $47 billion to plant trees on 28 Mha of formerly marginal agricultural land.[112] Notwithstanding these efforts, opportunities exist to improve the quality of this reforestation both to store more carbon and to support more biodiversity and ecosystem services—in line with the goals of the broad field of restoration ecology.

As just a single illustration, researchers have shown that planting leguminous trees in abandoned fields of Brazil's Atlantic Forest region dramatically increases the rates of biomass growth and enables other, more varied trees to grow as well.[113] Governments now often support reforestation of abandoned agricultural land, but they typically focus on plantation forests, often using a single fast-growing commercial tree species. These kinds of trees are better suited to meet demands for timber products and therefore also earn a more rapid economic return. However, they are less capable of storing carbon, have limited biodiversity when compared to natural ecosystems, and are more prone to risks of fire, storm damage, and pest damage.[114] For example, a study of China's reforestation program in Sichuan province estimated that the planted forests, typically monocultures, had a dramatically lower bird and bee diversity than even the croplands they replaced.[115]

In at least some situations, planting more diverse, native, and relatively slow-growing species provides a realistic economic option, potentially producing comparable or only slightly lower economic returns. In these cases, even modest government interest in biodiversity would warrant reforestation of higher quality. Even for plantations, one study in China has shown that just mixing blocks of two to five different plantation forest types results in substantially more diverse bird populations, with no reduction in economic returns.[116]

Because agriculture is likely to continue to shift locations both within countries and around the globe—at least to some extent—the shifting will likely continue to lead to carbon and biodiversity losses unless governments adopt more policies to establish more natural forests on abandoned agricultural lands.

Marginal lands with little intensification potential

Reforestation opportunities exist on agricultural lands that are producing only limited quantities of food today and whose potential for improved food production in future is low. Steeply sloped grazing land often falls into this category; examples include some of the pasturelands in Brazil's Atlantic Forest region. These hilly lands produce only around 30 kg of beef per hectare per year, which contrasts with the potential to produce around 150–200 kg/ha of beef on well-managed grazing land.[117] Yet the steep slopes make impractical the critical pasture intensification options, which rely on mechanized plantings. In contexts like this, an analysis of the trade-offs between cattle intensification and reforestation would support reforestation. Little-used, drained peatlands represent another prominent example of lands with good restoration potential. Peatlands are so significant globally that we address them separately in the next chapter. We do not know how many hectares of agricultural land truly qualify as "marginal lands with little intensification potential" because no one has yet done the right kind of analysis at this scale.

Reforesting even low-yield agricultural land has some potential to lead to land-clearing elsewhere, although it is less risky than taking high-yielding lands out of production. Taking full advantage of this opportunity therefore requires some additional yield gains on existing agricultural lands or equitable demand reductions.

Reforesting lands "liberated" by yield gains and sustainable demand strategies

Land might be liberated for potential reforestation if the strategies to moderate growth in food demand and/or increase crop and livestock yields achieve sufficient success to result in net global reductions in agricultural land area. Although we have described how challenging such goals are, some of our combined scenarios of multiple menu items

would in effect achieve net agricultural land reductions. We provide quantitative estimates of their potential in hectares and associated reductions in GHG emissions in the penultimate section of this report "The Complete Menu: Creating a Sustainable Food Future."

Overall, properly recognizing the limitations that food production imposes on reforestation highlights some important lessons. One is that reforestation at scale requires reducing the need for agricultural land first while protecting other natural areas from conversion. Another is that, precisely because there will probably be only limited areas where reforestation is the best use of agricultural land, those opportunities need to be exploited.

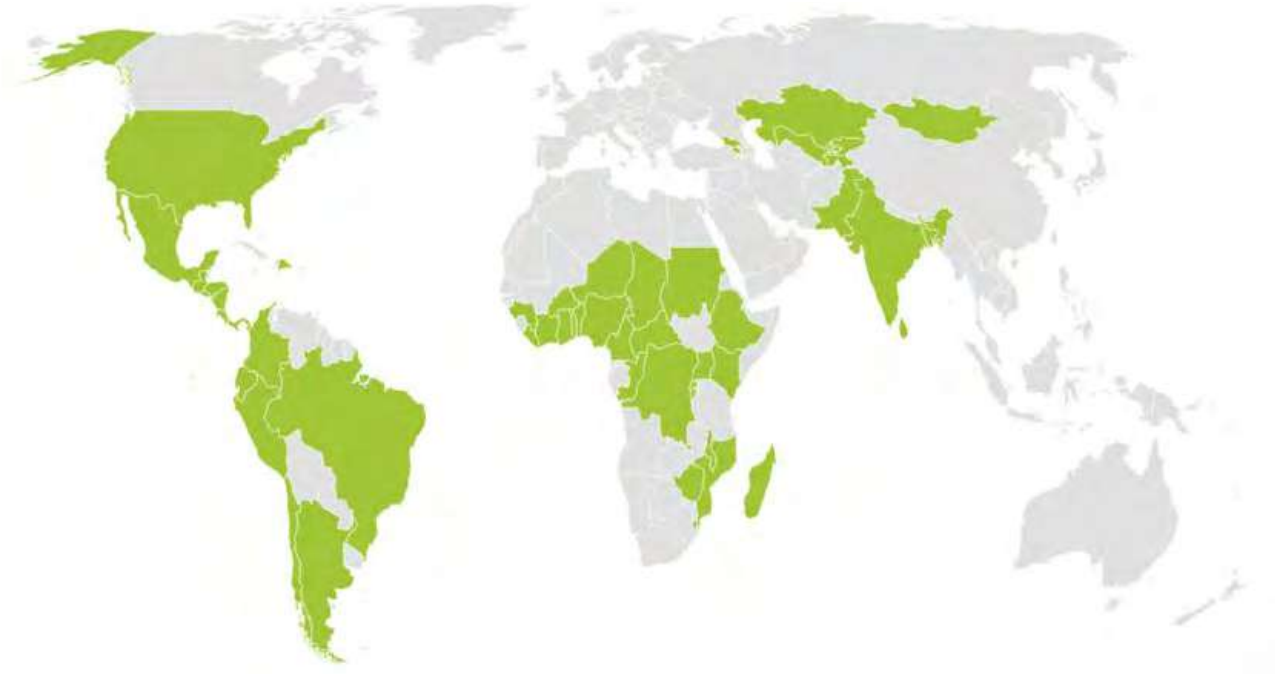
Recommended Strategies

Forest landscape restoration is increasingly prominent on the global agenda. Under the Bonn Challenge—a global effort to bring 350 Mha into restoration by 2030—57 national and subnational actors have thus far committed to restore 170 Mha (Figure 20-1).[118] More than 100 countries have included restoration in their nationally determined contributions to the Paris Agreement.

Some funding has also emerged. The World Bank is investing $1 billion in restoration projects between 2015 and 2030 in Africa, and more than $2 billion in private finance has been pledged under Initiative 20x20 in Latin America.

Other reports have provided useful guidance for moving ahead with reforestation,[119] and we focus here on three key recommendations for moving forward.

Figure 20-1 | Bonn Challenge commitments have been made by 57 national and subnational governments (as of February 2019)



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: Bonn Challenge (2019).

Properly identify "marginal and unimprovable" agricultural lands for reforestation

In a world that needs both more food and more carbon storage, the only way to increase both is to make more efficient use of land. Focusing on food and carbon storage alone, it makes little sense to remove land from food production if that food production is efficient or could be made efficient. Reforestation and other forms of restoration should in general therefore focus on land with good restoration potential but with low food production and limited realistic potential to improve it. For any particular hectare, how can one know if and when such reforestation or restoration of other natural habitats would be a more efficient use of land?

The challenge is to find a common measure for testing the efficiency of land use when producing different outputs, such as different foods, bioenergy, or forest. Intuitively, in a world that needs (for example) both maize and forest carbon storage, it is obvious that if land can produce a great deal of maize and little forest, it is best used for maize—and vice versa. But how much maize equals how much forest carbon? One approach is to calculate the carbon opportunity cost of using land one way rather than another.

The Carbon Benefits Index[120] provides an example of such an approach based on the assumption that producing a ton of any particular food in one location will avoid the need to clear other land to produce a ton of that same food. As a result, the carbon savings of producing a food on any particular hectare of land is the carbon that would otherwise be lost on average elsewhere to produce the same food. To estimate this "carbon opportunity cost," the index uses the average global loss of carbon from vegetation and soils that has resulted from producing a kilogram of that particular food. Each food—for example, corn, lentils, or chicken—has a particular cost based on the type of land that was cleared to produce it on average globally and the average yield of crop. The index also incorporates differences in production emissions, so that producing a kilogram of a food with fewer production emissions than the global average generates a carbon savings, while producing a kilogram of food with higher than global average emissions generates a carbon cost. In addition, the index counts any increase or loss in carbon on land as a carbon benefit or cost. Overall, the index makes it possible to compare the benefits in terms of total GHG emissions (CO_2e) avoided under the alternative options of generating a ton of any particular food, preserving land as forest, regenerating land as forest or other natural vegetation, or using land for bioenergy.

Using this analysis, for example, reforesting highly sloped, poorly grazed land in the original Atlantic Forest in Brazil produces clear net gains, but the best use of already-cleared land for pasture in the Cerrado would likely be to intensify its pasture production.[121] This index, or something similar, could also be used to identify the most suitable lands to convert to agriculture when agricultural expansion is inevitable—identified in this report as low environmental opportunity cost lands.

Increasing global carbon storage is not the only goal of reforestation. Protecting biodiversity could be reason enough to justify reforestation of some areas, even of productive agricultural lands, as could preventing high levels of erosion or encouraging tourism. Yet for climate purposes, the general principle should be that governments encourage changes in land use from one category to another when doing so would result in a sizeable net percentage increase in global carbon benefits. Mitigating climate change while meeting food needs will require that land-use decisions maximize the output of each hectare of land.

Integrate more native species in reforestation efforts

Although governments have a long history of financially supporting reforestation of abandoned agricultural lands—or lands where declining productivity implies that abandonment will be likely—their efforts have too often favored forest plantations. To achieve a better carbon balance, more biodiversity, and better forest protection from pests, storms, and fires, governments should support more regrowth of native species, as South Korea, among other countries, is now doing.[122]

Actively support farmer-assisted regeneration

Many farms include areas that are unsuitable for food production but where occasional cattle grazing or the spread of fires are enough to block tree regrowth. Farmer-assisted natural regeneration can occur in these conditions if soil, water, and climate are suitable for natural recovery, and if competing productive uses of the land are low. Another requirement is that native source populations for trees exist, for example, tracts of remnant natural forest, or root stocks of native trees.

We suggest that governments create programs to support farmer-assisted regeneration by specifically including regeneration in existing policy efforts:

- **Traditional agricultural loans.** Integrate lines of concessional credit to restore trees on marginal lands (e.g., poor soils, slopes, riparian areas) into traditional loans.
- **Farmer outgrower schemes.** Embed tree restoration in outgrower schemes, which combine multiple restoration success factors in one package: they provide seeds and seedlings, technical assistance, financing, and champions or leadership.
- **Tenure laws.** Reform tenure and titling laws (as discussed in Chapter 35) to assure farmers that, if they regenerate trees, they will be able to benefit from them.

BOX 20-1 | Why Estimates of Reforestation Potential Tend to Be Too Optimistic

Although the potential for reforestation is real and might be further increased with successful efforts to hold down the rate of growth in demand for food and boost yields, reforestation potential today is typically overestimated. Good policymaking depends on understanding why.

The economic costs of reforestation are typically gauged by estimating the costs of using land to plant trees that will sequester carbon. In such an approach, reforestation potential in any of the vast areas of agricultural land that occupy land where forests once existed is just a matter of price.

The most common method to estimate the cost of using land is simply to value land at its rental value and then to add the costs of planting and maintaining trees.[a] Although often incorporated into more elaborate models, the costs of carbon sequestration equal rental value and the annualized value of these other costs divided by the tons of carbon that can be sequestered each year. For example, if the rental value of a hectare of cropland is $100, and it would be possible for trees to remove 10 tons of carbon dioxide per hectare each year[b] then the land-use cost is $10 per ton of carbon dioxide removed. (For simplicity, we ignore planting costs in this example.) So long as people value climate mitigation at $10 per ton, this method would therefore conclude that it is economical to restore forest on this hectare of cropland.

Unfortunately, the rental price of land does not reflect the true cost of both sequestering carbon and meeting all food needs. Rather, the rental value reflects what farmers would pay to use land in one way, compared to the next cheapest market alternative, which includes actions that release carbon or diminish production. For example, one alternative to renting any hectare of land might be that farmers clear another hectare of land instead. Overall, farmers will only pay rent to use existing agricultural land if the cost is less than the cost of producing the same crops by clearing more land. For this reason, the cheaper it is for farmers to clear new land, the lower the rental value of existing agricultural land. Yet clearing other land releases carbon, which undermines the carbon sequestration benefits of reforestation. An irony of using the rental value method is that, the cheaper it is for farmers to clear more land, the more likely they are going to respond to reforesting one hectare of cropland by clearing another, which would reduce—and could eliminate—net gains in carbon storage. For this reason, rental values should not be used to estimate the costs of gaining net carbon sequestration benefits by taking land out of production.

BOX 20-1 | Why Estimates of Reforestation Potential Tend to Be Too Optimistic (continued)

Perhaps worse, rental values also are limited by the ability and willingness of people to pay for food. When land is taken out of production, some consumers will not be able or willing to pay the resulting higher prices for food and food consumption will decline. In fact, the more price-sensitive is food consumption, the lower will be the agricultural rental value. Again, lower rental values do not necessarily reflect a lower cost of restoring forests while still meeting the same food demands but rather may reflect a larger reduction in food consumption.[c]

In summary, while agricultural rental values do reflect the financial cost of restoring a particular hectare of land, they do not reflect the cost of sequestering carbon on a net basis or doing so while still supplying the same global quantity of food.

Removing some land from production may sometimes lead, through higher food prices, to some desirable results, such as reduced consumption by the wealthy of ruminant meat or reduced food loss and waste. But because any such effects occur through generalized increases in food prices, those same higher prices will also reduce food consumption by the poor, and will probably do so disproportionately because the poor are less able to afford higher prices.[d] The higher prices will also encourage farmers to expand crop area. Taking good agricultural land out of production for the purpose of reforestation is not therefore generally either an equitable or effective strategy for reducing undesirable consumption.

Even when underlying models to some extent reflect these issues, their results can easily be taken out of context and therefore fail to explicitly convey the conditions necessary for reforestation. For example, Griscom et al. (2017) suggest that there is potential to reforest millions of hectares of grazing land. They cite two modeling studies to support the proposition that this reforestation would be possible without sacrificing food production. One of these studies[e] assumes that reforestation occurs only on abandoned agricultural land. Although this paper (using the IMAGE model) does not explain why abandoned land becomes available, the land apparently becomes available only between 2050 and 2100. In other IMAGE modeling papers concerning this period, the abandoned land becomes available as a result of assumptions about limited population growth and high rates of yield gains. The other modeling study[f] estimates that the level of additional land-clearing could be reduced at carbon prices up to $100 per ton of carbon dioxide, in part by intensification of grazing systems, and in part by reductions in consumption of livestock products. This second study tries to estimate what would happen if the cost of climate change at different carbon prices were built into all food production and consumption decisions, so that farmers would be taxed to produce beef and other livestock products, people would pay those taxes when they consumed, farmers would also be rewarded for reforesting their land instead of producing food, and other farmers would be persuaded not to clear more forest in response because clearing would be taxed. Thus, the preconditions for reforestation potential in both studies are substantial. In one study, the condition is a net decline in agricultural land. In the other, stringent global policies are enacted to boost yields, protect existing forest, and discourage consumption of livestock products.

In effect, these conditions represent one way in which a global economic model can simulate successful adoption of many of the recommendations of this report to protect natural areas and reduce demand for agricultural land. As such, these estimates only reaffirm that large-scale reforestation depends on successfully implementing the various menu items in this report.

Notes and sources:

a. Examples of such efforts include Benítez et al. (2004) and a special paper prepared for the "Stern Report," published in updated form as Grieg-Gran (2008). In Benítez et al. (2007), the authors excluded more productive cropland but estimated sequestration costs based on the return to other agricultural land. In van Kooten and Sohngen (2007), the authors reviewed a wide range of studies and analyses and, although they did not describe all the studies in depth, none of the studies were described as focusing on the cost of meeting alternative food supplies on other land and instead were described, at most, as focusing on the opportunity cost of land, which we read as involving the economic return to land for alternative uses at present prices. The studies we have been able to analyze that use economic models also often incorporate this error although sometimes not technically using rent but net agricultural return, which is a way of estimating rent. In Sathaye et al. (2011), for example, the agricultural value of a hectare of land is estimated (and very roughly) by the price of the crops that could be grown minus the costs. In Sohngen and Sedjo (2006), the price of agricultural land is fixed at its rental value, which also effectively means the price of a crop reflects (a) the costs of producing it, including by clearing more land, and (b) the willingness or ability of consumers to pay for it. Therefore, the cheaper the supply of new cropland, and the larger the consumer response to prices, the cheaper the price of crops, and the lower the opportunity cost of using land. Economic models can attempt to get at the carbon costs of equilibrium. At a fundamental level, even equilibrium models are estimating net agricultural returns to land. The reason land receives an economic return is only because the cost of producing food on that land is less than the cost of clearing new cropland, growing food on that land, and transporting that food to consumers, or is less than the price consumers are willing and able to pay.

b. That level of carbon dioxide equals 2.7 tons of carbon per hectare per year, which is a reasonable figure for much reforestation.

c. Many economic models in fact estimate a large food reduction effect from diverting agricultural land to other uses, as discussed in our chapter on bioenergy.

d Regmi et al. (2001); Muhammad et al. (2011).

e. Strengers et al. (2008).

f. Havlík et al. (2014).



CHAPTER 21

MENU ITEM: CONSERVE AND RESTORE PEATLANDS

Only a small portion of the world's agricultural land sits atop peat, but these areas have large impacts on climate change—contributing as much as 2 percent of total annual human-caused GHG emissions, according to our calculations. Given this disproportionate impact, a dedicated effort is needed to avoid any further conversion of peatlands to agriculture and to restore some of the world's peatlands that have already been drained for crops or livestock.

The Challenge

According to one estimate, peatlands[123]—the most carbon-rich category of wetlands—occupy around 450 Mha of land, or roughly 3 percent of the ice-free terrestrial land surface, yet they store 450 to 600 gigatons of carbon.[124] This quantity is equal to between 60 and 80 percent of carbon in the atmosphere (and around one-quarter of all the carbon stored in global soils). Peatlands form because they are located in landscapes that retain moisture and thus have almost permanently saturated soils. The water blocks the penetration of oxygen, which is needed by most bacteria to break down biomass and release the carbon in dead plant material back into the air. As a result, peatlands can build up large deposits of carbon, sometimes over tens of thousands of years. Although grasslands and forests are generally believed to stabilize at maximum levels of soil carbon, peatlands, if undisturbed, tend to continue to build carbon in soils indefinitely. In the tropics, peatland carbon accumulation rates can reach 0.4 tons per hectare per year.[125]

Growing crops on peatlands typically requires draining them so that oxygen can penetrate soils and reach plant roots. (Although plants release oxygen when they photosynthesize, they need oxygen to metabolize sugars into energy just like animals, and this oxygen nearly always comes through the roots.) Drainage leads to a release of carbon to the atmosphere because the oxygen stimulates the activity of bacteria and other microorganisms that break down organic matter, and because dry peats are prone to fires, whether naturally occurring or set intentionally. The amount of carbon released and the propensity to lose carbon through fire depends on the depth of the peat, the incidence of drought in the area, and the depth of drainage (the deeper the drainage, the more peat that is exposed to microbial activities or that becomes dry enough to burn).

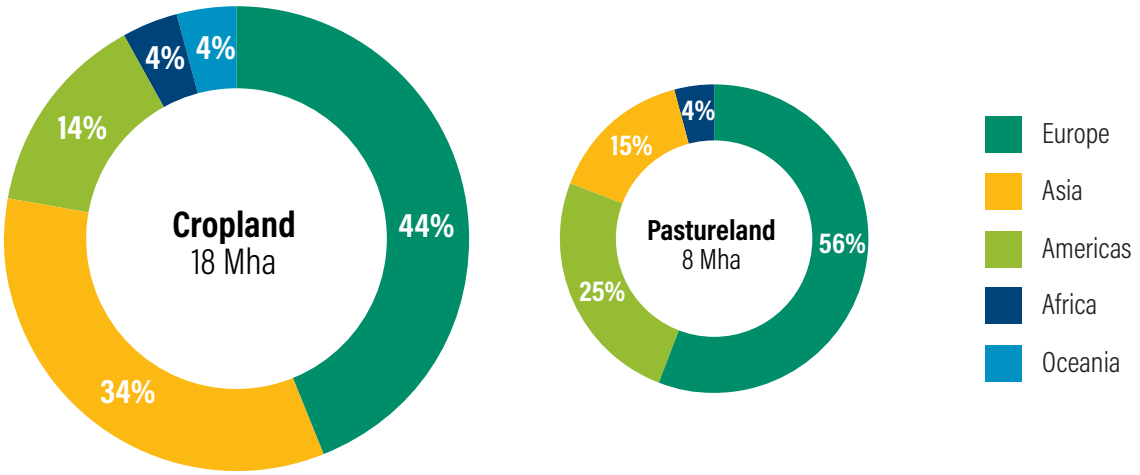
Although two-thirds of peatlands are in climates cold enough to be affected by permafrost, the deepest peat deposits occur in the 13 percent of global peatlands that are located in the tropics, where the combination of high, year-round plant production and saturated soils leads to large annual peat deposits. The best documented, largest expanses of tropical peatlands occur in Southeast Asia, particularly Indonesia and Malaysia, where they have typically supported dense rain forests.[126] In recent decades, these forested peatlands have been subject to large-scale, continuous drainage and clearing for agriculture and forestry. According to one analysis,[127] of the 15.7 Mha of peatlands in Malaysia and Indonesian Sumatra and Kalimantan,[128] only 6 percent (1 Mha) remained in relatively pristine condition as of 2015, and only 40 percent remained in some kind of natural forest (including forests regrowing after full clearing due to forestry activities). In contrast, 50 percent had been converted to use for agriculture or forest plantations. Forested peatland area declined by 1.8 Mha between 2007 and 2015 alone.[129]

Based on our own mapping analysis, we estimate that 20 Mha of cropland, globally, is located on peat; we assume that almost all of this area is probably drained.[130] FAO similarly estimates that 18 Mha of peatlands are both drained and used for cropland, while 8 Mha are drained and used for pasture (Figure 21-1).[131]

Climate assessments originally did not pay much attention to emissions generated by these drained peatlands, but massive fires in Southeast Asian peatlands in 1997, 2007, and 2015 have attracted increasing global attention to the issue. Climate change estimates began to incorporate peatland emissions from this region (Figure 21-2), and more recently they have included estimates of peatland emissions from other countries (Figure 21-3). Amazingly, these tiny fractions of global cropland (roughly 1 percent) and pasture (roughly 0.3 percent) generate emissions typically estimated in the range of 1 gigaton of CO_2e per year, or almost 10 percent of annual emissions from agricultural production and associated land-use change.[132]

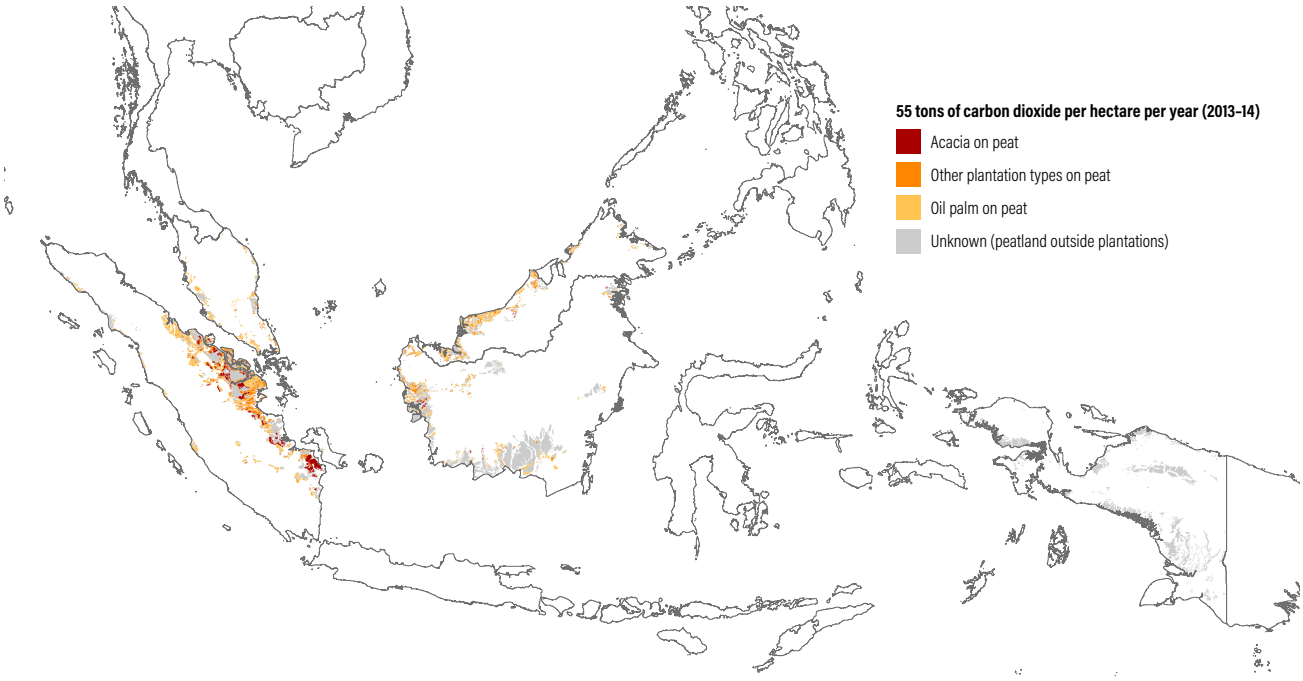
We developed our own estimate to ensure use of the most up-to-date maps of cropland area, peatlands, and emission factors, and to enable a specific focus on peatlands in agricultural use.[133] We estimate ongoing annual emissions at a total of 1,103 Mt CO_2e, of which 863 Mt result from microbial decomposition and 240 Mt (annual average) from fire. These emissions amount to roughly 2 percent of all anthropogenic emissions from all sources, and roughly 9 percent of 2010 emissions related to agriculture. These emissions will continue for decades unless the peatlands are rewetted.

Figure 21-1 | FAO estimates that 26 million hectares of peatlands are drained and used for agriculture



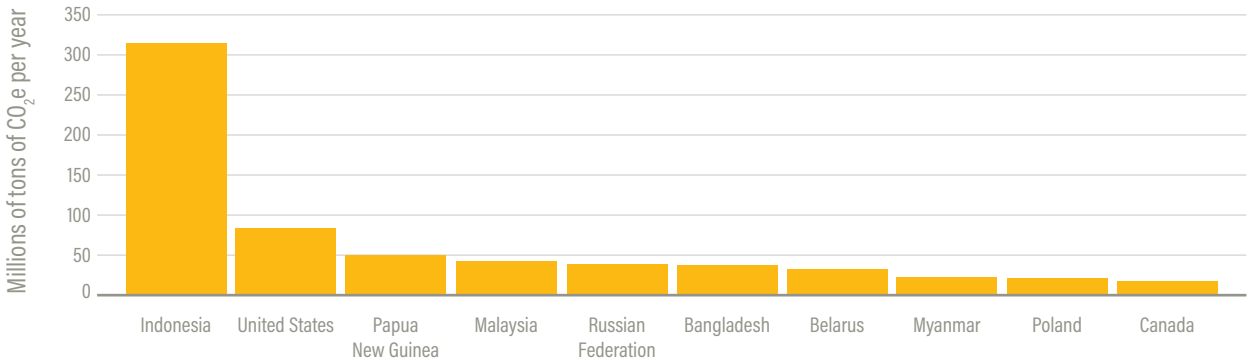
Source: Biancalani and Avagyan (2014), Figure 2.2.

Figure 21-2 | Greenhouse gas emissions from drained peatlands are ongoing in Indonesia and Malaysia



Source: WRI (2017a).

Figure 21-3 | Southeast Asia accounts for the majority of peatland emissions



Note: Graph shows the top 10 countries associated with annual GHG emissions from drained peatlands.
Source: Biancalani and Avagyan (2014), Figure 2.5.

These estimates of emissions from peatlands may be too low if we are underestimating peatland area. Datasets are highly varied because global field mapping is limited, and satellite imagery provides only limited guidance. Researchers recently used a variety of methods to estimate where peatlands should form, backed by some reasonably successful ground validation, and estimated tropical peatlands at 170 Mha, roughly three times the predominant previous estimates.[134] This study estimated much larger peatland areas in Latin America and Africa. Around the same time, a separate group of scientists reported discovery of the world's largest tropical peatland in the heart of the Congo rain forest in central Africa.[135] They estimated that it stores 30 gigatons of carbon, equivalent to roughly 20 years of U.S. fossil fuel emissions. Discoveries of more peatlands may lead to more estimates of drained peatlands and therefore higher estimates of existing emissions. These estimates show the potential for a much greater risk of additional emissions from agricultural expansion in the future. To date, relative land abundance in both Latin America and Africa has reduced the need for investment in drainage of peatlands and other wetlands. But the history of Europe, the United States, and China suggests that as countries develop they tend to drain much of their wetlands for agriculture.

The Opportunity

GHG emissions from peatlands will generally stop if peatlands are rewetted. Going further and restoring forests on naturally forested areas provides additional opportunities for sequestration. The precise techniques for rewetting vary by peatland, but they typically involve blocking drainage ditches and canals. In some situations, restoration may be more complex because roads or dams obstruct movement of water or divert water to other uses. Because peatlands shrink in elevation when drained, one complication typically involves rewetting peatlands to just the right level and avoiding too much flooding, which would prevent vegetation from regrowing. Still, even imprecise rewetting can avoid the ongoing degradation of peat.[136]

Globally, there are many relatively small-scale examples of successful peatland restoration projects. One project rewetted 36,000 ha in Belarus at a 10-year cost estimated at $5 million, or $140 per hectare.[137] A project in China has restored water to tens of thousands of hectares in the 2 Mha of drained peatlands on the Ruoergai (or Zoige) Plateau on the northeastern margin of the Qinghai-Tibet Plateau. Another prominent example in the United States involved the government purchase and rewetting of tens of thousands of hectares of agricultural land in an area that occupied one-quarter of Florida's Everglades. After a protracted

lawsuit and political controversy, restoration began as a means of filtering out phosphorus pollution from the remaining agricultural lands before the pollution entered the remaining natural portions of the Everglades.[138]

Although many drained peatlands are in intensive and successful agricultural use, few areas would justify the associated GHG emissions if those emissions were properly valued. For example, one study estimated the value of palm oil at $600 per hectare per year on the most productive oil palm plantations[139]—and oil palm plantations on peat are typically less productive than those on nonpeat soils. But the value of avoiding the likely peatland emissions alone would be $2,750 per hectare per year at $50 per ton of CO_2e,[140] which is well below typical estimates of the carbon costs the world will need to pay to solve climate change.[141] Because oil palm plantations need to be replanted at high cost roughly every 25 years, economically rational opportunities could exist in some situations to rewet peatlands in productive oil palm plantation areas at the natural end of their productive life.

Probably the easier restoration opportunities, politically and economically, are to be found in the millions of hectares of drained peatlands that have some kind of combination of shrub-like vegetation or dispersed, small-scale agriculture. Although no detailed compilation exists, peatland researchers broadly agree that such lands exist.[142] In the main islands of Indonesia, 45 percent of peatlands converted to agriculture as of 2015 were not in plantations but displayed the kind of dispersed cropland, shrubland, and cleared land that is characteristic of smallholder farming. Although there is no detailed analysis of the uses of such lands, the mapping used to identify them indicates that the overall farming intensity is relatively low (at least by comparison with plantations), and people do not typically live on these peatlands in large numbers. More drained peatland is probably included in areas that satellite images identify as shrublands or cleared lands.[143]

One prominent peatland is a roughly 1 Mha area in Central Kalimantan, Indonesia, that the government attempted to convert to rice production via the Mega Rice Project beginning in 1995. Due to poor yields and fires, rice production either never started or was abandoned. The area now exists largely as a drained, cleared, and degrading site. Established in 2008, the Indonesia-Australia Forest Carbon Partnership attempted to restore these peatlands, but it created a variety of local controversies as different communities negotiated the compensation or benefits they would receive for agreeing to restoration. Amid widespread frustration with the lack of progress, Australia abandoned the effort in 2014.[144]

Fortunately, Indonesian President Joko Widodo announced in 2016 a goal to restore 2 Mha of peatland by 2020 (Box 21-1). This announcement came after massive peatland fires in 2015 that, in addition to releasing carbon, caused 500,000 people to be hospitalized. Although this effort is far from fully funded, Indonesia allocated $35 million to peatland restoration in 2017. By 2018, the Peat Restoration Agency reported having rewetted more than 100,000 ha of land, although the standard used involves rewetting only up to 40 centimeters below the surface, so some degradation of soils will continue to occur.[145]

Massive peatland fires in Russia in 2010 also led to an effort with Wetlands International to rewet abandoned peatlands, although its reach has so far been very modest.[146]

Restoring peatlands in Southeast Asia and elsewhere also could generate ongoing economic returns to offset some of the costs.[147] For example, peatlands that naturally supported forests could likely accumulate an amount of carbon from reforestation at rates that could justify substantial carbon payments. Although it would forgo many biodiversity benefits, another option might involve use of rewetted peatlands for agricultural or forest products that could grow well under wet conditions. Some valuable woods, such as European black alder, grow naturally on peatlands. Some European wetland grasses, such as reed canary grass, grow at sufficient yields to contemplate their use for bioenergy. (If produced as part of a strategy to restore peatlands, wetland grasses would generate large climate benefits, although more from the restoration of peatland than from the provision of biomass.) A German project demonstrated that reed fibers could produce fire-resistant boards, while cattail could produce excellent insulation materials. Cultivation of sphagnum moss could produce a valuable additive for horticulture.[148] Another study found that native Indonesian peatland plants could

BOX 21-1 | Indonesia's commitment to peatland restoration

The 2015 fire season was the worst in Indonesia's history, resulting in more than 500,000 people being treated for respiratory illnesses, and causing more than $16 billion in economic losses.[a] Analysts estimate that 2.1 Mha of land and forest burned, resulting in 1.6 Gt CO_2e (more than Japan's annual total emissions) being released from fires that year.[b] The fires occurred largely on drained peatlands converted to oil palm and timber plantations.

To prevent another fire disaster of this scale, President Joko Widodo announced at the UN Framework Convention on Climate Change Conference of the Parties (COP) 21 in Paris the establishment of the Peat Restoration Agency (Badan Restorasi Gambut, or BRG), an agency mandated to restore 2 Mha of peatland by 2020.[c] The president established the BRG through Presidential Regulation No. 1/2016, which lays out a plan to coordinate and accelerate the recovery of Indonesia's critical peatlands.

The BRG's restoration efforts will prioritize seven provinces: Riau, Jambi, South Sumatra, Papua, and West, East, and Central Kalimantan. Out of Indonesia's estimated 12.9 Mha of peatland, 6.7 Mha are degraded and have potential for restoration, while 6.2 Mha are intact with potential for stronger protection. The BRG's first year focused on identifying and mapping the extent and depth of peat domes in four districts in Sumatra and Kalimantan, totaling an area of 644,000 ha. In 2017, the BRG began coordinating and implementing peatland restoration activities in the target districts. The agency is working to mobilize nongovernmental organizations, companies, civil society, and the development community to support its efforts.[d]

Sources:
a. Lamb (2015).
b. Harris et al. (2015).
c. Jong (2015).
d. Wardhana (2016).

produce a wide range of valuable products, including a candlenut that the study found could even exceed the returns for oil palm.[149] Taking advantage of these opportunities may require a coordinated set of investments to support their establishment or marketing, and few have been tested in the real world. But the fact that some plants can grow well even in undrained peatlands suggests that at least some economic opportunities might exist to help support their restoration.

To estimate the potential benefits of peatland restoration, we estimate the GHG emission reductions that would result from restoring 25 percent, 50 percent, and 75 percent of all drained peatlands globally. (The higher number would require some peatlands currently used productively for agroforestry or forest plantations to be rewetted at the time they would otherwise need replanting.) Table 21-1 summarizes the potential GHG emissions benefits of these three scenarios, which would close the overall GHG emissions gap by between 2 and 7 percent.

Recommended Strategies

Pursuing peatland conservation and restoration requires better data, resources, regulation, and political commitment.

Better peatlands data and mapping

As our discussion indicates, mapping of peatland extent is today based on rough estimates because peatlands often cannot be identified by satellite imagery. Mapping relies on national soil surveys, typically conducted for planning agricultural uses, which do not technically identify peatlands but rather identify soils that are characteristic of peatlands. But the quality and effort put into this type of soil mapping is uneven across the world, particularly in more remote areas. This information also does not convey the depth of peat, whether the peatland is presently cropped and drained, or the depth of the drainage. All this information is important to ensure conservation of existing undrained peatlands and identify the optimal restoration opportunities. An international entity or entities will need to step forward and supply the necessary resources and coordination for development of quality and detailed global maps of peatland extent, depth, drainage status, and use.

Resources

First and foremost, restoration requires resources both to fund the physical restoration and, usually, to compensate in some way existing users of the land for their forgone uses. Ideally, this compensation could take the form of assistance to help boost yields of crops outside of peatlands, replacing the forgone food production.

Table 21-1 | Potential of peatland restoration to reduce greenhouse gas emissions

SCENARIO	ANNUAL GHG EMISSIONS FROM PEATLANDS (2010–50) (MT CO_2E)	CHANGE IN SIZE OF GHG EMISSIONS GAP BETWEEN 2050 BASELINE AND 2050 TARGET
Baseline	1,103	
25 percent peatland restoration	827	-2%
50 percent peatland restoration	552	-5%
75 percent peatland restoration	276	-7%

Sources: WRI analysis based on Yu et al. (2010); You et al. (2014); Hiraishi et al. (2014); Biancalani and Avagyan (2014); and van der Werf et al. (2017).

To date, peatland restoration projects have demonstrated technical potential but have been carried out at small scales and in limited contexts. Yet they probably offer one of the least expensive carbon savings of any land-use option, particularly where drained peatlands are now little used. International financial entities aiming to support climate change mitigation, including the Green Climate Fund, the World Bank, and national development assistance agencies, should work together to develop a major global funding initiative on peatland restoration.

Regulation

There is little reason for governments of peat-rich countries or the world's wealthier nations to pay to restore peatlands in one location if farmers can easily shift food production and drain peatlands elsewhere. Governments should therefore establish, and enforce, strong laws protecting peatlands from further drainage or conversion. Indonesia, for example, issued a regulation in 2016 placing a moratorium on clearing peatland until a zoning system for the protection of peatlands and cultivation in peatlands is in place. The moratorium also specified that degraded areas must be restored, although implementation is still at an early stage.[150]

Governments should also consider laws that will not leave the continued use of drained peatlands as assured, regardless of their economic benefits. Although many of those who now benefit from drained peatlands have compelling social arguments for some form of compensation for restoration—preferably as other economic opportunities—emissions from peatlands should not be immune from government regulation any more than other sources of emissions.

Political commitment

Even when drained peatlands are little used, experience indicates that someone is nearly always using them in ways that take advantage of the drainage. Even in the largely abandoned Mega Rice Project area of Indonesia, local people engage in some modest agriculture, and they have used the canals as a means of transportation (for boats or timber), which is easier than trying to move directly through typically saturated peat.[151] Because peatland drainage typically requires networks of drainage ditches, restoration usually proceeds in a series of blocks (e.g., by blocking drainage ditches), affecting multiple people and sometimes multiple communities, and it is hard to get all to agree. Australia's efforts to restore the peatlands of the Mega Rice Project faltered in large part because some groups of people objected to the compensation deals as they unfolded, and occasional negative press emerged based on these objections.

Restoring peatlands, like most other infrastructure projects, has high potential to arouse opposition from some parties, even if the benefits to the public are clear and the project has the support of the vast majority of those directly affected. Efforts to move forward must be sensitive to issues of equity and seek participation and consent but should respect majority support. Projects will not succeed without a strong political commitment to see projects through.

ENDNOTES

1. FAO (2019a).
2. FAO (2019a).
3. Alexandratos and Bruinsma (2012), Table 4.8.
4. GlobAgri-WRR model.
5. To appreciate shifts in locations of agricultural land, an analysis must evaluate how small, specific areas of land change over time, and not simply calculate how the total agricultural land within a country changes over time. The shifts only became possible to analyze once satellites could track locations of all land-use changes over time.
6. Reprinted from Figure 11 of FAO (2012e).
7. Lindquist et al. (2012).
8. Aide et al. (2012) for Latin America; Lark et al. (2015) for U.S.
9. Kuemmerle et al. (2016).
10. Millennium Ecosystem Assessment (2005); Grenyer et al. (2006); Searchinger, Estes, Thornton et al. (2015); Sitch et al. (2015); Wheeler et al. (2016).
11. Aide et al. (2012); Lark et al. (2015).
12. Gibson et al. (2011).
13. West et al. (2010).
14. Hirsch et al. (2004).
15. Aide et al. (2012). The shift in grazing land from dry land in Australia to Latin America is also a good example of this type of shift.
16. Alexandratos and Bruinsma (2012).
17. GlobAgri-WRR model.
18. Van Ittersum et al. (2016).
19. Van Ittersum et al. (2016).
20. Searchinger, Estes, Thornton et al. (2015).
21. FAO (2019a).
22. Bruinsma (2009) predicts an increase in soybean production from 218 Mt in 2006 to 514 Mt in 2050, with a rise in yield from 2.3 t/ha to 3.7 t/ha during that period, leading to an increase in harvested area to 141 Mha. Masuda and Goldsmith (2009) only look out to 2030 and project a "business as usual" scenario in 2030 where 371 Mt of soybeans will be produced on 141 Mha of land.
23. In Latin America, Brazil and Argentina are two of the three largest soybean producers in the world. Africa's potential to produce soybeans is described alternatively in Gasparri et al. (2016) and Searchinger, Estes, Thornton et al. (2015).
24. Soyatech (n.d.).
25. Oil World (2015).
26. UNCTAD (2015).
27. UNCTAD (2015).
28. Pacheco (2012); Greenpeace (2012); Rainforest Foundation UK (2013).
29. For example, see Rainforest Foundation Norway (2012).
30. Corley (2009). Corley's estimate is for palm oil for edible purposes and "traditional" nonedible purposes (which do not include biofuels). Rushing and Lee (2013) project up to an additional 15 Mha of palm oil plantation expansion globally from 2010 or 2012 level (the base year is unclear in the publication) to 2050. The implications of current (2015) low prices for palm oil remain to be seen. For instance, it could delay the timing of expansion until prices rise again. One should note that some oil palm clones are capable of yielding 11 metric tons per hectare (which is way above the current average 4–5 metric tons per hectare), so there is still an upside potential in palm oil yields (D. McLaughlin, personal communication, April 30, 2015). However, getting selected clones to become mainstream is not a foregone conclusion.
31. Laurance et al. (2014); Laurance et al. (2009); Edwards et al. (2014); Busch and Ferretti-Gallon (2017); Seymour and Busch (2016); Vera-Diaz et al. (2009); Fearnside (1982); Chomitz and Gray (1996).
32. Seymour and Busch (2016).
33. Laurance et al. (2009); Laurance et al. (2006). See also summary of articles in Searchinger, Estes, Thornton et al. (2015).
34. Ahmed et al. (2014); Blake et al. (2007).
35 Laporte et al. (2007).
36. Laurance et al. (2014).
37 Ali et al. (2015); Delgado et al. (1998); African Agricultural Development Company (2013); Gollin and Rogerson (2010).
38. Jouanjean (2013).
39. Vera-Diaz et al. (2009)
40. Laurance et al. (2014).
41. Laurance et al. (2015).

42. Laurance et al. (2015).

43. AIIB (2016).

44. Angelsen and Kaimowitz (2001); Ewer et al. (2009); Rudel (2009).

45. Searchinger (2012); Villoria et al. (2014); Hertel et al. (2014).

46. Dorward (2012).

47. If yield increases occur because of increases in other inputs, including chemicals, machinery, or labor, then these nonland costs are likely to increase. This issue is often confused in the literature because studies tend to model effects on land not from increases in yield alone but rather from increases in total factor productivity, which assumes increases in productivity of all inputs and therefore declines in costs of producing crops and, in turn, prices. See, for example, Hertel et al. (2014).

48. Stevenson et al. (2013).

49. Searchinger, Edwards, Mulligan et al. (2015); HLPE (2011); Dorward (2012); Filipski and Covarrubia (2010).

50. Gallett (2010).

51. Hertel et al. (2014).

52. The same yield growth may not precisely influence costs of production in the same way in each country, so this statement is only true roughly and in general.

53. Estimates of these rates of conversion of grasslands to croplands vary but are all in millions of hectares. Lark et al. (2015); WWF (2016).

54. Hoering (2013).

55. Van Ittersum et al. (2016); FAO (2002).

56. Butler (2013).

57. Rosenbarger et al. (2013).

58. Mulyani and Jepson (2013).

59. Recio (2015).

60. Jackson (2015); Nepstad et al. (2014); Assunção et al. (2012); Gibbs et al. (2016).

61. Do Carmo (2017).

62. Wormington (2016).

63. Cameron (2015).

64. Fagan et al. (2013).

65. Murdiyarso et al. (2011); Austin et al. (2012).

66. Palmer (2015).

67. Busch and Ferretti-Gallon (2017). See also Porter-Bolland et al. (2012).

68. Seymour and Busch (2016).

69. Busch and Ferretti-Gallon (2017).

70. Blackman et al. (2017).

71. Busch and Ferretti-Gallon (2017).

72. This paragraph is based on Seymour and Busch (2016); see esp. Chap. 7 for a fuller discussion of how to stop tropical deforestation. See also Colchester et al. (2006).

73. See www.globalforestwatch.org.

74. Seymour and Busch (2016).

75. See, for example, Frank et al. (2017). We do not necessarily endorse the specific findings of this paper, but it does provide one estimate of the likelihood that stopping land-use changes without sufficient, exogenous yield gains will result in an increase in food prices and food insecurity.

76. Data for the following paragraph come from Assunção et al. (2013).

77. Assunção et al. (2013).

78. Annual deforestation rates in Brazilian Amazon with data from INPE (Brazilian National Institute of Space Research) are summarized by Butler (2017).

79. The Brazil story is summarized in Jackson (2015).

80. Jackson (2015).

81. Laurance et al. (2014).

82. Estes, Searchinger, Spiegel, et al. (2016).

83. Climate Focus (2016); Donofrio et al. (2017).

84. Consumer Goods Forum (2014).

85. University of Cambridge, Institute for Sustainability Leadership (2019).

86. University of Cambridge, Institute for Sustainability Leadership (2019). The founding member banks are Barclays, Deutsche Bank, Lloyds Banking Group, Santander, Westpac, BNP Paribas, RBS, and UBS.

87. Fabiani et al. (2010).

88. Gibbs et al. (2015).

89. Gibbs et al. (2015).

90. Soy production in Brazil in 1991 was about 20 million metric tons. In 2005, it was about 56 million metric tons. In 2007, it was about 61 million metric tons. In 2011 and 2013, it was about 75 million metric tons and 82 million metric tons, respectively. Data for 1991 through 2009 are from the U.S. Department of Agriculture, as reported in Boucher et al. (2011). Data for 2011 and 2013 are from USDA (2019).

91. Taylor and Streck (2018).

92. Nepstad et al. (2014).

93. Boyd et al. (2018).

94. Papers using this term in the bioenergy context include Gelfand et al. (2013); Nijsen et al. (2012); and Wicke et al. (2011).

95. Cai et al. (2011).

96. Borras et al. (2011); Baka and Bailis (2014).

97. Federici et al. (2015); Pan et al. (2011); Richter and Houghton (2011).

98. For example, in Palm et al. (2013), an important and oft-cited book focusing on tropical land conversion, the approach recommended focuses on calculations of costs per hectare, not per ton of crop.

99. Nijbroek and Andelman (2016).

100. Estes, Searchinger, Spiegel, et al. (2016).

101. Koh and Ghazoul (2010).

102. *Imperata* grasslands store less than 20 tons of carbon per hectare (tC/ha), compared to more than 100 tC/ha in secondary forests and more than 200 tC/ha in the primary forests of Sumatra and Kalimantan, Indonesia. Figures include both biomass and necromass (Fairhurst et al. 2010).

103. Chapin et al. (2000).

104. Fairhurst and McLaughlin (2009).

105. This figure reflects the area classified as "grassland" by Sarvision's radar-based satellite imagery of Kalimantan in 2010. Unpublished analysis conducted by WRI.

106. Garrity et al. (1997).

107. One study estimates a need for 3 to 7 million hectares of additional oil palm plantations in Indonesia between 2010 and 2020; for links and citations of these figures, see Gingold (2010).

108. Maginnis et al. (2005).

109. See, for example, Stern (2006); Nabuurs et al. (2007); Sathaye et al. (2011); and Sathaye et al. (2005).

110. Griscom et al. (2017).

111. Buckingham and Hanson (2015b).

112. Hua et al. (2016).

113. Siddique et al. (2008).

114. Jactel et al. (2017).

115. Hua et al. (2016). For example, bee diversity in plantations was 5% of that of croplands overall except for eucalyptus.

116. Hua et al. (2016).

117. These estimates of beef production come from Cardoso et al. (2016), which discusses the level of beef production per hectare on pastureland under different forms of management in the Cerrado. Although the Atlantic Forest is a separate region, we estimate that the beef production on sloped pasture in this region is similar to that of the lowest management in the Cerrado, based on personal communications with the authors.

118. See http://www.bonnchallenge.org/commitments.

119. Hanson et al. (2015).

120. Searchinger et al. (2018).

121. Searchinger et al. (2018).

122. Buckingham and Hanson (2015b).

123. Global soil maps tend to map not peat but "organic soils," which are soils with 12% or more soil organic matter. Our mapping of peatlands globally uses organic soils designations.

124. Kolka et al. (2016).

125. Kolka et al. (2016).

126. Morrogh-Bernard et al. (2003); Posa et al. (2011); Sunarto et al. (2012).

127. Mietinnen et al. (2016).

128. For all of Indonesia, and using its own definition, Indonesia's Ministry of Environment and Forestry as of 2017 estimates 24.14 Mha of peatland hydrological units on National Zoning of Peatland Ecosystems.

129. Mietinnen et al. (2016).

130. See full description of methodology for estimating both land areas on peatlands and emissions in note 139.

131. Biancalani and Avagyan (2014).

132. IPCC (2014).

133. Our analysis used the global map of peatland regions from Yu et al. (2010) to calculate the area of cropland on peat soils, the SPAM maps of crop distribution (You et al. 2014), emission factors recommended by the IPCC in a special report on wetlands (Hiraishi et al. 2014), except that we used a single emission factor of 55 tCO_2/ha/yr for both oil palm and acacia plantations based on work by scientists with Wetlands International for reasons described in Biancalani and Avagyan (2014). We also estimated annual average peatland fire emissions based on the Global Fire Emissions Database version 4 (van der Werf et al. 2017).

134. Gumbricht et al. (2017); Joosten et al. (2012).

135. Dargie et al. (2017).

136. Joosten et al. (2012); Biancalani and Avagyan (2014); Rochefort and Andersen (2017); Bonn et al. (2016).

137. Biancalani and Avagyan (2014), Box 7.

138. Grunwald (2018).

139. Abram et al. (2016).

140. This calculation is based on the emission rate of 15 tons of carbon per hectare per year for oil palm in peat based on the emission factors discussed in Biancalani and Avagyan (2014).

141. Cost estimates vary greatly, but $50 is still below the mean, undiscounted estimated mitigation cost in 2030 to hold warming to 2 degrees Celsius based on analysis by the IPCC. See Rogelj et al. (2018), Figure 2.26(a).

142. Joosten et al. (2012).

143. Mietinnen et al. (2016).

144. Davies (2015).

145. Gewin (2018).

146. Wetlands International (n.d.).

147. The examples in this paragraph are all summarized by FAO in Biancalani and Avagyan (2014).

148. Biancalani and Avagyan (2014).

149. Biancalani and Avagyan (2014).

150. See ANTARA News (2016) and Pickup (2017) for more details on Indonesia's Government Regulation no. 57/2016.

151. Nugraha and Jong (2017).

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COURSE 4

Increase Fish Supply

The global wild fish catch reached a peak in the mid-1990s but it has since stagnated and may even have declined. Roughly one-third of marine fish stocks are now overfished, with another 60 percent fished at maximum sustainable levels. This course explores ways to improve wild fisheries management and raise the productivity and environmental performance of aquaculture to meet rising demand for fish.

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CHAPTER 22

MENU ITEM: IMPROVE WILD FISHERIES MANAGEMENT

Fish are an important source of protein, especially for people in developing countries. Yet the annual amount of fish caught in the wild—particularly from the oceans—has stagnated and may have significantly declined since the 1990s. Continued overfishing threatens future catch levels and improved management will be essential to allow fish stocks to rebound.

The Challenge

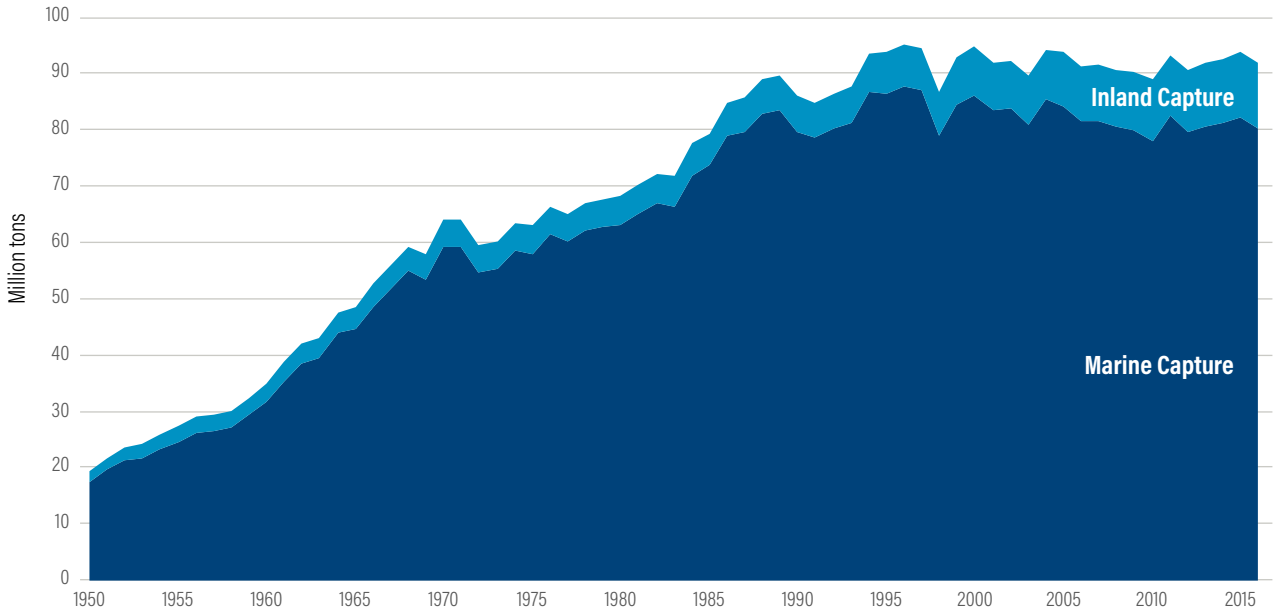
Fish, including finfish and shellfish,[1] are a minor source of the global calorie supply, but they contributed 17 percent of global animal-based protein for human consumption in 2010 (Figure 6-4).[2] Fish are particularly important in developing countries, which consume more than 75 percent, and produce more than 80 percent, of global fish supply.[3] Fish also contain important micronutrients—such as vitamin A, iron, and zinc—and long-chain omega-3 fatty acids that are essential for maternal health and early childhood development but are often deficient in the diets of the poor.[4]

According to the Food and Agriculture Organization of the United Nations (FAO),[5] the world produced 171 million tons (Mt) of fish in 2016. Wild fisheries produced 91 Mt, which provided 71 Mt of fish for people and 20 Mt for animal feed and other nonfood uses.[6] The global fisheries catch has grown almost fivefold since 1950. Yet since the 1990s, the catch has at best stagnated. FAO data show such a stagnation with a slight increasing trend in inland fish landings offsetting a slight decline in marine fish landings (Figure 22-1).[7] Research by Pauly and Zeller (2016) is even more pessimistic, concluding that FAO's numbers underestimate both total marine fish catches and the rate of decline since the 1990s. Using an approach called "catch reconstruction," Pauly and Zeller estimate that the global marine fish catch peaked at 130 Mt in 1996 (nearly 50 percent higher than FAO's estimate for that year) and since then has declined at an average rate of 1.2 Mt per year, with serious implications for the future marine catch.[8]

The percentage of marine fish stocks that are overfished is also near an all-time high. By 2015, 33 percent of marine fish stocks were overfished, with another 60 percent fished at maximum sustainable levels, and only 7 percent fished at less than their full potential (Figure 22-2).[9]

The tropics present particular challenges. Fish catches are greatest in the tropics—particularly in Southeast Asia.[10] Climate change is also likely to have substantial future effects by reducing productivity and fish size, disturbing fish habitats, and changing species composition as fish move toward cooler waters.[11]

Figure 22-1 | The wild fish catch has stagnated (or possibly declined) since the 1990s



Note: "Wild catch" includes finfish, mollusks, crustaceans, and other aquatic animals from marine and freshwater ecosystems. It excludes all aquaculture. It does not include catch reconstruction as in Pauly and Zeller (2016).

Source: FAO (2019b).

The Opportunity

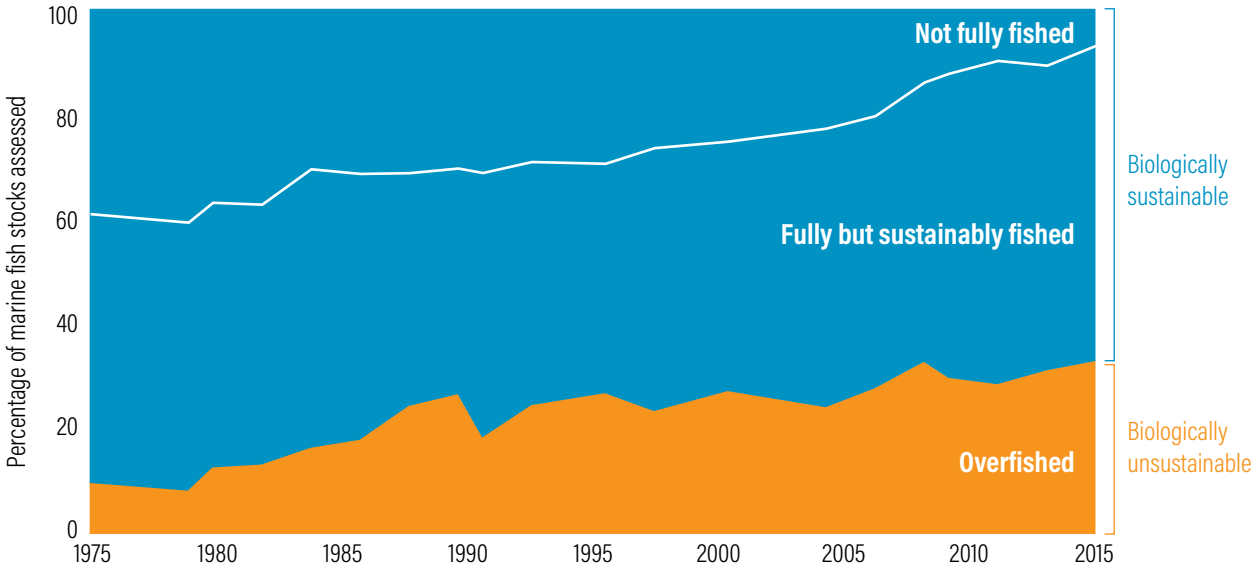
Reducing overfishing, which would prevent future declines and allow depleted stocks to recover, is the first important step toward a sustainable fish supply. The World Bank suggests that world fishing effort[12] needs to decline by 5 percent per year over a 10-year period, which would allow fisheries to rebuild to an ideal level over three decades.[13] Although this approach would likely reduce catches in the short term, it should lead to productive and sustainable wild fish catches over the long term—possibly 10 Mt above 2012 levels.[14] Another study has estimated that economically optimal global fisheries management could even lead to a sustainable annual fish catch 18 Mt above 2012 levels by 2050.[15]

Some recent experience supports this claim. Although fisheries in developed countries have also been overfished, fish stocks appear to be rebounding along the coasts of a few developed countries such as Australia, New Zealand, Norway, and the United States.[16]

The United States has made significant progress in reducing overfishing in recent decades. The Magnuson-Stevens Fishery Conservation and Management Act, signed in 1976 and strengthened through subsequent amendments, created a mandate to rebuild overfished stocks. Since 2000, 44 fish stocks have been rebuilt and, as of 2017, just 15 percent of U.S. stocks were overfished—the lowest percentage since assessments began.[17] Overall U.S. fish catch, which peaked around 6 Mt in the late 1980s and dropped to just over 4 Mt in 2009, seems to be stabilizing around 5 Mt.[18] Success has come about through a variety of measures, notably through strict enforcement of annual catch limits—including use of catch share programs—and monitoring of fish stock health.

In Kenya, a comanagement program between the Fisheries Department and traditional fisheries leaders led to a rebound of coastal coral reef fish populations and increased the profitability of fishing. Two management strategies—gear restriction (a ban on small-meshed beach seine nets, implemented between 2001 and 2004), and closing off areas of the sea from fishing (implemented between 2005 and 2009)—were responsible for these results. In areas where these management strategies were in place, catches per fisher per day rose by approximately 50 percent between 2000 and 2012, and fisher incomes

Figure 22-2 | The percentage of overfished stocks has risen over the past 40 years



Source: FAO (2018).

doubled during this period, all while maintaining overall catch levels. At landing sites near the Mombasa Marine National Park, a no-fishing area, the sizes of fish caught were higher (fetching higher prices). Catches also contained species of higher market value relative to the catches in areas farther from no-fishing areas.[19] These positive changes occurred even in the wake of the 1997–98 El Niño event that caused widespread loss of coral cover in the fishing grounds, suggesting that (at least during the study period) the improved fisheries management practices were able to counter the effects of disturbances from climate change.[20]

We project fish consumption to rise 58 percent between 2010 and 2050,[21] but the wild fish catch peaked at 94 Mt in the mid-1990s and has since stagnated or perhaps declined. For our 2050 baseline scenario, we assume a 10 percent decrease in global wild fish catch between 2010 and 2050 (an annual catch in 2050 that is 9 Mt below 2010 levels). This baseline assumes a continuation of business as usual, with some stocks rebuilding and others continuing to decline due to overfishing.[22] We also use GlobAgri-WRR to model an improvement scenario where wild fish catch—instead of declining between 2010 and 2050—stays constant at 2010 levels, a scenario where many, but not all, stocks have measures in place to stop overfishing and rebuild. The effect in GlobAgri-WRR of being able to harvest an additional 9 Mt of wild fish (relative to 2050 baseline) is to avoid the need for an additional 9 Mt of farmed fish, which reduces aquaculture's total land demand in 2050 by 5 million hectares (Mha), and closes the emissions gap by 0.6 percent (Table 22-1).[23]

Recommended Strategies

Strategies to curb overfishing and maintain harvests at sustainable levels are well documented in other studies.[24] They focus on several key principles:

- Limiting fish catch (including bycatch) to a level that allows the population to reproduce
- Limiting the number of fishers to an economically sustainable level
- Protecting habitat
- Avoiding harvest during important breeding times or in important breeding areas[25]

Tools to implement these strategies include establishing total allowable catches based on optimum sustainable yield, gear restrictions, seasonal limits, regulation or direct government management of key habitats, and closure of breeding areas.

Widespread implementation of these strategies is difficult for various reasons—listed below—most of which are political and socioeconomic and based on the fact that wild fish are a public resource that individual fishers have incentives to exploit before others can do so:[26]

Table 22-1 | Global effects of 2050 fisheries improvement scenario on the food gap, land use, and the GHG mitigation gap

SCENARIO	FOOD GAP, 2010–50 (%)	GHG MITIGATION GAP (GT CO_2E)	AQUACULTURE LAND USE (MILLION HA)		
			Ponds	Cropland for feed	Total
2010	N/A	N/A	19	27	46
2050 BASELINE	**56.5**	**11.1**	**40**	**52**	**92**
Stable wild fish catches between 2010 and 2050 *(Coordinated Effort, Highly Ambitious, Breakthrough Technologies)*	56.3	11.0	38	49	87

Source: GlobAgri-WRR model.

- Rebuilding a fishery or halting overfishing typically involves a decline in fishing activity and landings for some period of time. Consequently, fishers and others in the value chain can experience financial losses over the near to medium term. There is no compelling short-term economic reward for acting sustainably.
- There are economic winners and losers in efforts to rebuild stocks, and the potential losers often wield enough power to thwart reform and fishery restoration efforts.
- Many countries subsidize fishing in a variety of ways that lead to overfishing.[27] Recent studies estimate global annual fisheries subsidies at $35 billion—equivalent to one-third of the value of global fisheries production.[28] In total, the World Bank estimated that annual lost revenues from mismanagement of global fisheries was $83 billion in 2012.[29]
- Because of global power imbalances, foreign fleets from richer countries often are able to obtain "fishery access agreements" to fish in the waters of poorer countries with weaker laws and enforcement capacity.[30]
- Illegal, unregulated, and unreported fishing is a widespread problem, particularly in developing countries. Worldwide, losses from illegal fishing and unreported fishing have been estimated at $10 billion and $23.5 billion per year, respectively, representing an additional catch of between 11 Mt and 26 Mt that goes unmanaged.[31]
- Lack of data and lack of infrastructure and resources for monitoring and enforcement can be a barrier to active management.
- Fishing is often a livelihood of last resort in many poor coastal communities, and small-scale fishing continues to grow across the developing world. In addition, fishing has played an important cultural role in coastal areas for centuries. In the absence of alternative livelihoods, governments can be hesitant to curtail local fishing operations out of social concerns, even in depleted coastal waters.

In recent years, some developed countries have been able to overcome these challenges by limiting the number of fishers and using "catch shares." These systems establish shares of fish that may be taken and allocate them among individual fishers. These fishers therefore acquire a long-term stake in the health of the fishery, and can often trade their shares.

In the United States, progress in rebuilding fisheries has resulted in part from shifting to systems of "catch shares" that reduce the "race to fish."[32] Based on evidence from 39 commercial fisheries, researchers have credited these programs with making catch levels more predictable and stable, reducing the number of fishing boats, improving fishing crew safety, reducing bycatch, and promoting other favorable environmental and economic outcomes.[33] However, because catch share programs can facilitate industry consolidation and the marginalization of small-scale fishers,[34] governments will need to address the social consequences of this consolidation.

In developing countries where oversight, rule of law, and monitoring arrangements are weaker, additional approaches are needed. In these governance environments—as the Kenya example illustrates—community-based comanagement systems may prove more effective. Such systems combine territorial fishing rights and no-take reserves designed and supported by coastal fishing communities.[35]

All told, overcoming the barriers listed above requires a set of complementary strategies, adapted to suit specific circumstances.[36] For example, establishing resource rights and removing perverse subsidies can control access to fish resources at economically and biologically feasible levels. Adoption of sustainable procurement practices and certification systems by actors in fish supply chains could help create demand for sustainably sourced fish. Both these rights and markets strategies, in turn, could build support for governance reforms regarding fishing practices and marine spatial management. However, for these strategies to succeed, enabling conditions such as sound data and science, supply chain transparency, and law enforcement need to be in place.[37] Advocacy, public pressure, technical and financial support, and outreach to major players in fish supply chains can all help put these enabling conditions in place and advance these strategies.



CHAPTER 23

MENU ITEM: IMPROVE PRODUCTIVITY AND ENVIRONMENTAL PERFORMANCE OF AQUACULTURE

Despite stagnating or declining wild fish catches, world fish consumption has continued to increase as aquaculture has grown to meet global demand. This menu item involves increasing production of farmed fish relative to the amount of land, freshwater, feed, and energy used—while minimizing water pollution, fish diseases, and escapes.

The Challenge

The aquaculture (fish farming)[38] sector is diverse. Fish farming produces more than 300 species and occurs in nearly every country in the world.[39] Aquaculture is practiced in three different environments: In 2016, 63 percent of production was in freshwater (mostly in ponds on land), 28 percent in marine waters, and 9 percent in brackish water (coastal ponds).[40]

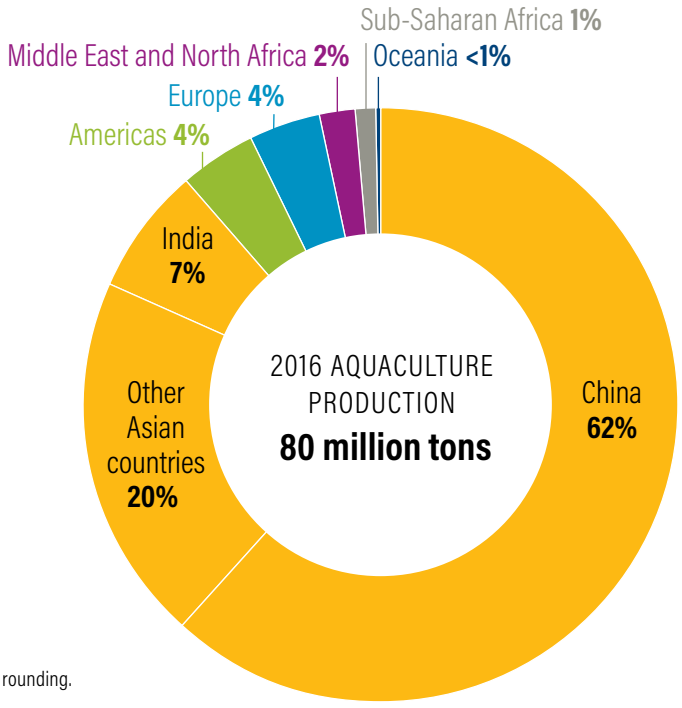
Between 2011 and 2016, aquaculture production rose in every world region.[41] In 2016, aquaculture provided more than half of all fish people consumed—80 Mt—making it one of the world's fastest-growing animal food-producing sectors.[42] Asia accounted for nearly 90 percent of global aquaculture production in 2016, and China alone accounted for more than 60 percent (Figure 23-1). In terms of percentage increase, sub-Saharan Africa had the fastest rate of growth—increasing production by nearly 50 percent between 2011 and 2016—but because its baseline was low, the region contributed less than 1 percent of global aquaculture production in 2016.

Because the wild fisheries catch peaked years ago, virtually all of the future increase in world fish consumption will need to come from aquaculture. If global per capita fish availability is to meet projected demand under our 2050 baseline scenario, where wild fish supply declines by 10 percent, we estimate that aquaculture production would need to more than double between 2010 and 2050, rising from 60 Mt in 2010 to roughly 140 Mt in 2050 (Figure 23-2). Meeting this demand presents environmental, production, and social challenges.[43]

Land-use change

In 2010, global aquaculture occupied an estimated 19 Mha of land—an area the size of Syria—including 13 Mha of inland (freshwater) areas and 6 Mha of coastal (brackish water) ponds. Aquaculture also indirectly used an additional 27 Mha that year—an area larger than the United Kingdom—to grow plant-based feeds.[44] In total, aquaculture occupied about 1 percent of global agricultural land,[45] and conversion of agricultural lands or natural ecosystems to aquaculture contributes to the overall competition for land.

Figure 23-1 | Nearly 90 percent of aquaculture production is in Asia



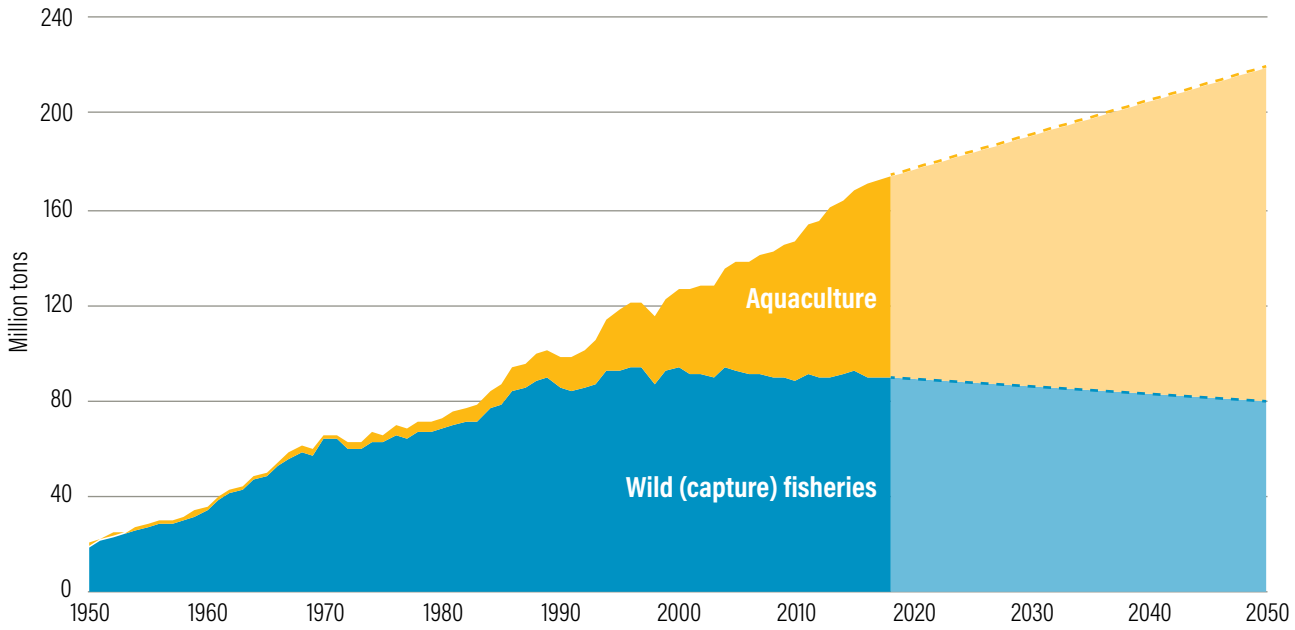
Note: Data may not sum to 100% due to rounding.
Source: FAO (2019b).

Aquaculture's impact on mangroves raises particular concerns. Mangroves are among the most productive ecosystems in the world, serving as nursery grounds for many fish and protecting coastlines. In the 1980s and 1990s, a largely unregulated boom in shrimp aquaculture led to clearing of significant areas of mangroves for aquaculture ponds.[46] Conversion of mangroves to aquaculture has slowed since 2000, thanks to improvements in shrimp-farming practices and mangrove protection policies.[47] Between 2000 and 2012, however, the world lost 192,000 hectares of mangroves, about 1 percent of total global mangrove cover,[48] with more than 100,000 hectares being lost in Southeast Asia alone. Richards and Freiss (2016) estimate that 30 percent of the mangrove losses in Southeast Asia in this period were due to aquaculture expansion (followed by clearing for rice [22 percent] and oil palm [16 percent]). Indonesia, in particular, witnessed major aquaculture expansion: of 60,000 hectares of mangroves lost, half were cleared for aquaculture.[49] It remains an ongoing challenge in some areas to reconcile plans for increasing aquaculture production with mangrove protection.[50]

Greenhouse gas emissions

In 2010, we estimate that aquaculture production was responsible for greenhouse gas (GHG) emissions of 332 million tons of carbon dioxide equivalent (Mt CO_2e)—less than 1 percent of total human emissions but 5 percent of emissions from agricultural production.[51] Aquaculture's emissions arise from on-farm energy use; feed production; transportation, processing, and packaging of produce; and disposal of wastes. Aquaculture's largest energy demands tend to occur during production of fish and feeds.[52] Untreated pond sediments can lead to methane emissions.[53] A further source of emissions is the conversion of land and coastal habitats for aquaculture development, both directly through conversion of carbon-rich ecosystems (such as mangroves, seagrass beds, and wetlands) and indirectly by displacing croplands.

Figure 23-2 | Aquaculture production must continue to grow to meet world fish demand



Source: Historical data 1950–2016: FAO (2019b) and FAO (2018). Projections to 2050: calculated at WRI; assume 10% reduction in wild fish catch from 2010 levels by 2050, linear growth of aquaculture production of 2 Mt per year between 2010 and 2050.

Additional environmental challenges

Aquaculture can trigger other environmental challenges, as well. First, the use of wild fish as feed ingredients can exacerbate pressure on marine ecosystems. The small, oily fish commonly harvested for aquaculture feed—such as anchovy—are near the bottom of the marine food chain. In 2016, 15 Mt of wild fish (or nearly one-fifth of the marine catch) was converted to fishmeal and fish oil, most of which was consumed by aquaculture.[54]

Another challenge is water pollution. Discharges can contain excess nutrients from fish feed and waste, antibiotic drugs, other chemicals (e.g., pesticides, hormones, antifoulants), and inorganic fertilizers. In comparison to terrestrial livestock production, it is difficult to collect wastes from aquaculture production because they are rapidly dispersed into the surrounding water.[55] Pollution associated with aquaculture can cause degradation of aquatic habitats and eutrophication of lakes or coastal zones, and can even directly threaten the aquaculture operation itself.[56]

A third challenge is infectious disease, which has devastated shrimp production in parts of Asia. Early Mortality Syndrome (first noted in 2009) presents ongoing threats to the shrimp sector. Parasites, such as sea lice, have caused problems for salmon production, for example in Chile and Norway.[57] Diseases and parasites can also be transferred from farmed to wild fish (and vice versa) in open production systems.[58]

Another concern is that farm-raised fish can escape, or be intentionally released, from aquaculture facilities and cause genetic contamination. Escaped fish can breed with, outcompete, or prey on native fish, altering ecosystem structure and composition.[59]

Finally, food safety worries exist, too. These include the excessive use of antimicrobial products at fish farms, which can spread antimicrobial resistance in human pathogens (e.g., *Salmonella*). Another is the potential for farmed fish to contain high levels of chemical contaminants, such as persistent organic pollutants, pesticides, and heavy metals, which could be harmful to consumers.[60]

Social concerns associated with aquaculture

Human nutrition. Farmed fish are generally as lean and protein-rich as chicken,[61] but one concern of aquaculture is that farmed fish as a whole tend to have lower levels of long-chain omega-3 fatty acids than wild fish.[62] Nutrient composition of fish depends on a number of factors including the species, whether the fish is wild or farmed, and the feeding methods.[63] If fish are to continue to meet this valuable nutritional need, they will require an enhanced, alternative supply of complex oils.

Availability and affordability of fish for human consumption. The use of wild fish for aquaculture feed is a complicated issue. On the one hand, it may reduce the amount of wild fish available for direct human consumption while it produces relatively large fish targeted at middle-class markets.[64] As the vast majority of the small fish harvested for feed is of food-grade quality, aquaculture could reduce fish access for the poor. On the other hand, there is limited market demand for direct consumption of these small fish.[65] Aquaculture can also benefit the poor if its output becomes cheap enough. For example, in Egypt and Bangladesh, strong recent growth of aquaculture production has pushed the prices of farmed fish below those of wild fish, making fish more broadly accessible to the poor.[66]

Input constraints and climate change

Land-use limitations are a key constraint on aquaculture growth. In Asia, for instance, little land is available for aquaculture (or any agricultural) expansion.[67] An important challenge will be for aquaculture to more than double production between 2010 and 2050 while minimizing land expansion.[68]

In 2010, aquaculture consumed an estimated 201 cubic kilometers (km^3) of freshwater, accounting for approximately 2 percent of global agricultural water consumption.[69] Freshwater inland aquaculture uses water to maintain pond levels, compensating for water lost through seepage, evaporation, and intentional discharge. More intensive systems use frequent water exchanges to aerate and filter ponds.

Production of plant-based fish feeds also consumes water.[70] However, freshwater is becoming increasingly scarce in many aquaculture-producing areas because of upstream dams and diversion of water for agriculture and urban uses.[71]

Feed could be another constraint. In 2016, at least 70 percent of aquaculture production used some form of feed, whether fresh feeds (e.g., crop wastes), feed mixed and processed on the farm, or commercially manufactured feed.[72] Carnivorous species[73]—such as salmon, shrimp, and many other marine finfish—tend to rely on wild-caught fish (in the form of fish meal and fish oil in commercially manufactured feeds) to receive adequate protein and lipids in their diets.[74] Conversely, roughly 80 percent of aquaculture production in 2014 consisted of omnivores, herbivores, and filter feeders that consume little to no fish-based ingredients.[75] Commercial feeds for omnivores and herbivores tend to contain cereals, oilseeds, and pulses, often in the form of meals and oils.[76] The fact that the supply of fish meal and fish oil from wild sources is already near its historical highs and ecological limits represents a clear constraint on aquaculture production growth, particularly of farmed carnivorous fish.[77] However, it will also be a challenge to ensure an adequate supply of plant-based proteins, oils, and carbohydrates for aquaculture feed as the sector grows, while minimizing the associated land and water-use impacts.[78]

Land, water, and feed are all likely to be adversely affected by climate change.[79] Farms in deltas and coastal and marine areas are most immediately exposed to flooding, sea level rise, and extreme weather events. Increases in water temperature will likely increase the occurrence of harmful algal blooms, which reduce water quality and can render farmed fish unfit for human consumption.[80] Ocean acidification also threatens the long-term viability of shellfish aquaculture.[81] At the same time, climate change may also open up new production opportunities in certain areas and make aquaculture an adaptation strategy. In colder regions, warmer temperatures may enable aquaculture, and in coastal land areas that become too saline for agriculture, aquaculture could become an important adaptation strategy (Chapter 15).[82]

The Opportunity

If annual aquaculture production were to increase from 60 Mt in 2010 to 140 Mt by 2050, as projected in our baseline food demand scenario, significant food security and development benefits could result. For example, this level of growth would boost annual fish protein supply to 19 Mt, or 6 Mt above 2010 levels.[83] Such an increase would meet 13 percent of the increase in global animal protein supply between 2010 and 2050 under our baseline scenario.[84] It would boost income and employment, particularly in developing countries, where most aquaculture growth will occur.[85] And the global value of farmed fish could increase from $120 billion in 2010 to $308 billion in 2050, with the number of people engaged in aquaculture for a living increasing from 100 million in 2010 to 176 million by midcentury.[86]

Even though aquaculture poses environmental challenges, it has potential advantages relative to most other animal-based foods. Because finfish live in an environment that supports their body weight, are cold-blooded, and excrete waste nitrogen directly as ammonia, they devote less energy to metabolism and bone structure than terrestrial animals.[87] As a result, most farmed species convert feed into edible meat quite efficiently. As discussed in Chapter 6 on shifting diets, farmed finfish are similar in feed conversion efficiency to poultry, and much more efficient than beef and sheep (Figure 6-5).[88] Filter-feeding carp and mollusks are even more efficient producers of animal protein, as they require no human-managed feeds and can improve water quality by removing excess microalgae and nutrient pollution from lakes and coastal waters.[89] Furthermore, expansion of marine aquaculture could help alleviate the land constraint relative to other animal-based foods and their associated emissions from land-use change.

Per ton of edible protein, aquaculture species require between 0 ha (mollusks) and 16 ha (shrimp) of land per year, which is less than pork and chicken (both around 20 ha per year) and far less than beef (140 ha per year) (Figure 6-6).[90] Aquaculture also produces lower GHG emissions than ruminant meats. Per ton of edible protein, farmed fish production emits around 30 tons of CO_2e per year, which is similar to emissions from pork and chicken production, and again far less than emissions from beef production (more than 200 tons of CO_2e per year). Another consideration is that, because the aquaculture sector is relatively young compared with terrestrial livestock sectors, there is great scope for technical innovation to further increase its resource efficiency.

Opportunities to sustainably intensify aquaculture production (Box 23-1), to reduce its environmental impacts, and to overcome basic production constraints exist in at least five interrelated areas:[91]

BOX 23-1 | Classifying aquaculture production systems by intensity

The aquaculture literature commonly classifies production systems by their level of intensity. Intensity of production runs along a spectrum from *extensive* (less than 1 ton of fish per hectare per year [t/ha/yr]) through *semi-intensive* (2–20 t/ha/yr) and *intensive* (20–200 t/ha/yr) farms.[a] Yields from intensive cage, raceway, or recirculating systems can be higher still.[b] In general, according to Hall et al. (2007), levels of intensity can be summarized as follows:

- *Extensive* production requires a low level of control, relies on natural productivity and crop wastes as feed, and has relatively low operating costs.
- *Semi-intensive* production uses fertilizers and farm-made feed to boost fish yields, which requires a higher level of management control and involves higher operating costs.
- *Intensive* production requires the highest degree of management control, relies completely on off-farm inputs (e.g., high-quality feed, seed, and fertilizers), and uses more energy, leading to high operating costs.

Sources:
a. Bunting (2013).
b. Dugan et al. (2007).

Breeding and genetics

To overcome land-use constraints, aquaculture needs to improve growth rates and conversion efficiencies. Fish bred for faster growth rates[92] could lead to more efficient use of land and sea area, water, feed, and labor.[93] Fortunately, there are large opportunities to breed more efficient fish, as aquaculture lags far behind crop and livestock agriculture in the use of selective breeding; in 2010, less than 10 percent of world aquaculture production was based on genetically improved stocks.[94] Because feed often accounts for 50 percent or more of all production costs, these efficiencies should also improve the economics of production.[95]

Of the approximately 100 large-scale aquaculture breeding programs in the world in 2010, more than half were focused on just three species: Atlantic salmon, rainbow trout, and Nile tilapia. Less than 10 percent focused on carp, which is by far the most abundant aquaculture species group.[96] Selective breeding efforts could be expanded, aimed at countries and species with the highest levels of production (e.g., Chinese carps), and at areas of current low productivity yet high need for aquaculture growth (e.g., sub-Saharan Africa). Selective breeding also could reduce disease problems, enable increased use of plant-based ingredients in feed, and lead to the eventual development of truly domesticated fish that do not survive or breed in the wild, lessening problems of escapes.

Fish oil alternatives and other feed improvements

Aquaculture continues to rely heavily on wild fish-derived fish meal and fish oil. However, since both are finite resources, the aquaculture industry cannot continue this reliance as it continues rapid growth into the future. The supply of fish meal and fish oil from wild sources is already at historical highs and is near ecological limits, which represents a clear constraint to aquaculture growth.[97] To continue its growth, the aquaculture industry will therefore need an alternative source of the key nutrients found in fish oil—omega-3 eicosapentaenoic acid (EPA), and docosahexaenoic acid (DHA) (Box 23-2). Both EPA and DHA omega-3 are required for optimal fish health and growth and are also important essential fatty acids for human nutrition.

Microalgae (the origin of omega-3 fatty acids in fish oil) can provide a viable substitute for wild fish-based ingredients and use much less land and water than is required for plant-based oil crops.[98] Another possible plant-based substitute for fish oil is genetically engineered yeasts or oilseed plants (e.g., rapeseed) that produce omega-3 fatty acids.[99] However, further investments in research and development will be necessary to bring costs of these replacement ingredients below fish oil prices. Continued research is also necessary to further improve understanding of optimal omega-3 fatty acid nutritional efficiency of all important aquaculture species, while also minimizing waste and production costs.

Disease control

Disease outbreaks continue to constrain aquaculture production, especially in more intensive systems. New technologies will be essential to lessen risks from disease and reduce the need for antibiotics.[100] Promising technologies include advanced diagnostics, vaccines, dietary supplements, and genetic improvements. Also helpful will be wider application of best management practices, such as reducing water exchange in ponds or tanks, reducing water seepage in ponds, improving feed and feeding practices, improving sanitation, and not stocking fish too densely in ponds or cages.

Water recirculation and other pollution control

Recirculating water used in aquaculture can save water and allow the producer greater control over water temperature, oxygen levels, and other aspects of water quality. As a result, conditions improve for the farmed fish, allowing for better growth, lower disease levels, more predictable harvests, and higher levels of intensity. However, recirculation also adds to operating costs and energy use (and production-related GHG emissions).[101] Water recirculation is not the only option for pollution control; other improved management practices, such as using settling ponds before releasing wastewater, can also reduce waste.

BOX 23-2 | Microalgae are a promising alternative to fish oil in aquaculture feeds

Fish and the fish-derived product, fish oil, currently represent the main dietary source of long-chain omega-3 fatty acids for human nutrition. Omega-3 fatty acids generally refer to three fats, namely alpha-linolenic acid (ALA), eicosapentaenoic acid (EPA), and docosahexaenoic acid (DHA). Of these, EPA and DHA are the long-chain omega-3s, which are naturally present in fish, marine algae, krill, and human milk. They are associated with key human health benefits. Daily intake of at least 250 mg of EPA and DHA has been shown to benefit eye, brain, and heart health.[a] However, there are currently no large-scale alternatives to fish oil that are rich in both EPA and DHA omega-3 fatty acids, meaning that fully replacing fish oil in aquaculture feed with other animal or plant-based oils would reduce the level of EPA and DHA omega-3 and therefore the nutritional benefit of farmed fish to the consumer.[b]

The omega-3 fatty acids EPA and DHA are naturally produced by algae in the natural marine food chain and gradually accumulated in larger fish. These larger fish are harvested for fish oil production, and fish oil therefore contains EPA and DHA omega-3 fatty acids. Fish oil alternatives are essentially based on utilizing the ability of microalgae to produce omega-3 fatty acids, either by direct production of microalgae or by transferring their biochemical capability (e.g., genes) to other organisms such as yeast or oilseed plants through genetic engineering. Although it remains to be seen which technologies ultimately prove to be economically viable, and socially acceptable, at large scale, it appears that several fish oil alternatives will be available on the market within the next few years.

One example of a promising fish oil alternative is an algal strain of *Schizochytrium sp.* that naturally produces both EPA and DHA omega-3 through fermentation. Using sugar as an energy source, the algae cells grow, multiply, and convert sugar into the omega-3 fatty acids EPA and DHA. A refining process then produces an algal oil rich in both EPA and DHA that can substitute for fish oil—as well as a by-product that can be used for animal feed or bioenergy. Evonik and DSM have founded a joint venture, Veramaris®, to commercialize this technology, which they say will be on the market in 2019 and initially able to meet 15 percent of the salmon aquaculture industry's demand for EPA and DHA.[c]

Sources:
a. Zhang et al. (2018).
b. Sprague et al. (2016).
c. Van der Hoeven (2018); Veramaris (2018).

Expansion of marine-based systems

Offshore marine aquaculture, which would avoid additional land-use change as well as problems of competition for space in coastal areas by locating farms in the open sea, is still in its infancy.[102] One recent study found that the global physical potential for expanding marine aquaculture is vast—that marine aquaculture could fully supply farmed fish demand by 2050 even if only 1 percent of the suitable area in each coastal country were developed. However, the study did not assess important economic or biodiversity-related constraints to expansion of marine-based systems, suggesting that the true growth potential was still significant, but lower than the pure physical potential.[103]

To better understand the efficacy of various strategies to meet these challenges while boosting aquaculture production to 140 Mt by 2050, we use GlobAgri-WRR to build on lifecycle assessments performed by WorldFish and Kasetsart University. These assessments are reported in more detail in Mungkung et al. (2014) and Waite et al. (2014).[104] The analysis divides world aquaculture into 75 major production systems, which accounted for more than 80 percent of total world aquaculture production in 2010. We integrated this analysis into the GlobAgri-WRR model and used the model to explore a 2050 baseline and three additional aquaculture production scenarios with the following characteristics:

- **Baseline**. Aquaculture production rises to 140 Mt in 2050. Proportions of fish species cultivated and production systems used (e.g., composition of feeds, intensity level of production) remain unchanged between 2010 and 2050. But increasing resource scarcity leads to market conditions that cause farmers to improve their production efficiency so that they produce each kg of fish with 10 percent less use of all major inputs (e.g., water, feed, energy, fertilizers).
- **Doubling efficiency gains** (Coordinated Effort scenario). Between 2010 and 2050, farmers improve production efficiency by 20 percent instead of 10 percent thanks to further improvements in fish breeding, feeds, and disease and pollution control.
- **Accelerated intensification on land** (Highly Ambitious scenario). Freshwater pond farming—the current dominant production system around the world—becomes significantly more intensive as farmers invest in the technologies described in the preceding

Table 23-1 | Global effects of 2050 aquaculture improvement scenarios on the food gap, land use, and the GHG mitigation gap

SCENARIO	FOOD GAP, 2010–50 (%)	GHG MITIGATION GAP (GT CO_2E)	AQUACULTURAL LAND USE (MILLION HA)		
			Ponds	Cropland for feed	Total
2010	N/A	N/A	19	27	46
2050 BASELINE	**56.5**	**11.1**	**40**	**52**	**92**
Doubling efficiency gains (from 10% to 20% between 2010 and 2050) *(Coordinated Effort)*	56.3	11.0	36	49	85
Accelerated intensification on land *(Highly Ambitious)*	57.0	11.1	27	60	87
Doubling efficiency gains plus accelerated intensification on land *(Breakthrough Technologies)*	56.7	11.0	24	56	80

Source: GlobAgri-WRR model.

section. Fifty percent of all farms classified as "extensive" (Box 23-1) in 2010 shift to "semi-intensive" by 2050, and 50 percent of "semi-intensive" farms in 2010 shift to "intensive" by 2050.

- **Doubling efficiency gains plus accelerated intensification on land** (Breakthrough Technologies scenario). This scenario is a combination of the two previous scenarios.

Table 23-1 shows the results from these scenarios. Under the 2050 baseline scenario, land under aquaculture ponds doubles between 2010 and 2050 and cropland for aquaculture feeds also doubles because there is no additional potential to provide more feed from wild fish.

Doubling the increase in production efficiency from 10 percent (under baseline) to 20 percent reduces total land demand by 7 Mha relative to the baseline scenario, closing the food gap by 0.4 percent and the GHG emissions gap by 0.8 percent.

The scenario of accelerated intensification on land leads to a trade-off among two types of land use. The switch to more intensive production systems by 2050 leads to a savings in 13 Mha of land under aquaculture ponds relative to baseline. However, since more intensive production systems tend to require more feeds—and we required all additional feeds to be crop-based rather than wild-fish-based—the land savings from the reduced pond area are offset by an 8 Mha increase in cropland used to produce aquaculture feeds. This surprising result suggests that extensive ponds are essentially functioning both as homes for the fish and as producers of algae for feed. GlobAgri-WRR also estimated that overall emissions (even with the reduced land overall relative to baseline) would actually *increase* by 19 Mt per year, due to the higher energy use in intensive ponds.

The third scenario, which combines the doubled efficiency with the accelerated intensification on land, eases the trade-offs from the intensification-only scenario. Under this third scenario, cropland use rises by only 4 Mha relative to baseline (instead of 8 Mha in the intensification-only scenario), while



the use of land for ponds falls by 16 Mha relative to baseline (instead of 13 Mha in the intensification-only scenario). Overall, emissions would decrease by 66 Mt per year relative to baseline, as the avoided land-use change offsets the higher energy use in intensive ponds.

Overall, we favor shifts toward more intensive ponds in part because land "saved" overall from pond expansion is likely to be more carbon-rich than the additional land required for feed crop expansion. This is because ponds must generally use wet, flatter lands. In addition, potential exists to reduce the land-use demands for feed either by further increasing crop yields or by further accelerating efficiency gains (e.g., breeding fish to convert feed to flesh more efficiently or to grow faster and therefore increase output per hectare of pond). Connecting intensive ponds to renewable sources of energy could reduce production emissions from intensive aquaculture.

This analysis, and the broader life cycle assessment done by Mungkung et al. (2014) that examined additional aquaculture growth scenarios and other environmental factors, including water use and pollution, illustrate a real challenge. Under a projected doubling in global aquaculture production between 2010 and 2050, it will be hard enough to hold aquaculture's environmental impacts to 2010 levels, let alone reduce them. Mungkung et al. (2014) also showed that intensification, while reducing aquaculture's freshwater demand, would lead to a rise in water pollution unless accompanied by further technological advances. A deeper analysis of the trade-offs under scenarios of aquaculture growth, with more detailed data, is needed to provide insights at finer scales (e.g., national level). For example, Phillips et al. (2015) analyzed scenarios of Indonesian aquaculture growth to the year 2030. Their analysis underscored the challenges of meeting projected fish demand while safeguarding high-conservation-value ecosystems such as mangroves and wetlands, limiting freshwater use, and finding alternatives to wild-fish-based feed ingredients.

Recommended Strategies

If aquaculture is to more than double production, sustainably, between 2010 and 2050, the sector must increase its natural resource efficiency and reduce other environmental impacts, including fish diseases and escapes. Several strategies are necessary to realize this potential.

Increase investment in technological innovation and transfer

Technological advances by scientists, researchers, and innovative farmers—and widespread uptake of improved technologies—will be necessary to address the various land and feed constraints and to fully exploit the opportunities for aquaculture to grow efficiently and with minimal environmental impacts, as demonstrated by the salmon farming industry in Norway (Box 23-3). These advances could also help aquaculture adapt to a changing climate.[105] While numerous initiatives are directed at technological innovation and transfer, their present scale is insufficient to achieve the necessary change by 2050. Because most aquaculture occurs in



developing countries, where production growth in coming decades is expected to be highest, initiatives should focus on helping small- and medium-scale producers in developing countries access and adopt improved technologies.[106] In India, for example, small-scale shrimp farmers organized into "societies" that enabled them to access new technologies, services, and markets that otherwise might have been limited to large-scale farmers.[107]

National governments, development agencies, the aquaculture industry, international organizations, nongovernmental organizations (NGOs), private foundations, and farmers all have a role to play. Because public budgetary resources are limited, innovative financing arrangements with the private sector, such as private equity investment, will be needed.[108]

Use spatial planning to optimize aquaculture siting

Much of aquaculture growth to this point has been "organic" or "opportunistic" and led by a dynamic private sector.[109] Resource and economic constraints, the potential for increased conflicts between resource users, and the need to boost production significantly in a short time mean that the locations of future aquaculture systems must be chosen more strategically.

Spatial planning and zoning include processes and tools such as land-use planning, water-use planning, ecosystem modeling, marine spatial planning, integrated coastal zone management, and integrated watershed management. These approaches can lessen the conflicts between a growing aquaculture industry and other economic actors competing for the same resources, such as land, especially if done in a participatory way. Planning focused at the landscape and seascape level can also reduce cumulative impacts caused by many farmers operating in the same area and help minimize risks associated with climate change. In Norway, for example, zoning laws ensure that salmon producers are not overly concentrated in one area, reducing disease risk and helping mitigate environmental impacts.

BOX 23-3 | Sustainability gains in Norway's salmon farming industry

Norway, the world leader in salmon (*Salmo salar*) production, has made dramatic sustainability gains over the past 30 years. The share of fishmeal and fish oil in salmon diets has been reduced by about two-thirds between 1990 and 2013, antibiotic use virtually eliminated, and fish escapes reduced from nearly 1 million in 2006 to roughly 143,000 in 2018.[a] Meanwhile, salmon production has grown from about 150,000 tons in 1990 to 1.2 million tons in 2016.[b]

Technological improvements, stimulated by high levels of public and private investment in research and development, have been at the core of these improvements in productivity and environmental performance. Development of vaccines and disease control methods has greatly reduced the need for antibiotics.[c] Selective breeding and improved feeds have both led to greater production efficiency and reduced the reliance on wild fish for feed.[d] Industry consolidation and vertical integration has enabled companies to invest heavily in research and development, increasing production efficiency and driving down production costs. And public policies—including permitting, spatial planning and monitoring systems, as well as establishing protected areas for wild salmon—have helped stimulate and support these improvements.[e]

In the last few years, salmon farming has encountered an enhanced problem from sea lice, a parasite that thrives in confined salmon pens, kills or makes unmarketable large numbers of fish, and spreads to wild salmon, possibly reducing their numbers greatly. The lice problem has become sufficiently large that farmed salmon production fell between 2015–16, both in Norway and globally.[f] Overall, parasites and disease present some of the biggest threats to continued aquaculture expansion.

Sources:
a. Ytrestøyl et al. (2015); Taranger et al. (2014); WHO (2015); Directorate of Fisheries (2019).
b. FAO (2019b).
c. WHO (2015).
d. Ytrestøyl et al. (2015).
e. Torgersen et al. (2010).
f. Castle (2017).



Spatial planning and zoning can also prevent aquaculture development in high-conservation-value areas, such as mangroves (as in Thailand) or wild salmon areas (as in Norway), and protect upstream areas essential to maintaining coastal water quality (as in the United States).

More national and subnational governments need to establish legal frameworks for spatial planning and zoning for aquaculture, create aquaculture development plans that link to wider development plans, and invest in monitoring and enforcement to ensure plan implementation. A number of initiatives are already in place that promote participation in aquaculture planning and take landscape- and seascape-level concerns into account,[110] but additional effort is necessary.

Introduce policies to reward sustainable intensification

Complementary policies, namely regulations, standards, taxes, subsidies, and market-based mechanisms, can encourage sustainable intensification. For example, in Thailand, the government has provided shrimp farmers operating legally in aquaculture zones with access to free training, water supply, and wastewater treatment. The Thai government has also provided low-interest loans and tax exemptions to small-scale farmers, helping them adopt improved technology that increased productivity, reducing pressure to clear new land.[111] Similar policies have helped stimulate the growth and intensification of the catfish industry in Vietnam (Box 23-4). And in Denmark, stringent wastewater standards have encouraged investment in recirculating aquaculture systems.[112]

Establish aquaculture monitoring systems

Advances in satellite technology, digital mapping, ecological modeling, open data, and connectivity mean that global-level aquaculture monitoring and planning systems may now be possible. A global-scale platform that integrates these technologies and builds on existing information-sharing efforts could help companies, governments, and civil society encourage and support sustainability in the aquaculture sector. Such a platform could combine national- or global-level map layers (e.g., on farm locations, land use and type, water quality, weather), georeferenced data (e.g., on fish

production and value, fish trade, environmental performance), and bottom-up crowdsourcing of information (e.g., photos or stories to report successes, best practices, or areas of concern). Many different users could benefit from information technologies:

- Fish buyers could ensure that their purchases are from responsible suppliers, and producers and suppliers could use objective data to demonstrate that their operations are sustainable.
- Producers could access market information, as well as early warnings about water quality issues, disease outbreaks, and risks associated with natural disasters.
- Producers could communicate success stories, access technical guidance, and network with other producers and technical assistance agencies to improve operations.
- Governments could use data on current facility locations and environmental and social factors to improve spatial planning, detect illegally sited operations, and target monitoring and law enforcement efforts.
- NGOs and communities could report stories of improvements in productivity and social and environmental performance that could inspire actors in other areas. Conversely, they could monitor aquaculture operations in their area and raise an alarm if laws are being broken or resources are threatened.

A globally applicable monitoring and planning system could also help concerned citizens everywhere learn more about this dynamic, rapidly growing food production sector, helping to ease often polarized debates around aquaculture and build coalitions in favor of sustainable aquaculture growth.

For more detail about this menu item, see "Improving Productivity and Environmental Performance of Aquaculture," a working paper supporting this World Resources Report available at www.SustainableFoodFuture.org.

BOX 23-4 | Technology and government support drive intensification of catfish farming in Vietnam

In Vietnam's upper Mekong Delta region, striped catfish (*Pangasius hypophthalmus*) production grew 20-fold between 2000 and 2010, while catfish farming areas only roughly doubled, indicating a very rapid period of intensification. Catfish exports brought in $1.4 billion in foreign exchange in 2010.[a] This rapid production increase has led to the development of other sectors along the value chain, including hatchery production, fillet processing, and feed production. The catfish boom during the first decade of the 21st century created nearly 180,000 new jobs in the Mekong Delta, the majority of which are performed by rural women in the processing sector.[b] A recent life cycle analysis noted that pollution from catfish ponds was equal to or less than that of other food production sectors in the Mekong Delta, and that water quality had not degraded to a point where it threatened the viability of aquaculture production or compromised other downstream water uses.[c]

Technological improvements—including a breakthrough in artificial propagation of striped catfish in hatcheries around the year 2000, adoption of higher-quality pelleted feed, and improvements in pond farming techniques—combined to trigger the boom in catfish production. Supportive government policies, including research and extension programs, subsidized bank loans for producers and processors, and trade liberalization and promotion, have also helped to grow and support this export-oriented industry, and allow it to provide an affordable "white fish" substitute in Europe and the United States.[d]

Going forward, the biggest short-term risk to the industry's sustainability is the continued economic viability of farm operations if production costs (e.g., feed) rise. Protectionism in importing countries also poses a threat; wild fishing and aquaculture sectors in the United States and Europe have lobbied during the past 15 years to restrict imports of Vietnamese catfish.[e] In addition, the Vietnamese catfish industry will also need to secure sustainable supplies of feed and water, while continuing to limit disease outbreaks.[f]

Sources:
a. De Silva and Phuong (2011).
b. De Silva and Phuong (2011).
c. Bosma et al. (2009).
d. Phuong and Oanh (2010).
e. Little et al. (2012).
f. Phuong and Oanh (2010).

ENDNOTES

1. Throughout this report, "fish" refers to both finfish and shellfish. More precise definitions of these terms, and others used throughout this report, include *finfish*—a cold-blooded animal that lives in water, breathes with gills, and has fins and scales; *shellfish*—refers to both crustaceans and mollusks; *crustacean*—an animal belonging to the phylum Arthropoda that (usually) lives in water, has several pairs of legs, a body made up of sections, and is covered in a hard outer shell; *shrimp*—a decapod crustacean of the suborder Natantia; and *mollusk*—an animal belonging to the phylum Mollusca that has a soft unsegmented body without a backbone and usually lives in a shell (FAO 2008).

2. Authors' calculations from FAO (2019a). In 2015, fish provided roughly 3.2 billion people with 20% of their animal protein intake (FAO 2018).

3. Authors' calculations from FAO (2019a). In 2013, 77% of the human food supply of fish was located outside of North America, Europe, Oceania, and other OECD countries, suggesting a similar percentage of world fish consumption in developing countries.

4. Allison (2011).

5. Many figures in this report are based on statistics from the FAO FishStat global database of wild fisheries and aquaculture production (FAO 2019b) and the FAO's *State of World Fisheries and Aquaculture* (FAO 2018). However, the FAO fisheries and aquaculture production data rely on reports of member countries, and the quality of the data varies by country and may be subject to reporting bias. Many member countries have been found to misreport fisheries landings, catch levels may be underreported as discussed in note 9, and collection of aquaculture data remains relatively new. See Kura et al. (2004) (Annex B); Campbell and Pauly (2013); CEA (2012); and Pauly and Zeller (2016) for further discussion of FAO fisheries and aquaculture data, limitations, and caveats.

6. FAO (2018).

7. FAO (2019b). While the FAO capture fisheries data show a decline in marine fish catch since the 1990s, the data also show that the inland fish catch is still slightly rising. As with marine fisheries, inland fisheries are important to human protein consumption, especially for the poor. However, the slight increase in inland fish catch in the FAO data is probably a result of better reporting of actual catches rather than an increase in the amount of fish landed, and many believe that inland fisheries are in decline as well because of overfishing and aquatic ecosystem degradation (Welcomme 2011).

8. Pauly and Zeller (2016) cited underestimates in the FAO FishStat data around small-scale (both commercial and subsistence) fisheries, recreational fisheries, discarded bycatch, and illegal or otherwise unreported catch—and estimated the extent of these missing components to "reconstruct" true levels of marine fish catches.

9. FAO (2018). Data are from periodic FAO fish stock assessments. According to FAO (2018), *overfished* stocks produce lower yields than their biological and ecological potential, *maximally sustainably fished* stocks produce catches that are very near their maximum sustainable production, and *underfished* stocks are under relatively low fishing pressure and have some potential to increase their production.

10. Watson and Tidd (2018).

11. Cheung et al. (2010, 2013).

12. As defined by the World Bank (2017d), fishing effort is a composite indicator of "the size and efficiency of the global fleet, usually measured in terms of the number of vessels, vessel tonnage, engine power, vessel length, gear, fishing methods, and technical efficiency."

13. World Bank (2017d).

14. World Bank (2017d).

15. Costello et al. (2016).

16. Examples summarized in CEA (2012); and Worm et al. (2009).

17. NOAA (2018).

18. FAO (2019b).

19. McClanahan and Abunge (2014); McClanahan (2010); McClanahan et al. (2008).

20. McClanahan and Abunge (2014).

21. Authors' calculations, assuming a 12% increase in per capita consumption between 2010 and 2050 due to growth in income and urbanization. This projection corresponds well to recent trends; fish demand and supply would match if wild fish supply were to fall by 10% between 2010 and 2050 and aquaculture supply were to continue to expand at its recent rate of ~2 Mt per year during that period.

22. This 10% decline to 2050 is also in line with the "business as usual" fisheries management scenario in Costello et al. (2016) (Table S15).

23. GlobAgri-WRR model.

24. See, for example, Worm et al. (2009); CEA (2012); Melnychuk et al. (2016); and World Bank (2017d).

25. CEA (2012).

26. The following observations about these six factors are based on and more thoroughly examined in CEA (2012).

27. World Bank (2017d).

28. Sumaila et al. (2010, 2012, 2016).

29. World Bank (2017d).

30. Worm et al. (2009).

31. Agnew et al. (2009). Some recent estimates of fish catch underreporting are even higher; Pauly and Zeller (2016) estimated that true marine fish catches could be 53% higher than those reported in FAO (2019b).

32. Birkenbach et al. (2017).

33. Grimm et al. (2012); Essington (2010); Brinson and Thunberg (2013); Birkenbach et al. (2017).

34. Spalding (2013); Costello et al. (2008). Although individual transferable quota (ITQ) programs have reduced fishing effort and improved the economic efficiency of the fishing industry, these programs also have disadvantages (the following examples are summarized in Kura et al. 2004). As with other forms of catch limits, it can be difficult to determine the optimal sustainable yield level of a given fishery, leading to continued overexploitation. ITQs can give fishers incentive to discard smaller or lower-priced fish back into the sea to avoid counting these fish against the quota, again leading to continued overexploitation. There are also social and equity issues associated with ITQs. ITQs reduce the number of fishers and vessels in a fishery, leading to increased unemployment and vulnerability in fishing-dependent communities in the short term. ITQs often encourage consolidation within a fishery, and as quota prices increase these programs may become monopolized by larger, better-funded fishing companies at the expense of more vulnerable small-scale fishers. The design of ITQ programs, like the overall regulation of fisheries, must be sensitive to the socioeconomic factors facing fisher communities, which vary considerably among countries.

35. CEA (2012).

36. The following observations are based on and more thoroughly examined in CEA (2012).

37. Melnychuk et al. (2016).

38. Aquaculture is commonly defined as the farming of aquatic organisms, which include both animals and plants (FAO 2008). Because the focus of this report is on aquaculture's potential to contribute to fish supplies, all data on aquaculture production omit production of aquatic plants (seaweeds). For the rest of the report, *aquaculture* is used to mean "the farming of aquatic animals."

39. FAO (2019b).

40. FAO (2019b).

41. This paragraph contains authors' calculations from FAO (2019b).

42. FAO (2018). Aquaculture is the fastest-growing animal production sector when measured by annual percentage rate of growth. By absolute annual amount of growth, aquaculture, poultry, and pork production have all grown at roughly 2–2.5 Mt per year since 1990, although aquaculture's growth since 2010 has been even faster at roughly 3.5 Mt per year.

43. The discussion below, unless otherwise cited, is from Tacon et al. (2010); Kura et al. (2004); Costa-Pierce et al. (2012); and Bunting (2013). Note also that aquaculture can have sometimes positive ecosystem effects; for example, providing seed for restocking of overexploited fish populations, or by providing wastes that can be used to fertilize terrestrial crops (Soto et al. 2008, 16).

44. Authors' calculations from GlobAgri-WRR model and Mungkung et al. (2014) (unpublished data). Assumes the following: all bivalves and coastal cage/pen aquaculture (e.g., of salmonids) occupied marine area and thus no land; everything classified as "coastal ponds" occupied brackish water area; everything else occupied freshwater area.

45. Authors' calculations. According to the GlobAgri-WRR model, total agricultural land was 4,785 Mha in 2010.

46. Lewis et al. (2002).

47. Lebel et al. (2016).

48. Strong and Minnemeyer (2015).

49. Richards and Freiss (2016).

50. See Phillips et al. (2015) for an example from Indonesia.

51. Mungkung et al. (2014). Figures do not include emissions from land-use change associated with aquaculture or agriculture.

52. Hall et al. (2011b).

53. Bunting and Pretty (2007).

54. FAO (2018).

55. Bouwman et al. (2013).

56. Kura et al. (2004).

57. Castle (2017); Bravo (2003).

58. Cooke (2018). Looking beyond issues of disease, some groups have raised concerns about the welfare of farmed fish—especially those raised in intensive systems. These groups make the case that fish are sentient beings and self-aware organisms, capable of feeling pain and stress. Intensive aquaculture systems raise concern about the well-being of fish as they undergo and experience stressful situations and conditions.These concerns are similar to animal welfare concerns related to intensive livestock farming, including overcrowding, feeding and handling, transport, and stunning and slaughter methods.

59. Lorenzen et al. (2012).

60. Hine et al. (2012).

61. USDA (2013a).

62. Beveridge and Brummett (2013).

63. Beveridge and Brummett (2013).

64. Cai et al. (2012).

65. Cashion et al. (2017).

66. Beveridge and Brummett (2013); Belton et al. (2012); Hernandez et al. (2017).

67. FAO (2007).

68. Croplands that have become too saline for rice cultivation are an example of such lands with low economic and environmental value.

69. Authors' calculations. Aquaculture water consumption given in Mungkung et al. (2014), global agricultural water consumption of 8,363 km^3 per year (not counting aquaculture) given in Mekonnen and Hoekstra (2012).

70. Beveridge and Brummett (2013).

71. Costa-Pierce et al. (2012).

72. FAO (2018). As a low-bound estimate, "fed aquaculture production" consisted of at least 56 Mt of fish (out of 80 Mt of total aquaculture production in 2014, excluding seaweeds). This estimate excludes filter-feeding fish species (silver carp and bighead carp), freshwater fish production not reported down to the species level, and bivalve mollusks. Because even filter-feeding carp can be fed formulated feeds, the true amount of "fed aquaculture production" is likely higher than 70% of all production (Tacon et al. 2011).

73. Although the terms *carnivore*, *omnivore,* and *herbivore* are commonly used when describing the feeding habits of a fish species, it is more scientifically and etymologically correct to use the trophic level, which is an indication of how high a species sits in the aquatic food chain. For example, the "carnivorous" Atlantic salmon has a trophic level of 4.43, while the "herbivorous" common carp has a trophic level of 2.96 (Tacon et al. 2010). Farmed fish species have varying digestive and metabolic capacities to deal with different feed resources; for example, a high-trophic level "carnivore" requires a relatively high level of protein in its feed (Tacon et al. 2010). However, distinctions between "carnivores" and other groups can be misleading in aquaculture, because fish diets can be altered. For example, although the average salmon diet in 2008 contained 25% fishmeal and 14% fish oil (Tacon et al. 2011), it is technically possible to feed an Atlantic salmon using no fish-based ingredients at all. Still, in this section, we follow common usage to use the term *carnivores* to refer to salmonids, shrimp, and most marine finfish, and *omnivores/herbivores* to refer to other fed fish species.

74. Tacon et al. (2011).

75. Authors' calculations from FAO (2019b).

76. Tacon et al. (2011).

77. Naylor et al. (2009).

78. Tacon et al. (2011).

79. De Silva and Soto (2009).

80. De Silva and Soto (2009).

81. Watson et al. (2012).

82. De Silva and Soto (2009).

83. Authors' calculations based on an assumption of the same ratio of fish protein weight to total fish weight in 2050 as in 2010 (implying the same mix of fish species).

84. Authors' calculations.

85. See Hall et al. (2011b) for a discussion predicting the geographic distribution of aquaculture growth to 2030.

86. Authors' calculations:

    Global value of farmed fish. Here, we assume that between 2010 and 2050, real prices of fish rise on average by 10%. The World Bank, FAO, and IFPRI (2013) project that real prices of all farmed fish will rise between 2010 and 2030, by 5 to 10% depending on the species. We therefore believe that a global real price increase of 10% by 2050 is reasonable.

    Livelihoods from aquaculture. Here, we assume that between 2010 and 2050, average family sizes will remain constant, and that aquaculture labor productivity will continue to grow at its 2000–10 historical rate. FAO data show that between 2000 and 2010, world aquaculture production grew by 82%, while aquaculture employment grew by only 47% (FAO 2014a, 2014b). A similar trajectory between 2010 and 2050—where the aquaculture employment growth rate is only 57% of the aquaculture production growth rate—would lead to the industry providing livelihoods for 176 million people by 2050.

87. Costa-Pierce et al. (2012).

88. Costa-Pierce et al. (2012). However, while the feed efficiency figures in Figure 7-4 count grass consumed by terrestrial animals, they do not count plankton and other organic (nonfeed) matter consumed by fish, as data on volume of aquatic organic matter consumed by fish are sparse. Fry et al. (2018) come to a similar conclusion on the relative conversion efficiency of aquaculture and terrestrial livestock, while also noting that farmed fish and shrimp require higher levels of protein and calories in feed compared to chickens, pigs, and cattle.

89. Hall et al. (2011b). However, in order to provide food that is safe for consumers, filter-feeders must be raised in high-quality waters. And although coastal waters tend to have more than abundant nutrients, there are often many competing uses of these areas (analogous to competition for agricultural land), limiting scope for expansion of aquaculture.

90. GlobAgri-WRR model; Waite et al. (2014).

91. Volpe et al. (2010); Asche (2008).

92. This section focuses on "conventional" selective breeding (as opposed to genetic modification).

93. Gjedrem et al. (2012).

94. Gjedrem et al. (2012). Nearly all Atlantic salmon production is based on genetically improved stock, but the rates of use of improved stock for production of other species is much lower.

95. Garnett and Wilkes (2014).

96. Gjedrem et al. (2012).

97. Naylor et al. (2009).

98. Smith et al. (2010); Taelman et al. (2013). Table 4 in Taelman et al. (2013), which displays the results of a lifecycle assessment comparing algae-based feeds to conventional aquaculture feed, shows that algae-based feeds reduced land use demands by 90% and water use by 67% relative to the conventional feed. GHG emissions for the algae-based feed were 40% higher than those of the conventional feed, but this increase may be offset by the reduced land-use requirement (and avoided emissions from land-use change).

99. Ruiz-Lopez et al. (2014).

100. Browdy et al. (2012).

101. Bregnballe (2015).

102. Kapetsky et al. (2013).

103. Gentry et al. (2017) found that if all suitable marine areas were developed for aquaculture, approximately 15 billion tons of finfish could be grown annually—more than 100 times our projection of aquaculture demand in 2050 (140 million tons). However, the study did not filter out areas that would be uneconomic due to distance from ports, access to markets, or shoreside infrastructure—as well as environmentally sensitive areas such as coral reefs—which would limit suitable areas.

104. WorldFish's *Blue Frontiers* report (Hall et al. 2011b) used the life cycle assessment (LCA) method to examine, quantify, and compare the environmental performance of major aquaculture production systems around the world. The LCA compiled data on inputs (e.g., land, water, feed, and energy) and environmental releases (e.g., waste nitrogen and phosphorus), and evaluated the potential environmental impacts associated with each. *Blue Frontiers* analyzed environmental impacts of 75 major aquaculture production systems that accounted for 82% of total world aquaculture production in 2008. For this World Resources Report, WorldFish and Kasetsart University updated the *Blue Frontiers* data to assess the environmental performance of aquaculture in 2010 and developed a baseline production scenario for 2050 and several alternative scenarios. Environmental impacts associated with each of the 75 major production systems, in each of the scenarios, were modeled using the LCA. As in *Blue Frontiers*, the scope of analysis was from cradle to farmgate, covering raw material production (crops, fishmeal, and fish oil), feed production, aquaculture production (farming), and water emissions (nitrogen and phosphorus). The LCA did not cover infrastructure, seed production, land-use change, packaging and processing of produce, transport of feed and produce, or waste disposal. See Mungkung et al. (2014) for more details.

105. De Silva and Soto (2009).

106. Brummett et al. (2008).

107. Umesh et al. (2010).

108. Fort (2013).

109. See, for example, Hernandez et al. (2017) on the growth of aquaculture in Bangladesh just over the past decade.

110. Global examples include the FAO/World Bank Ecosystem Approach to Aquaculture; the Assessment of Sustainable Development of Aquaculture (EVAD) initiative, led by the French National Research Agency; and the Global Aquaculture Alliance initiative on best aquaculture practices for zone management. Regional initiatives include the FAO, Asia-Pacific Fishery Commission (APFIC), and Network of Aquaculture Centres in Asia-Pacific (NACA) initiative on Sustainable Intensification of Aquaculture in Asia-Pacific; the New Partnership for Africa's Development (NEPAD) Action Plan for Development of African Fisheries and Aquaculture; and the European Aquaculture Technology and Innovation Platform.

111. See Waite et al. (2014).

112. Heldbo and Klee (2014).

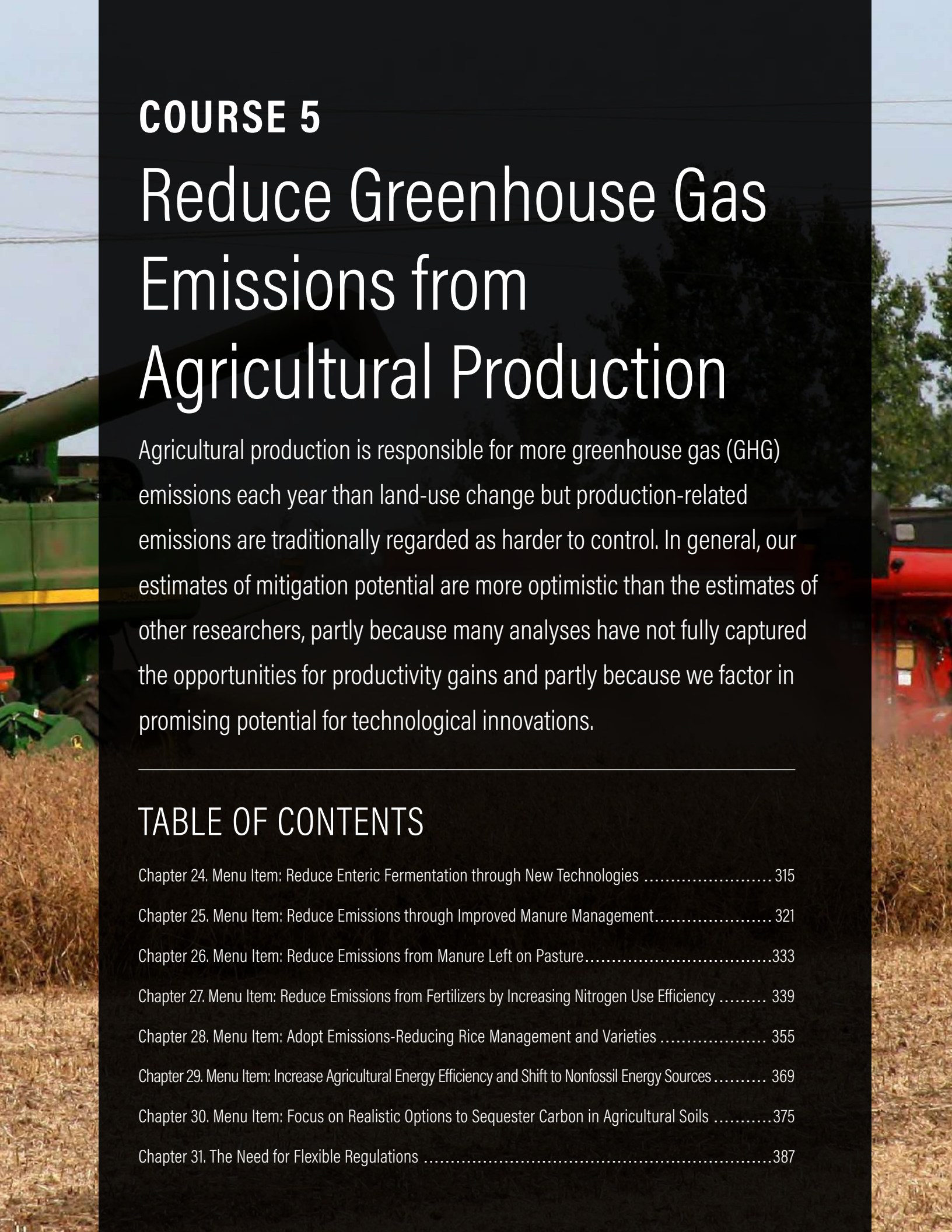
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To find the References list, see page 500, or download here: www.SustainableFoodFuture.org

PHOTO CREDITS

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COURSE 5

Reduce Greenhouse Gas Emissions from Agricultural Production

Agricultural production is responsible for more greenhouse gas (GHG) emissions each year than land-use change but production-related emissions are traditionally regarded as harder to control. In general, our estimates of mitigation potential are more optimistic than the estimates of other researchers, partly because many analyses have not fully captured the opportunities for productivity gains and partly because we factor in promising potential for technological innovations.

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Introduction

GHG emissions from agricultural production processes alone (i.e., excluding emissions from converting land to agricultural use) reach 9 gigatons (Gt) by 2050 in our baseline scenario, an increase from 6.8 Gt in 2010 (Figure C5-1). These production emissions arise mainly from six sources:

- "Enteric" methane emitted from the stomachs of cattle, buffalo, goats, and sheep (ruminants)
- Manure produced by some ruminants, pigs, and chickens kept in confined animal facilities (large and small)
- Unmanaged manure left on pasture and paddocks
- Crop and pasture fertilization, particularly with nitrogen
- Rice production
- Energy use in on-farm activities and in the production of agricultural inputs such as fertilizer

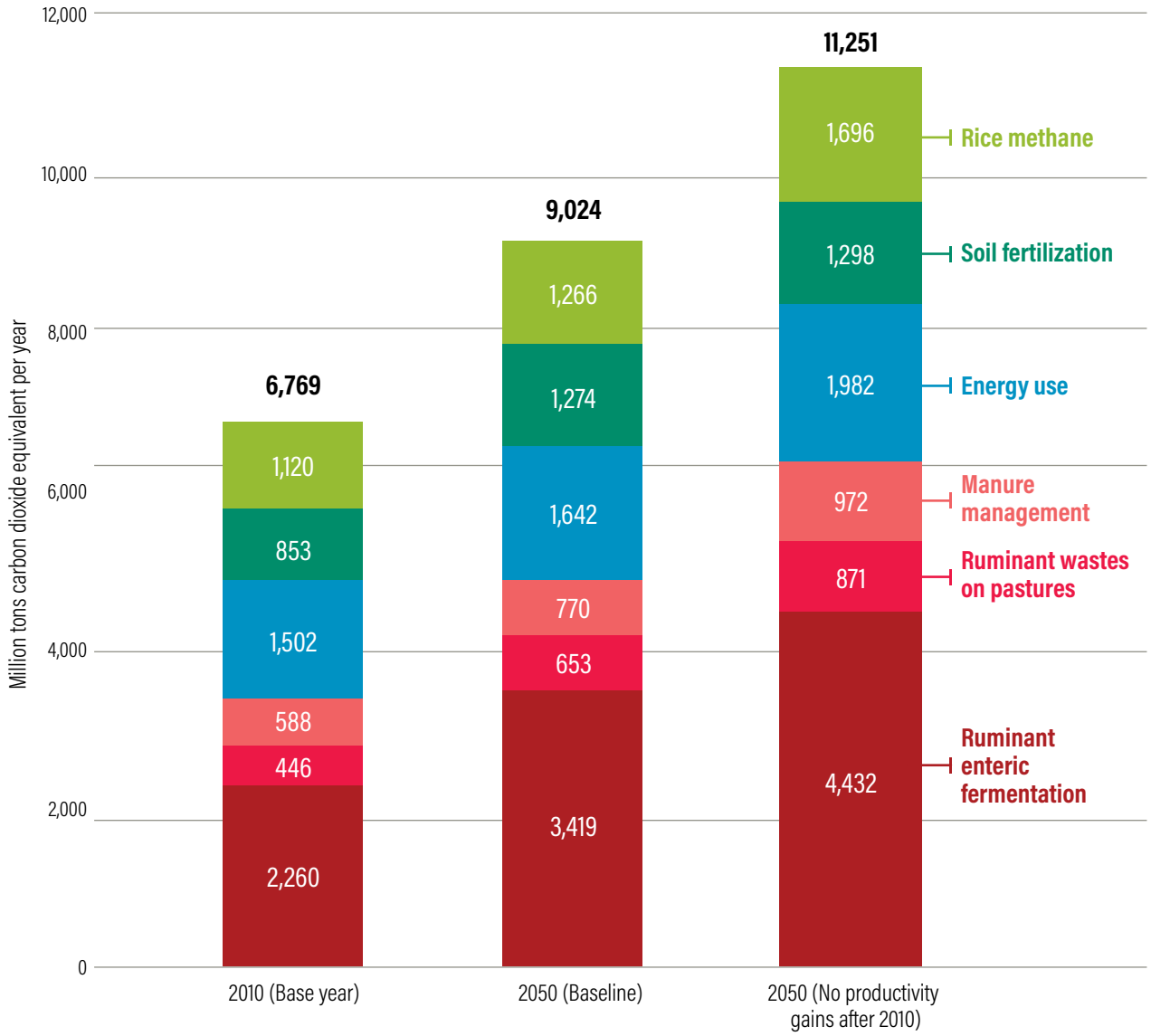
A baseline emissions level of 9 Gt results in a GHG mitigation gap of 5 Gt relative to our target of 4 Gt of total emissions from agriculture, even if we assume that all net emissions from land-use change, including peatland degradation, are eliminated or offset (as we contemplate in some scenarios).

Our 2050 baseline already builds in many productivity gains, without which agricultural production emissions in 2050 would rise even further (Figure C5-1). Even with highly optimistic estimates of changes in demand discussed in Course 1 (e.g., reducing food loss and waste, shifting diets to less ruminant-based foods), annual production emissions would still reach 7.2 Gt in 2050. Additional increases in livestock productivity analyzed in Chapter 11 would reduce production emissions to only about 7 Gt.

To reach our target of total agricultural emissions of 4 Gt by 2050 (see Figure 2-6 in "Scope of the Challenge and Menu of Possible Solutions"), efforts to reduce agricultural production emissions will be essential. Many possible approaches would also reduce other environmental impacts of agriculture, including air and water pollution caused by manure and fertilizer.

The following chapters explore menu items that could reduce agricultural production emissions by changing production processes. We find that meaningful potential exists today and that innovation offers the possibility of much greater mitigation in the future. Achieving these innovations will require both public support for research and development and flexible regulations that provide incentives for farmers and the private sector to pursue cost-effective solutions.

Figure C5-1 | **Annual agricultural production emissions could reach 9 gigatons or more by 2050**



Source: GlobAgri-WRR model.

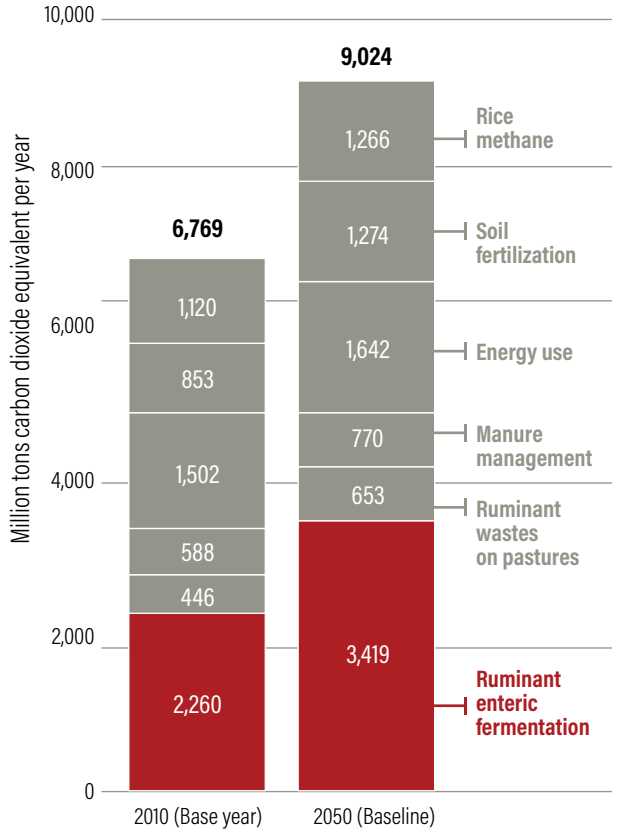


CHAPTER 24

MENU ITEM: REDUCE ENTERIC FERMENTATION THROUGH NEW TECHNOLOGIES

Methane produced by digestive processes in the stomachs of ruminants—mainly cattle, sheep, and goats—is the largest source of GHG emissions from livestock. Productivity improvements will reduce methane emissions, mainly because more milk and meat is produced per kilogram of feed, but additional measures will be needed to help offset growth in demand for ruminant meat. This chapter explores technological approaches to reducing enteric methane emissions.

Figure 24-1 | Greenhouse gas emissions from agricultural production, 2010 and 2050



The Challenge

Livestock generate roughly half of agricultural production GHG emissions today (Figure 24-1), even when excluding the emissions resulting from feed production. In 2050, two-thirds of livestock emissions, and more than one-third of total agricultural production emissions, will be methane generated by "enteric fermentation." This methane, which exits mainly from the animal's mouth, is produced by the natural breakdown of forages and other feed by anaerobic microorganisms (technically archaea) in the stomachs of ruminants—cattle, goats, sheep, and buffalo.

Strategies to reduce enteric methane emissions, in addition to improving livestock productivity, rely on four approaches to manipulate the dominant microbiological communities in the rumen: using vaccines, selectively breeding animals that naturally produce fewer emissions, incorporating special feeds or supplements into diets, and using compounds that can be thought of as drugs.

Governments have supported more research on this issue than on other sources of agricultural GHGs. Some dedicated scientific facilities are evaluating mitigation options. For example, at one New Zealand facility, scientists for years have systematically tested thousands of possible drugs or feed supplements. They start by adding compounds in small glass containers filled with rumen fluids. The most promising compounds are fed directly to animals temporarily housed in clear, tightly sealed glass chambers, which permit researchers to carefully measure the methane they release. The same chambers allow researchers to test different food additives, vaccines, and breeds to minimize methane emissions.

Unfortunately, the vast majority of results have been disappointing, mainly because the archaea that produce methane have found ways to overcome whatever initially suppresses them.[1] Although testing of animals has shown that different individual animals at different times produce very different levels of methane,[2] breeding has not yet produced animals that systematically generate below-average methane levels.[3] Vaccines also have proven only modestly and temporarily effective.[4] Although many feed compounds at first reduced methane emissions, most quickly lost their effectiveness. The digestion of cellulose results in a hydrogen gas that provides an energy source for microorganisms that can use it. As one paper summarized the problem, "The rumen microorganisms have the ability to adapt to foreign agents or changes in the feeding regimen and, therefore, short-term responses are not representative of the effect of a given mitigation compound or practice in real farm conditions."[5]

A few chemical compounds have provided persistent benefits so far, such as bromoform and chloroform.[6] These compounds are found in the red algae that make up some kinds of seaweed and explain why feeding experiments using small quantities of such seaweeds in feed, around 0.5 percent, have achieved greater than 50 percent reductions in methane emissions.[7] Unfortunately, these compounds are associated with important animal health or environmental concerns.[8] As a result, scientists are divided on whether to continue investigating



seaweed, with researchers in New Zealand discontinuing work while some researchers in Australia and the United States continue their studies. Separately, New Zealand researchers announced the identification of five promising compounds in 2015,[9] but peer-reviewed publications with results have yet to emerge.

As alternatives to chemical or drug compounds, some feed supplements—including vegetable oils and nitrate—have shown limited effectiveness at reducing methane emissions without health or productivity concerns.[10] But the financial costs of these supplements are high relative to emissions avoided. One analysis estimated that the potential costs of mitigation using these supplements start at $100 per ton of carbon dioxide equivalent (CO_2e) and rise with higher levels of mitigation. The analysis further estimated that even at a marginal cost of $300 per ton, the potential mitigation from these feed supplements amounted to only a few percent of enteric emissions.[11] We consider these approaches too expensive and their emissions-reduction benefits too small to be worthy of inclusion in our menu for a sustainable food future.

The Opportunity

Fortunately, since about 2015, at least one promising chemical feed additive has emerged. Multiple studies of cattle have shown that a small molecule, called 3-nitrooxypropan (3-NOP), generates sustained methane reductions of 30 percent or more in both cattle and sheep over at least several weeks.[12] This additive appears to have a persistent effect because the compound interferes with part of the fundamental chemical reaction that produces methane in *all* archaea.[13] The fundamental nature of this pathway may also reduce the rate at which archaea can mutate around it. On the basis of existing research, the chemical appears to have no adverse effects on animal health.

There is also good evidence from 3-NOP and other studies so far that reducing methane harms neither animals nor their productivity. This testing alleviates concerns that cows might be harmed by a build-up of hydrogen in the rumen when it no longer binds with carbon to form methane.[14]

3-NOP may also increase meat productivity, although the results to date have not demonstrated such gains clearly. Because ruminants lose up to 12 percent of the gross energy in feed as a result of the rumen's methane production,[15] reduced methane production in theory has the potential to increase productivity or reduce the quantity of feed needed. Yet studies of 3-NOP in dairy cows have not found increased production of milk, and only some have

found increases in daily weight gain (and only in dairy cows, not beef cows). Research is still ongoing, and DSM, the company that makes 3-NOP, is exploring the alternative route of maintaining output while reducing feed input.

Steps remain before 3-NOP can be broadly adopted. Researchers are still conducting experiments to obtain approval.[16] DSM hopes to have 3-NOP available on the market by 2020, though problems could still emerge. Yet overall, the progress made so far increases confidence that researchers will ultimately identify a cost-effective, safe, and effective compound.

Mitigation Potential

Although the novelty of effective compounds makes any projections uncertain, our mitigation options are based on assumptions about using 3-NOP or a comparable compound. The principal limitation of 3-NOP now is that it requires daily ingestion, and preferably frequently. In the leading study, it was mixed with feed in stall-fed dairy animals, which therefore ingest it throughout the day.

In our modeling, we assume that a feed compound will reduce emissions by 30 percent, which is the claim now being made by the producers of 3-NOP. We apply it in our first (Coordinated Effort) scenario to half of animals that receive more than a small amount of concentrated feed, which would facilitate their ingestion of a compound. In our Highly Ambitious scenario, we apply these reductions to all animals receiving concentrated feed. Under our Breakthrough Technologies scenario,

Table 24-1 | Global effects of enteric fermentation reduction scenarios on greenhouse gas emissions from agricultural production

SCENARIO	ENTERIC FERMENTATION EMISSIONS (MT CO_2E)	TOTAL PRODUCTION EMISSIONS (MT CO_2E)	PRODUCTION EMISSIONS GHG MITIGATION GAP (GT CO_2E)
2010	**2,260**	**6,769**	**–**
No productivity gains after 2010	4,432	11,251	7.3 (2.3)
2050 BASELINE	**3,419**	**9,023**	**5.0**
30% methane emissions reduction (animals receiving half of concentrated feeds) *(Coordinated Effort)*	3,126	8,730	4.7 (-0.3)
30% methane emissions reduction (all animals receiving concentrated feeds) *(Highly Ambitious)*	2,807	8,411	4.4 (-0.6)
30% methane emissions reduction (all ruminants) *(Breakthrough Technologies)*	2,393	7,997	4.0 (-1.0)

Notes: Numbers not summed correctly are due to rounding. Numbers shown in parentheses are changes relative to 2050 baseline.
Source: GlobAgri-WRR model.

the feed compound and associated 30 percent emissions reduction is assumed to apply to all ruminants including those permanently grazed. We make this assumption only in that scenario because such an achievement would likely require additional technological innovation to develop ways of delivering 3-NOP or alternative compounds, such as long-lasting, slow-release additives (Table 24-1).

The three mitigation scenarios lead to a reduction of enteric fermentation emissions of between 9 percent and 30 percent relative to our 2050 baseline. They would close between 6 percent and 20 percent of the production emissions GHG mitigation gap.

Recommended Strategies

Governments first need to continue their support for developing compounds to reduce methane from enteric fermentation. Without such support, the opportunities are less likely to be realized.

Researchers and corporations also need to know that if they develop a measure that provides cost-effective mitigation, it will be used. It is possible that compounds like 3-NOP will eventually pay for themselves through reduced need for feed or increased productivity, but they also might not, and cost-effective mitigation benefits should be considered sufficient justification to require their use.

We therefore recommend that governments provide incentives to the private sector by promising to require use of compounds if and when they prove to mitigate emissions at a reasonable cost. A first step could require use of such compounds as a condition of receiving farm subsidies. Because this recommendation applies to several mitigation strategies, we elaborate more on it in the final chapter of this course.



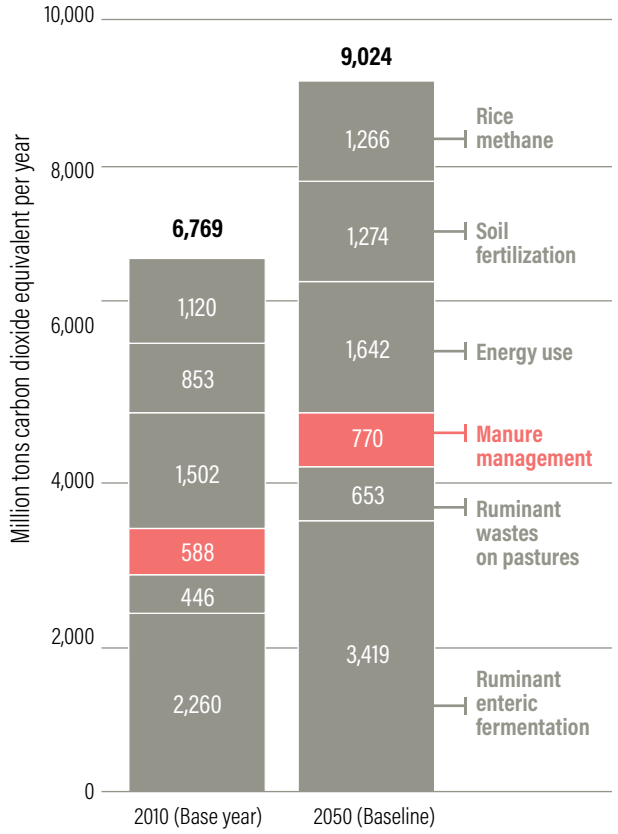


CHAPTER 25

MENU ITEM: REDUCE EMISSIONS THROUGH IMPROVED MANURE MANAGEMENT

The breakdown of manure by microorganisms under waterlogged conditions generates both methane and nitrous oxide emissions, which are powerful GHGs. Concentrated manure presents many other environmental challenges: it compromises water quality, contributes to local and regional air pollution, harbors pathogens, and generates noxious odors. This menu item focuses on ways to reduce GHG emissions from managed manure—but the same measures that reduce GHGs also tend to mitigate other environmental problems.

Figure 25-1 | Greenhouse gas emissions from agricultural production, 2010 and 2050



The Challenge

Livestock produce vast quantities of manure. Manure is "managed" when ruminants, pigs, or poultry are raised in confined settings and farmers remove manure and dispose of it in some way. (The manure that cattle, sheep, and goats deposit on grasslands and paddocks is considered unmanaged, and we address emissions from this source in the next menu item.) Manure begins to emit GHGs immediately after it is deposited in the barn where animals are kept,[17] but the majority of emissions occur in the manure storage system.

Dry and wet manure management systems

Some manure is managed in "dry systems," in which farms allow the urine to partially dry where it falls before scraping and piling the manure. Dry systems are found in virtually all poultry facilities because low volumes of urine leave poultry manure naturally dry. In the case of cattle and pigs, partial saturation of pockets of manure by urine creates the kinds of low-oxygen, high-carbon conditions that, when present for a day or more, are ideal for the microorganisms that produce nitrous oxide. More permanently saturated pockets tend to generate methane. Although the majority of the world's managed manure is managed dry, dry manure produces roughly 40 percent of global manure management GHG emissions (using estimates generated by the Global Land Evaporation Amsterdam Model [GLEAM] developed by the Food and Agriculture Organization of the United Nations [FAO]),[18] mostly in the form of nitrous oxide. Dry systems also result in high losses of nitrogen in a variety of forms, which reduces the nutrient value of the manure and typically generates abundant ammonia, an air pollutant.

Roughly 60 percent of managed manure emissions occur in "wet systems," in which farmers collect both feces and urine and sometimes add some water to flush manure into storage areas. These storage systems can take a variety of forms. When farmers use relatively small pits dug out of the earth, which they must empty several times a year, they are often called pits or slurries. When farmers use much larger dug-out pits, they are called "lagoons." These storage systems provide ideal conditions for archaea to generate methane. Per ton of manure, wet systems generate on the order of 20 times more methane than dry-managed manure, according to guidance from the Intergovernmental Panel on Climate Change (IPCC) and more recent studies.[19] Dry systems produce far more nitrous oxide although they have lower total emissions. When and if farmers ultimately apply wet manure to cropland and pasture, the manure also generates emissions, but we count and discuss those emissions as part of "soil fertilization," which we address in Chapter 27.



Managed manure volumes and emissions

We estimate GHG emissions from managed manure at nearly 590 million tons (Mt) of CO_2e in 2010. We project that these emissions will rise to 770 Mt CO_2e in our 2050 baseline (Figure 25-1). Of this total, we estimate that roughly one-third is in the form of nitrous oxide and two-thirds is in the form of methane.

Our estimates and projections are similar to those of other researchers. Perhaps because all global managed manure estimates use some form of guidance from the IPCC, seven of eight estimates recently summarized ranged only from 470 to 590 Mt CO_2e for recent years.[20] In all studies, the estimated emissions from methane are very similar.[21] Differences arise primarily in estimates of nitrous oxide emissions. There is also evidence from a meta-analysis of available field data that IPCC emission factors are too low, at least for dairy cows in developed countries, which would suggest higher total global emissions.[22]

Although estimates are rough, estimates by FAO using the GLEAM model indicate that manure from pigs is responsible for half of all managed manure emissions, primarily through methane generated in wet systems. Dairy cows generate around one-third of all emissions, roughly evenly divided between methane and nitrous oxide. Beef operations produce roughly one-sixth of all GHGs, primarily through nitrous oxide, because their predominant manure management systems are dry. Poultry produce relatively low GHG emissions (although they tend to generate abundant ammonia) because their wastes are dry enough to inhibit production of nitrous oxide or methane.

The critical question is what farmers can do to mitigate emissions from managed manure. More efficient production has only modest effects on managed manure emissions, unlike most other sources of agricultural emissions. To date, global estimates of technical—let alone economic—mitigation potential tend to be modest. For example, one review estimated the potential at 100 Mt CO_2e per year.[23] Such a level would mitigate only around one-sixth to one-eighth of present estimates of emissions from managed manure. Although we are ultimately more hopeful, we too consider mitigating managed manure emissions to be challenging for three reasons:

First, because most manure managed under dry systems generates relatively low emissions per kilogram of manure,[24] any control technology must be fairly inexpensive if it is to be cost-effective.[25]

Second, one-third of managed manure emissions today take the form of nitrous oxide, which is harder to control than methane—and this share is likely to rise by 2050.[26] Nitrous oxide emissions occur when manure is moist but not in liquid form and starts to occur as soon as wastes are deposited by the animal.[27] We discuss below opportunities to use solid separation on pig and dairy farms, but, in dry beef operations and many smaller farms, the main strategy suggested in the literature is to reduce overfeeding of protein (and therefore nitrogen) to livestock. In some countries, farmers feed excess protein, so reductions are practicable. In advanced systems, feed can more closely match the specific amino acid needs of livestock.[28] But in large parts of the developing world, livestock underconsume protein. Even where cows consume more nitrogen than they need, reducing protein in feed may result in more methane emissions from manure management through a complex and poorly understood microbial interaction.[29] In addition, efficiency gains in consumption of nitrogen by animals are mostly tied to the overall efficiency of feeding, and our baseline analysis already assumes substantial increases in overall feeding efficiency.

Third, farmers cannot practically influence many of the factors that influence emissions. For example, emissions from stored manure can be much higher in warmer climates than cool climates.[30] But strong economic factors influence where farmers raise animals, so it generally would be expensive, and socially and politically challenging, to shift livestock production to cooler areas just to reduce GHG emissions. Managed manure emissions also increase the longer farmers store manure before spreading it on farm fields. But spreading manure more frequently would often mean fertilizing crops when they cannot use the nutrients and thus increasing water pollution and nitrous oxide emissions in the field.

The Opportunity

Despite these challenges, we see greater potential for mitigation if countries take reasonable steps to advance manure-management technologies. There appears to be abundant opportunity for innovation. Even existing technologies appear capable of reducing emissions at a cost equal to only a small percentage of the price of meat and milk and at an acceptable cost per ton of emissions.

In this section, we discuss the opportunities for controlling managed manure emissions with a simple technology, solid separation, that can mitigate emissions from wet and dry manure alike and can grow in complexity and levels of mitigation as required. We then consider some lessons from research into manure management at a North Carolina pig farm, which offer insight into the potential to develop truly sophisticated manure management systems. Finally, we discuss digesters, which have received much of the manure management focus. They have potential to improve manure management but also present risks if not properly managed.

Separating solids, liquids, and nutrients

Separating liquids from solids is a relatively simple measure to reduce emissions and improve manure management generally. Since the solid portions of manure are drier after separation, they are likely to emit somewhat less methane. The liquid portion also causes fewer emissions because its lower carbon content gives microorganisms less to feed on and turn into methane.

Even without government incentives, a wide variety of systems already exist that can separate solids and, in the process, improve potential use of manure's nutrients. The simplest systems use gravity and a series of grates or ponds to let solids settle out. Many dairy farms in the United States use these systems. But mechanical systems can include screw presses or centrifuges that squeeze or whisk water out of solids and greatly increase the extent of the separation. Use of chemical "flocculents," which cause small particles to bind together, can increase removal rates of solids to 75–90 percent or higher, and can remove nearly all the phosphorus. More advanced systems use a variety of techniques to strip out nitrogen and phosphorus.

Separating liquids from solids also helps segregate nutrients; more nitrogen tends to remain with the liquid and more phosphorus stays with the solids. Two waste streams make it possible to better direct nitrogen and phosphorus to fields that need them. The phosphorus content of manure tends to be particularly high relative to local field needs, so concentrating and drying out phosphorus in solids makes it cheaper to transport the manure to fields that can benefit from it.[31]

The degree of GHG mitigation that separation can achieve will probably vary according to the type of farm and the extent of the solid separation. Studies to date use modeling assumptions rather than real field data. One study of pig farms in China found that solid separation would reduce emissions by more than half compared to even a basic dry management system (which mixes manure with straw), mostly by reducing nitrous oxide emissions. If compared to storage of manure in a deep pit, solid separation systems would reduce emissions by two-thirds.[32]

Achieving large reductions requires more than a low level of solid separation achieved by simple gravity-fed, grated systems. For example, a study of manure management changes on large dairy farms conducted for the California state government estimated only an 11 percent reduction in methane using solid separation.[33] But this study assumed that only 15 percent more solids would be separated, which would require only simple systems of solid separation.

One analysis of dairy farms in the United States estimated the cost of simple separation systems at only about $5–$6 per cow per year, with more advanced systems costing $50–$75 per cow per year.[34] A cost of $75 per cow in the United States is roughly equivalent to only 1 cent per liter of milk,[35] and these systems can still potentially pay for themselves because they save other costs of manure management, including hauling costs, and because they enable more valuable use of nutrients.[36] One analysis of dairy farms in Iowa found that farms using advanced solid separation actually had the lowest manure management costs.[37] To indicate the potential, some dairy farms in Michigan and New York have installed a system that uses reverse osmosis to clean up effluent almost to drinking water standards for reuse. Although the system is expensive, the farm owners believe it will ultimately save them money, mainly by lowering hauling costs and making more valuable use of nutrients.[38]

With good, daily solid separation, perhaps half or more of remaining emissions will result from the storage of solids, perhaps in equal parts methane and nitrous oxide.[39] These emissions can be reduced by the use of chemical additives to inhibit nitrous oxide emissions, some of which have proven effective at least during composting.[40] Other approaches that may improve performance and reduce costs include integrating systems into initial barn design and construction that help separate urine, which is high in nitrogen, from feces, which are high in phosphorus.[41]

Although solid separation receives relatively little attention in the mitigation literature, it represents both a good technology for initial implementation and one that farmers are likely to improve over time. It has many characteristics that make it promising across multiple farms:

- Because even simple separation can help to reduce emissions, solid separation is not an all-or-nothing strategy. Opportunities exist for incremental improvements, which in turn create opportunities for the kinds of small-scale innovations that tend to push down costs.
- Unlike some technologies, small farms should be able to employ solid separation because the technology should scale up or down according to the size of the farm and the costs will depend mainly on the quantity of manure.
- Solid separation is a pretreatment technology for almost all other likely advanced manure management techniques, whether designed to reduce emissions or other air and water pollution problems.
- Once systems are installed, farmers will have incentives to make them work well to reduce hauling costs and to increase the value of the use of nutrients.

Mitigating manure managed as a liquid

Manure that is currently stored as a liquid in lagoons or smaller storage facilities presents the largest opportunities for mitigation because the manure provides a concentrated source of emissions. Based on GLEAM data, wet manure generates 90 percent of pig farm emissions globally. Studies and experience with manure management systems for pig farms in the U.S. state of North Carolina illustrate the potential, given some financial encouragement (Box 25-1). In that state, roughly $15 million of research and development funding, distributed competitively, resulted in development of a sophisticated wastewater system that would virtually eliminate not just GHGs but all other forms of air and water pollution, odor, and disease risk. The system should add only around 2 percent to the retail price of pork.[42] These technologies emerged without the advantages of "learning by doing" or economies-of-scale production. They suggest that with more incentives, broader application, and without the need to meet such stringent standards for other pollutants, variations in liquid manure technology would likely emerge at even lower costs.

Digesters and covered storage

Advanced manure management has focused much of its attention on systems that "digest" manure, so these systems merit special attention here. One lesson from substantial work to date is that digesters have promise for manure already managed in wet systems but are unlikely to reduce overall emissions from manure otherwise managed in dry systems. A second lesson is the critical importance of controlling leaks wherever digesters are used, whether low-technology digesters in poorer countries or higher-technology digesters in rich ones.

Digesters typically confine liquid manure without oxygen to generate and capture methane, which is then often burned to provide heat or to make electricity. Digesters can be large and simple (e.g., lagoons covered with plastic tarps), large and more sophisticated (e.g., various forms of metal tanks), or small and simple (e.g., small clay or brick structures). In developed countries, where digesters are mostly large, the gas is typically used to run an electric turbine or cleaned of its many impurities and fed into a natural gas grid. These steps greatly raise the cost despite the energy they generate. For a 700-cow dairy operation in the United States, the overall costs of installation including the electricity-generating turbine may be $4 million. Operating costs can be high—as much as the annualized cost of the installation.[43] By contrast, household-level digesters in developing countries typically feed the gas back for use by the households, which is inexpensive and provides a cheaper, easier, and cleaner source of energy than wood or charcoal—even if the gas contains impurities that would fail the standards of most grid systems. The vast majority of the world's digesters are in developing countries, with 7 million in just five large Asian countries.[44]

Digesters were generally developed not to reduce GHG emissions but to provide energy and to reduce odor and organisms that cause disease. Whether they reduce emissions depends on how much they leak and whether farmers would otherwise manage their manure wet or dry. With no leaks in either the digester or in transport and use of the gas, a digester and its ultimate use should eliminate all the methane and convert it to carbon dioxide, a much less potent GHG. But leaks raise concerns. The IPCC accounting guidance establishes a high, default emission factor for digesters of 10 percent of the methane-producing potential of the manure. In addition, the liquid "digestate" that comes out of the digester is itself stored in a covered form and continues to generate methane. Unless this digestate is itself captured and its methane recovered, it can add leakage of an additional 10 percent or more of the total methane produced by the digester.[45]

In contrast to the IPCC standard leakage rates of 10–20 percent from digesters, the IPCC estimate of methane emissions from manure stored in dry form is 4 percent. As a result, switching from dry storage to a leaky digester would increase methane emissions (and the reduction in nitrous oxide emissions would typically not make up the difference).[46] At typical leakage rates, even factoring in use of the energy to displace fossil fuels, switching from dry manure to wet manure managed by a digester is likely to increase emissions.[47]

By contrast, the IPCC default emission factors for wet manure systems are much higher. The standard emission rate for a lagoon, typically a large earthen pond, is around 70 percent of the methane-producing potential of the manure in the lagoon. The

BOX 25-1 | The opportunities for improved manure management on North Carolina pig farms

Eastern North Carolina experienced massive growth in large-scale pork production in the 1980s and 1990s. The management of manure in large, open lagoons contributed to a wide array of local problems including obnoxious odors, air pollution, nitrogen enrichment, pathogens, and dangerous algal blooms in North Carolina's principal estuary. Large fish kills occasionally occurred when lagoons broke or were flooded.[a]

After legal action from the state government, the principal pork producer and pig purchaser in the state agreed to provide $15 million to fund research into "environmentally superior" manure management technologies under the supervision of North Carolina State University. It also agreed to implement any such technologies found to be economically feasible by the university. Reflecting the many other concerns about manure, the criteria for "environmentally superior" were stringent but unrelated to climate change: technologies must substantially eliminate all pathogens, threat of nutrient pollution, odor, and air pollution.

The project's conclusions in 2006 were in one sense a disappointment because the university found that no technologies qualified as economically feasible. Yet the economic analysis for the study assumed that pork facilities in North Carolina alone would implement these technologies, so anything more than trivial costs would put them at a competitive disadvantage with farms in other states. The study did not analyze whether requiring all pork producers in the United States to control their pollution would be economically advantageous.

Review of the findings of that study indicates that even an extraordinarily sophisticated, tank-based manure management system would cost-effectively reduce GHG emissions without even factoring in the other pollution-reduction benefits. This system employed a series of tanks to separate pollutants, flocculent chemicals helped to achieve high levels of solid separation, and alternating tanks with and without oxygen drove out the nitrogen.[b] Although the system in effect employed the most advanced technologies of sewage waste management, we estimate from the project's documents that the system would mitigate emissions at a cost of only $22 per ton of CO_2e, while eliminating 99 percent of the methane emissions.[c] Costs for other manure management systems studied, ranging from simple covering of lagoons to more complex digesters, ranged from $12 to $55 per ton of CO_2e, excluding any GHG savings from fossil fuel use and any economic value of the solid material left over after digestion.[d] If judged in relation to the mitigation costs that will be involved in meeting global GHG emissions targets, these costs are not high. In fact, the GHG reduction could be considered free from a social perspective, although not to the pork producers, because of the large cobenefits from reduced water and air pollution, odor, and risk of disease.

If all pork producers were required to implement these manure management measures, they would add most of the additional cost to the product price. However, the cost of the tank system for an average farm would represent 1.4 to 2.5 percent of the average retail price of pork over the past six years in the United States. That cost is much smaller than the fluctuations in pork prices during this time.[e]

Notes:

a. National Geographic (2014).

b. Oxygen tanks turn other forms of nitrogen into nitrate, and tanks without oxygen break down the nitrate into nitrogen gas.

c. Costs for the treatment technology are from Vanotti et al. (2013) and are provided per pig in the form of SSLW/year (steady state live weight per year). Griffing et al. (2004) Table 50, estimated methane emissions at 21,353 kg/1,000 pigs of 45 kg weight average. At the most recent 100-year global warming potential (GWP) of 34, that translates into 726 tons CO_2e. Zering et al. (2013) estimate costs of the "tank system" on a large pig farm in North Carolina at $158 per SSLW/year and costs for more typically sized farms ranging from $202 to $280 per SSLW/year. The unit dollars per 1,000 SSLW translates into dollars per 10 pigs of this weight. As a result, manure management systems capable of handling 100,000 SSLW are needed to address these emissions of 726 tons, which equals 100 x $158 or $15,800 per year. Assuming 99 percent abatement of methane, this calculation results in a cost estimate of $22 per ton and even assuming abatement of only 95 percent only increases that cost to $23 per ton.

d. This figure uses the same method as above except it uses digester costs based on Zering et al. (2006) and updated by communication with Kelly Zering, November 3, 2016.

e. USDA/ERS (2015b) averages annual prices from 2010–15.



emission rate for a smaller "slurry tank" is around 35 percent. As a result, switching from wet manure systems to digesters should reduce emissions, even if digesters have 10–20 percent leakage rates.

Even so, the benefits are not certain. Digesters produce energy more efficiently if they combine manure with food waste, so this is a common practice. Because this food waste typically would generate less methane if left alone in a landfill—the combination of digesting manure and food waste will likely lead to higher overall methane emissions from even a moderately leaky digester.[48] Fortunately, studies show that leakage rates from sophisticated digesters can be kept to a few percent.[49] If those low leakage rates are achieved, digesters can achieve large mitigation benefits.[50]

In developing countries, where the vast majority of the world's digesters are located, the GHG benefits are especially contingent on controlling leaks. In typical, simple digesters, methane is likely to leak from the input and output components and from cracks in systems that are not well maintained.[51] Because the biogas is typically used directly by households, biogas production sometimes exceeds household needs and is deliberately vented to avoid harm to the digester. Studies in the south of Vietnam estimated these intentional releases at 34 percent of the biogas (and therefore of the methane), while a study in the north of the country estimated intentional releases at only 7 percent. Because the alternative manure management system is likely to be dry storage, the potential for savings from the use of digesters in manure management alone is doubtful.

Yet even in these systems, the potential for overall GHG savings exists if the biogas replaces coal or wood harvests as a source of energy or enables more efficient use of the manure as fertilizer. Factoring in these nonmanure benefits, one study estimated that even quite leaky digesters could reduce overall emissions on small farms in Asia.[52] Digesters also provide important cobenefits, including reduced disease-bearing organisms, improved water quality, and replacement of inefficient indoor stoves—which reduces unhealthy indoor smoke and wood cutting. One Chinese study used scanning devices to detect household-based digesters and observed lower leakage rates than those generally found in other Asian studies (although the study probably did not capture intentional venting).[53] This finding suggests that inspection systems may be feasible and could help identify and reduce leakages.

Overall, the lesson is that digesters could provide a viable means of controlling manure management emissions—particularly using more sophisticated digesters to control wet manure—but only if they are properly managed to control leaks both from the digester itself and from the storage of the digestate liquid that comes out of the digester.

In addition to the leakage challenge, the large up-front costs of installing sophisticated digester systems tend to inhibit their use. The main costs relate either to the turbine and related components if the biogas is used to generate electricity, or to cleaning the biogas so that it can be used as natural gas in developed countries. A simpler alternative is to cover a lagoon or storage pit with an impermeable plastic cover and to capture the gas and burn it. Doing so converts methane to carbon dioxide, which has a much smaller warming potency. The cost is more modest in part because a cover helps reduce hauling costs by reducing the addition of rainwater. Cost-effectiveness also increases with larger operations.[54]

Model Results: Mitigation Potential

Any effort to properly evaluate the costs of mitigating GHG emissions from manure must start with the enormous environmental and social problems presented by badly managed manure. Leaking storage systems contribute to groundwater pollution and drinking water problems.[55] In China, the world's largest producer of pork, some 30–70 percent of manure is discharged directly into water bodies without any treatment, creating the primary source of pollution that causes algal blooms and dead zones in the South China Sea.[56] The southeastern United States experienced massive flooding during Hurricane Florence in September 2018, when at least 60 hog farm lagoons overflowed, releasing contaminated water into surrounding communities.[57] Ammonia also contributes to serious air pollution problems.[58] Manure carries disease-bearing organisms that pose health risks, and ammonia emissions often contribute substantially to small-particle air pollution, a major source of ill health in humans and animals. And large feedlots often cause major odor problems for surrounding communities, which can even be unhealthy.

These concerns, not GHG emissions, have to date driven most efforts to improve manure management. Health concerns and the need to mitigate the impacts of climate change together justify more vigorous action to manage manure effectively.

We used GlobAgri-WRR to test three GHG emissions mitigation scenarios for managed manure (Table 25-1). Although the mix of farm systems changes between 2010 and 2050, our 2050 baseline projection assumes that the share of each type of manure management system for each type of farm remains unchanged. Based on our analysis above, we believe that 90 percent reductions in methane are possible from wet manure systems. For dry manure pork production systems, the study of pig farms in China described earlier suggests that 60 percent reductions in nitrous oxide emissions (but no change in methane emissions) are achievable with good solid separation.[59]

Less research has been conducted into dry beef and dairy systems, so the evidence is not clear. However, dry systems tend to leave manure uncollected for long periods in feedlots, and there is evidence that collecting and distributing the manure more frequently can reduce nitrogen losses by 20–30 percent.[60] Although we do not expect large gains from animal dietary changes, we believe that 10 percent reductions in nitrous oxide from feed changes are plausible. Based on these considerations, we develop the following scenarios:

- In our first scenario, we assume mitigation of 40 percent of the methane from manure that is managed in wet form.
- In a second scenario, we assume that all farms, including both wet and dry manure farms, reduce their total manure management emissions by 20 percent. We include this scenario for perspective but consider it less realistic.
- In our most optimistic scenario, we assume 80 percent reduction of emissions of methane from wet manure, 20 percent mitigation of methane emissions from dry manure, and 20 percent mitigation of nitrous oxide emissions from all manure.

These scenarios reduce emissions from managed manure (relative to 2050 baseline) by 13 to 37 percent.

Table 25-1 | Global effects of manure management scenarios on agricultural greenhouse gas emissions

SCENARIO	MANURE MANAGEMENT EMISSIONS (MT CO_2E)	TOTAL PRODUCTION EMISSIONS (MT CO_2E)	PRODUCTION EMISSIONS GHG MITIGATION GAP (GT CO_2E)
2010	**588**	**6,769**	**–**
No productivity gains after 2010	972	11,251	7.3 (2.2)
2050 BASELINE	**770**	**9,023**	**5.0**
40% reduction in methane emissions from wet manure *(Coordinated Effort)*	673 (–13%)	8,925	4.9 (-0.1)
20% reduction in manure management emissions across all farms *(Illustrative, not included in any combined scenario)*	617 (–20%)	8,869	4.9 (-0.2)
80% reduction in wet manure emissions, plus 20% reduction of all other manure management emissions *(Highly Ambitious, Breakthrough Technologies)*	489 (–37%)	8,742	4.7 (-0.3)

Notes: Numbers not summed correctly are due to rounding. Numbers shown in parentheses are changes relative to 2050 baseline.
Source: GlobAgri-WRR model.



Recommended Strategies

We make a number of specific recommendations:

Build spatial databases of large concentrated livestock facilities. Information about manure management is remarkably rough because in most of the world there has been no effort to map and identify the types and levels of manure management systems used, even on large livestock operations. That not only frustrates analysis but also inhibits action. By contrast, Denmark not only tracks information on every substantial pig and dairy farm but tracks each animal as well. As a first step, governments need to develop reasonable data on each sizable livestock operation and its manure management system.

Adopt regulations immediately to require improved manure management on all new farms, as well as on all medium and large concentrated livestock farms that currently use wet manure management systems. New livestock farms can more easily incorporate at least basic solid separation into their design. Even in parts of developing countries without power, farms can use gravity systems to help separate solids and liquids. Standards should be extended to increasing numbers of existing farms over time. In this way, sounder manure management by 2050 should be feasible.

Many of the farms that manage manure in wet form are relatively large, commercial operations,[61] particularly pig farms. In the U.S. pork industry in 2012, for example, just 13 percent of pig farms held 2,000 or more pigs, but these farms held 87 percent of all pigs nationally.[62] These farms should also be required to meet the standards for new operations. Based on the technology analysis in North Carolina, governments of wealthier countries should require that farms emit methane and other pollutants at no more than 10 percent of the rate of today's standard facilities. To avoid placing facilities at a competitive disadvantage, regulations should be adopted at the national or regional level. Large food companies should also adopt standards to require proper manure management by their suppliers.

Phase in regulation of all existing livestock operations with managed manure systems, focusing on livestock purchasers. One goal of any regulatory system should be to find the cheapest options for mitigation first, which allows technology to improve and become cheaper before addressing more expensive challenges. For manure management, this would likely entail imposing regulations on larger wholesale operations and requiring increasingly large percentages of their product over time to come from farms certified as meeting higher manure management standards. For example, in the United States in 2012, five large firms controlled 62 percent of the nation's pig slaughtering capacity.[63] To facilitate this ratcheting up of standards, the government could issue certificates to farms that meet different standards of emissions per kilogram of meat or milk or, if easier, per animal. Wholesalers would then be required to hold certificates sufficient to demonstrate that they meet increasingly stringent targets of emissions per kilogram of meat or milk. Wholesalers would pass on the bulk of these costs to consumers and reimburse the costs borne by producers who meet manure management standards by purchasing certificates. Such a system would encourage improved management by those farms that could do so at the least cost. If such a system assigned more credit to farms that meet higher standards of performance, it could also create powerful incentives for innovation and improvement wherever cost-effective.

Adopt competitive programs to encourage new technology. The challenge in manure management is often just to refine mechanical and chemical engineering approaches for handling manure. These are engineering challenges well suited to the capabilities of the private sector, which can build upon waste-treatment technologies already developed for industrial wastes and municipal sewage. Governments can play a role by establishing competitive grants programs for private companies, based on criteria such as cost, environmental performance, and promise of technological improvement.

Adopt inspection systems to monitor digester leaks. For manure management systems using digesters, particularly in developing countries, governments should require future use of digester technologies with lower leakage potential. In addition, governments should adopt inspection systems that use methane detectors to monitor leaks.

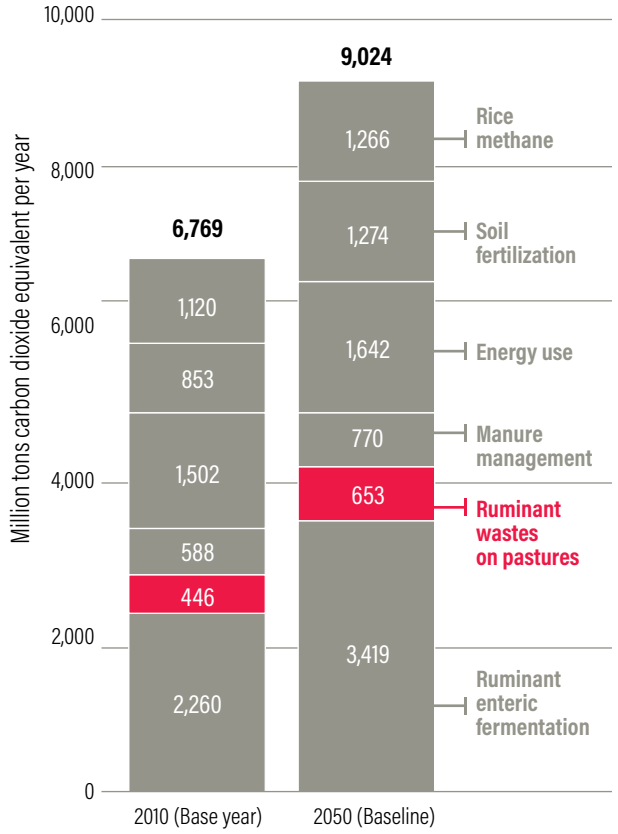


CHAPTER 26

MENU ITEM: REDUCE EMISSIONS FROM MANURE LEFT ON PASTURE

Manure deposited by cattle, sheep, and goats on grazing lands or in paddocks can concentrate nitrogen in carbon-rich, saturated conditions that encourage the production of nitrous oxide by microorganisms. Manure consists of both feces and urine, and, in general, urine contains most of the nitrogen and generates nitrous oxide at a greater rate than feces. Reducing emissions from pasture manure is challenging because sources are diffuse; biological and chemical nitrification inhibitors hold the most promise.

Figure 26-1 | Greenhouse gas emissions from agricultural production, 2010 and 2050



The Challenge

According to standard emission factors used by the IPCC, nitrogen deposited in feces and urine turns into nitrous oxide roughly twice as fast as nitrogen in fertilizer. According to FAO (reported in FAOSTAT), these deposits, all from ruminants, are rising rapidly, contributing 800 Mt CO_2e emissions in 2010 and 846 Mt CO_2e in 2014. Our estimate, using GlobAgri-WRR, is substantially lower at 446 Mt CO_2e in 2010, and we project emissions of 653 Mt CO_2e by 2050 (Figure 26-1). FAO bases its estimates on the number of animals, assuming the same emissions per animal, whereas GlobAgri-WRR uses a method based on estimated nitrogen in excretions from different animals based on what they eat. Regardless of which source is used, these emissions are on a course to be substantial in 2050, and even our lower projection would contribute 16 percent of the total allowable emissions from agriculture (4 Gt target) in 2050.

As with enteric methane, one way to reduce emissions from unmanaged manure is to improve efficiency; that is, to improve the output of product per animal and per kilogram of feed. Under our "no productivity gains after 2010" scenario, emissions from unmanaged manure would reach 871 Mt CO_2e in 2050 (Figure C5-1), but our baseline estimates 25 percent fewer emissions due to the efficiency gains built into our baseline. Our Course 2 scenario that involves a higher efficiency target for livestock (discussed in Chapter 11) could reduce these emissions only modestly to 630 Mt in 2050. Even our 30 percent reduction in ruminant meat consumption scenario (Chapter 6) would only reduce these emissions to 524 Mt in 2050. Finding additional ways to reduce these emissions is therefore necessary.

The Opportunity

Other studies typically estimate little to no global potential to mitigate this source of diffuse emissions.[64] We are more optimistic, but our optimism rests on further development of some technologies that have shown good potential but are not yet ready for deployment. They focus on "inhibiting" the formation of nitrate.

Livestock deposit nitrogen primarily in the form of urea (CH_4N_2O). Through biochemical processes mediated by bacteria and archaea in soils, urea is typically converted into ammonia (NH_3), ammonium (NH_4+), and then nitrate (NO_3-). Nitrous oxide (N_2O) is primarily released by the bacteria that break down nitrate in waterlogged conditions, and, although the quantity is small, the warming effect is great because of the potent warming effect of nitrous oxide. Because nitrate is soluble in water and does not adhere to soils, it is also the primary form of nitrogen that runs off of fields or leaches into groundwater, causing water pollution. Inhibiting the formation of nitrate in soils reduces both losses of nitrogen through water runoff and leaching and emissions of nitrous oxide.

Spreading nitrification inhibitors

One way to reduce these emissions involves spreading chemicals that inhibit nitrification directly on pastureland. Most experiments have used dicyandiamide (DCD), the most commonly used inhibitor. A summary of six experiments using DCD on grazing land found reductions in nitrous oxide ranging from 17 percent to 88 percent.[65]



Inhibitors do not persist in their effects, however, particularly under higher temperatures, so a one-time application is not sufficient. In New Zealand, the practice has been to spread the inhibitor twice per year, each time shortly after animals are moved away from a field, when grass is grazed down and farmers can directly apply the inhibitors to the urine patches, which typically cover 20 percent of a field.[66] One study in the warmer parts of New Zealand suggested that three applications per year would be needed to achieve high effectiveness there because of a higher breakdown rate. Although bacteria might be able to develop resistance to inhibitors, no studies have yet shown this effect.[67]

The practicality of using inhibitors in this way also depends on the size of fields and on the effects of inhibitors on grass yields. Inhibitors are most likely to be practical and economical on farms such as dairy farms in New Zealand, where intensive, rotational grazing is practiced on generally well-watered, highly managed fields, and where grazing is concentrated in relatively small areas. Research studies in New Zealand have typically found positive effects of inhibitors on grass yields from 15 to 36 percent, although these studies are not necessarily representative of real, commercial operations.[68] Other studies in both New Zealand and the United Kingdom have found no beneficial effect on pasture yield, which suggests variability in inhibitor performance.[69] Use of inhibitors is likely to be less practical on more extensively managed grazing lands, although these lands will receive less manure and therefore produce fewer emissions per hectare.

Feeding nitrification inhibitors

An alternative approach to inhibiting nitrification involves feeding inhibitors directly to animals. A few studies have found that adding inhibitors to water or livestock feed provides effective reduction of both nitrous oxide emissions and nitrogen leaching, and that most of the inhibitor passes through the animal in the urine.[70] This method would be easier than pasture application and would probably require less inhibitor to be effective.[71] However, the inhibitor would probably need to be ingested frequently, even daily, by the animals.

Feeding inhibitors through water or feed does raise health issues. Although toxicological studies of DCD have found very low toxicity,[72] the lack of an agreed international safety standard caused New Zealand to suspend use of DCD in 2013 after trace levels were found in milk.[73] One New Zealand study also found that DCD washed off into freshwater ecosystems, where it might affect natural nitrification rates.[74] These concerns need to be thoroughly researched for any nitrification inhibitor, although the low toxicity ratings of DCD so far suggest that it could satisfy these health and environmental concerns.

Breeding biological nitrification inhibition

A third opportunity involves breeding and selecting grasses that inhibit the conversion of ammonium to nitrate, which is the first step in the process of generating nitrous oxide. Many studies have now found extremely low rates of nitrous oxide formation in fields of *Brachiaria humidicola*, which is one variant of the African *brachiaria* grass family used extensively in Brazil.[75] This "biological nitrifi-

cation inhibition" appears to be due in small part to stronger root uptake of nitrogen but in larger part to a chemical exuded by the roots of the grass (brachialactone), which blocks a key enzymatic pathway in the formation of nitrate. The production and exudation of this chemical varies widely among plants, but it has been found at significant levels in another *brachiaria* species (*Brachiaria decumbrens*).[76] It is also plausible, although not yet tested, that cattle consuming one of these grass species will excrete some of the chemical in their manure, which would also help to inhibit nitrous oxide production.

The results suggest in part that more widespread use of *Brachiaria humidicola* could reduce emissions. But this species is useful only in tropical and subtropical areas. It constitutes only a small percentage of total *brachiaria* use in Latin America, and its preferential use compared to other species depends on many agronomic factors. For grazing purposes, the alternative is to breed this inhibitory effect into other grass species.

Mitigation Potential

An important question for estimating mitigation potential is whether the present emission factors used by the IPCC are too high. The IPCC Tier 1 sets an emission factor of 2 percent of nitrogen in manure turning into nitrous oxide, which is double the rate assumed for fertilizer and is based on older measurements in temperate countries. A variety of recent evidence suggests lower rates. Because emissions require a high level of soil saturation, emissions factors in hotter and drier climates, where urine patches dry out quickly, should be substantially lower, which is the finding of several recent studies.[77] Even in wetter, temperate countries, some studies are finding lower emission factors, for example in New Zealand and the United Kingdom.[78]

Despite this evidence, there is a growing discrepancy between field-level estimates of nitrous oxide emission rates, studies that use flux towers, and studies that use modeling based on patterns of nitrous oxide sensed in the atmosphere by satellites.[79] It is already difficult to reconcile IPCC emission factors with measured global nitrous oxide levels, and estimated emissions rates that are lower than IPCC figures—whether from pasture or cropland—would create larger inconsistencies. One likely explanation is that the rates vary greatly depending on a range of soil and temperature conditions. There are also likely hotspots—areas that are more frequently saturated or that have the right acidity, which result in large releases of nitrous oxide.[80]

These differences could present an opportunity. Identifying hotspots would allow mitigation to focus on them. Mitigating nitrous oxide emissions from manure deposited on extensive grazing lands in arid regions would be difficult because urine patches will be spread over large areas, farmers do not provide daily feed supplements, and farmers do not use planted grasses. If evidence continues to confirm low emission rates from extensive grazing in more arid areas,[81] mitigation in these areas could be ignored. Mitigation efforts could then focus on more intensive grazing systems in wetter areas.

Overall, although promising technological approaches exist to mitigate nitrous oxide emissions from grazing operations, they all are too little developed to allow refined estimates of mitigation potential. We exclude additional mitigation in our Coordinated Effort scenario because all progress relies on some degree of technological improvement. We also assume that mitigation on arid grazing land will be economically or practically unfeasible because the emissions are too low to justify the expense of addressing them. We assume mitigation improvements on wetter grazing lands of 20 percent and 40 percent in our Highly Ambitious and Breakthrough Technologies scenarios, respectively. Finally, for illustrative purposes, we show one scenario with 60 percent mitigation on wetter grazing lands (Table 26-1).

Recommended Strategies

Because solutions for this source of emissions are underdeveloped, research and regulatory incentives have to focus on ways to develop them.

Increase research funding

The most obvious recommendation is that governments and research agencies should substantially increase research funding into methods for reducing nitrification of nitrogen on pasturelands. Three initiatives are appropriate:

Table 26-1 | Global effects of scenarios of emissions reductions from manure left on pasture on agricultural greenhouse gas emissions

SCENARIO	NITROUS OXIDE EMISSIONS FROM PASTURE, RANGE, AND PADDOCK (MT CO_2E)	TOTAL PRODUCTION EMISSIONS (MT CO_2E)	PRODUCTION EMISSIONS GHG MITIGATION GAP (GT CO_2E)
2010	**446**	**6,769**	**–**
No productivity gains after 2010	871	11,251	7.3 (2.2)
2050 BASELINE and Coordinated Effort	**653**	**9,023**	**5.0**
20% reduction of nitrogen left on wetter pastures *(Highly Ambitious)*	584	8,954	5.0 (-0.1)
40% reduction of nitrogen left on wetter pastures *(Breakthrough Technologies)*	515	8,884	4.9 (-0.1)
60% reduction of nitrogen left on wetter pastures *(illustrative, not included in any combined scenario)*	445	8,814	4.8 (-0.2)

Notes: Numbers not summed correctly are due to rounding. Numbers shown in parentheses are changes relative to 2050 baseline. Coordinated Effort scenario assumes no reduction in nitrous oxide emissions relative to levels projected in the 2050 baseline.
Source: GlobAgri-WRR model.

- **Research into development and uses of nitrification inhibitors.** Virtually all published research on their use in pastures comes from a few small research groups in New Zealand. Other countries need to expand these efforts.
- **Research into biological nitrification inhibition.** Analysis of biological nitrification inhibition is currently being undertaken by a small cooperative effort of four research institutions coordinated by the Japan International Research Center for Agricultural Scientists and the International Maize and Wheat Improvement Center. Not counting the salaries of participating researchers, the budget for their research is roughly $1 million per year.[82] A budget of tens of millions of dollars would be the minimum appropriate for this research given its level of importance and the many ways additional research could be performed.
- **Research on agricultural emissions rates**. As the discussion above indicates, it is likely that emissions rates of nitrous oxide vary greatly from one area to another and are concentrated in certain hotspots. Although some research shows these effects, it is not systematic. Field analyses have become cheaper, however, and can be combined with measures from tall towers and satellites. The world needs a comprehensive, international initiative to identify these hotspots and emissions rates.

Create private regulatory incentives

Opportunities also exist to craft regulations that give incentives to industry to develop workable new technologies by guaranteeing them a market. For example, governments could promise to require use of nitrification inhibitors on an increasing percentage of farms if industry could demonstrate products or technologies that achieve a specified level of nitrous oxide reduction at a specified cost per ton of nitrous oxide saved. We elaborate on these regulatory opportunities at the end of this course.

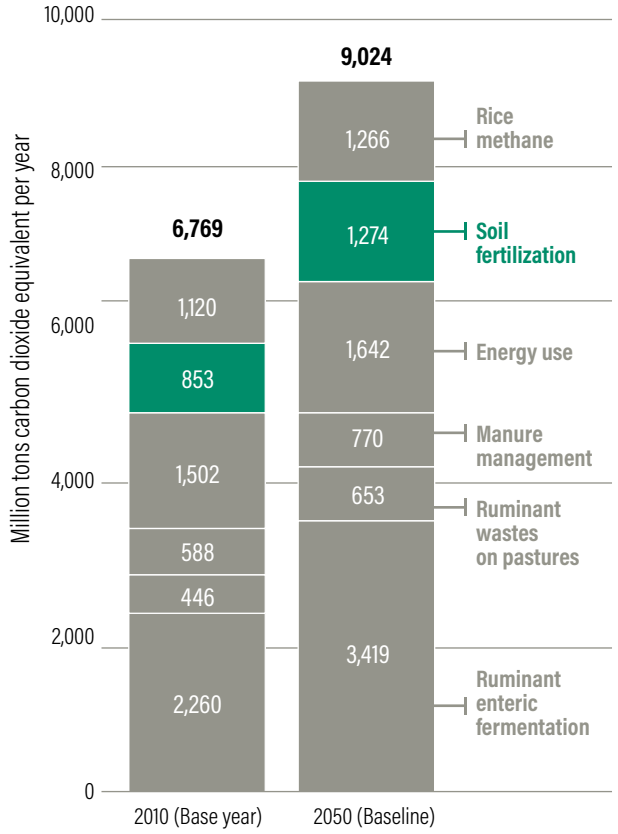


CHAPTER 27

MENU ITEM: REDUCE EMISSIONS FROM FERTILIZERS BY INCREASING NITROGEN USE EFFICIENCY

Less than half of the nitrogen added to crop fields is absorbed by crops and the remainder contributes to emissions and other forms of nitrogen pollution. This menu item involves increasing the efficiency of nitrogen use, in significant part by focusing on the composition of fertilizers themselves, to reduce both the quantity of fertilizer required and associated emissions.

Figure 27-1 | Greenhouse gas emissions from agricultural production, 2010 and 2050

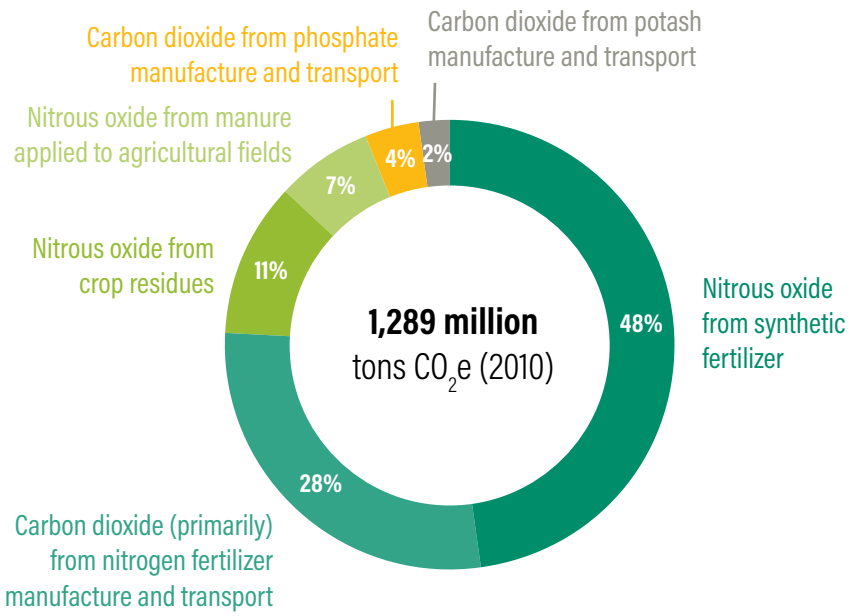


The Challenge

Although fertilizing crops with nitrogen, phosphorus, and potassium—the major nutrients—is vital to achieving high crop and pasture yields, it also contributes substantially to GHG emissions. Using GlobAgri-WRR, we estimate fertilizer emissions in 2010 at 1,289 Mt CO_2e, of which 94 percent resulted from nitrogen use (Figure 27-1). Two-thirds of these nitrogen emissions were in the form of nitrous oxide emitted in crop fields from all forms of applied nitrogen; the other one-third came from the energy used in the manufacture and transportation of nitrogen fertilizer (Figure 27-2).[83] (Because fertilizer production is so energy-intensive, and because more efficient nitrogen use would substantially reduce these emissions, we discuss emissions from fertilizer manufacture both in this menu item and in our menu item focused on ways of reducing fossil energy use.) Synthetic fertilizer accounts for roughly half of all nitrogen fertilization,[84] the other half comes from manure applied to crops (excluded from manure management calculations), the residues of nitrogen-fixing crops such as soybeans, nitrogen in rain, irrigation water and air dust; and even nitrogen fixed by freely associated microorganisms in soil.

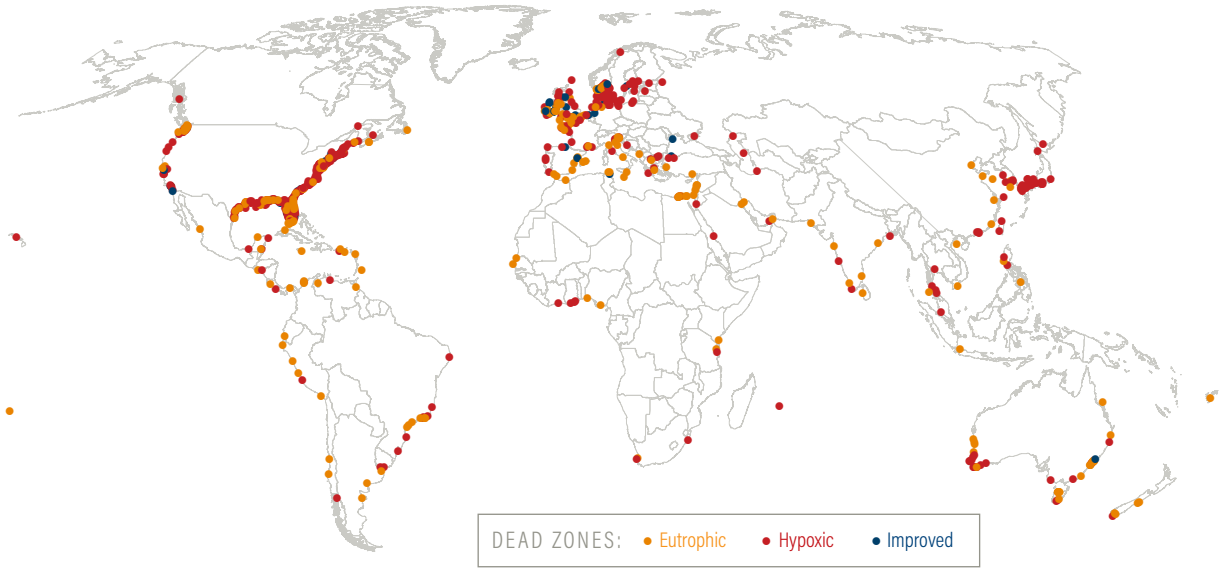
Fertilizer (mineral and organic) also contributes to a variety of other environmental challenges. These include small particulate smoke and smog (technically ground-level ozone), which are the leading air pollution problems for human health.[85] Agricultural runoff is the principal cause of unsafe levels of nitrate in drinking water from wells or rivers in many areas in the world. When nitrogen runoff or leachate into rivers reaches coastal waters, it can contribute to algal blooms, some of which are toxic to fish and other sea life. Other algal blooms lead to hypoxia—a condition where coastal waters have little or no oxygen—also called "dead zones." Both types of blooms have been increasing in size and frequency and now contaminate large portions of major water bodies such as the Gulf of Mexico, the Chesapeake Bay, and the China Sea during certain seasons. Figure 27-3 maps 762 overfertilized coastal waters around the globe.[86] Phosphorus runoff also contributes to algal blooms and dead zones in lakes and rivers and in brackish coastal waters, which mix fresh and saltwater.[87] One estimate suggested that alleviating the nitrogen contribution to environmental problems would require reductions in nitrogen losses to the environment of roughly one-half.[88]

Figure 27-2 | Approximately 94 percent of emissions from fertilizing soils are the result of nitrogen application



Note: This chart excludes emissions from manure left on paddocks and pasture, discussed above, and differs from FAOSTAT estimates in part because GlobAgri-WRR is based on nitrogen estimates underlying Zhang et al. (2015b) and nitrogen availability in manure from a livestock management component based on Herrero et al. (2013).
Source: GlobAgri-WRR model.

Figure 27-3 | More than 700 "dead zones" exist in the world's coastal waters



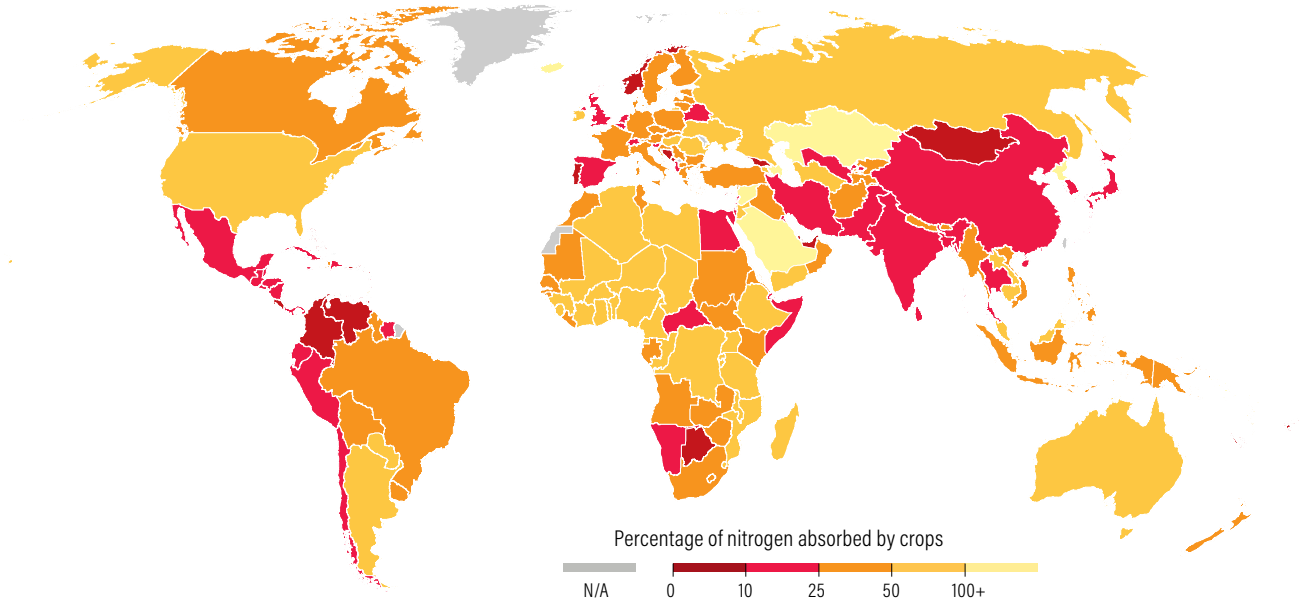
Note: Eutrophic water occurs when water bodies are oversupplied with nutrients and support rich plant and algal growth. Hypoxic water occurs when abundant plants and algae die and decompose, consuming oxygen and depriving other aquatic life of oxygen.
Maps are for illustrative purposes and do not imply 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: WRI (2013).

Increasing food production implies a growing demand for fertilizer and higher associated emissions and pollution. How much higher depends on how efficiently crops use nutrients. On a global basis, estimates of the efficiency with which crops absorb the nitrogen (from all sources) added to croplands range from only 42 to 47 percent.[89] As Lassellatta et al. (2014) found, this nitrogen use efficiency (NUE)[90] actually declined from around 68 percent to 47 percent between 1961 and 1980 as farmers around the world adopted synthetic fertilizers, and it has remained roughly at that level since.[91] Put another way, more than half of the nitrogen applied to crops is lost to the environment.

Countries differ greatly in both their NUE (Figure 27-4) and rates of nitrogen fertilizer application per hectare (Figure 27-5). Regions group into four broad categories. At one extreme, most countries in sub-Saharan Africa use little fertilizer, and whatever fertilizer they use is more fully absorbed by crops, leading to an average NUE of 72 percent and above.[92] At the other extreme, China and India—which accounted for 80 percent of the global increase in total nitrogen use between 2000 and 2009[93]—generally overapply fertilizer and have NUEs of roughly 30 percent.[94] In a third category, a few developed countries, such as the United States, Canada, and France, have NUEs approaching 70 percent. In the fourth category is the rest of the world which has NUEs of around 50 percent.[95]

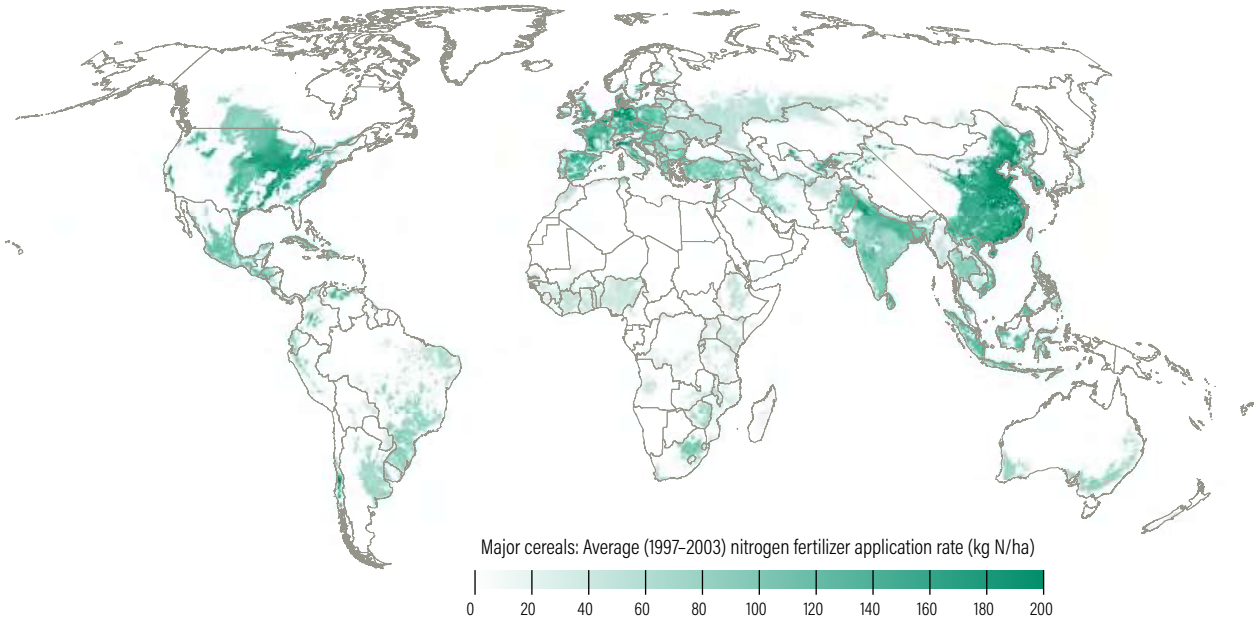
Rising NUEs in some regions and for some crops inspire confidence that increases in NUE are both possible and practical. The Netherlands, for example, cut back its nitrogen use from an astonishing level of around 600 kg per hectare in the late 1970s to around 300 kg in more recent years, mostly by exporting or processing some of the manure from the country's dairy farms instead of spreading it excessively on farm fields.[96] France, whose agriculture is more focused on crops, applies fertilizer at only a little more than half the per-hectare rate of the Netherlands. Total fertilizer application rates per hectare in France have remained stable now for many years. Yet yields in France have increased, meaning that fertilizer use per ton of crop has decreased, and NUE has increased from roughly 30 percent in the late 1970s to approximately 70 percent in 2010.[97] Nitrogen use efficiencies have also

Figure 27-4 | The percentage of applied nitrogen that is absorbed by crops varies widely across the world



Note: Absorption rates greater than 100 percent mean crops are mining nitrogen from soils. 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: Zhang et al. (2015b).

Figure 27-5 | Total nitrogen fertilizer application is heavily concentrated in China, the United States, India, and Western Europe



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: Mueller et al. (2012).

been growing in the United States, from roughly 60 percent in 1990 to around 70 percent in 2010, according to one study.[98]

Despite these improvements, there are reasons not to be overly optimistic about potential reductions in nitrous oxide emissions from fertilizer use.

First, in Africa, nitrogen use efficiency is likely to decline. The region's farmers today apply so little fertilizer that the annual removal of crops depletes the soils of nitrogen and phosphorus.[99] As farmers in Africa apply more fertilizer, which is necessary to boost yields, plants will be less able to absorb all the nitrogen and nitrogen use efficiency will decline.

Second, although Zhang et al. (2015b) showed that nitrogen use efficiency has stopped declining in most countries, and has improved in some, it has yet to start improving in most countries.

Third, major agronomic reasons help to explain the wide differences in NUE among countries. One reason China's NUE is so low is that it produces large quantities of rice and vegetables, which have low NUEs. Rice NUEs are low in part because the flooding and drainage required for paddy rice leads to increased nitrogen loss, while fruit and vegetable NUEs are low probably because their high economic value makes it economical for farmers to apply more nitrogen even when it leads to only modest additional production. According to Zhang et al. (2015b), half of the difference between NUEs in China and the United States is explained by China's crop mix.[100] In addition, farmers in countries with greater rainfall variability and less rich soils will find it harder to use nitrogen efficiently because crops will not be able to fully absorb available nitrogen in bad rainfall years. These differences help to explain why countries with similar yields for the same crops have different NUEs.[101]

Even for farming regions such as the U.S. corn (maize) belt that have achieved large increases in NUE, those increases have still been insufficient to reduce nitrogen losses to the environment because nitrogen used for higher production exceeds the nitrogen saved through higher efficiency.[102] Despite increases in NUE since 2005, U.S. agricultural nitrous oxide emissions have increased by 7 percent,[103] and the corn belt remains a global

hotspot for nitrous oxide.[104] Over the same period, the region's contribution of nitrogen to the major dead zone in the Gulf of Mexico has remained roughly constant.[105]

Overall, studies reveal no clear trend line in NUE across different crops and regions.[106] For this reason—although some increases in NUE would also be plausible—our baseline 2050 projection assumes that farmers in each region will produce each crop with the same NUE as today. As a result, we project an increase of 48 percent in the use of nitrogen fertilizer from 2010 to 2050, which is roughly in the middle of other prominent estimates.[107] That increased use is likely to increase overall losses of nitrogen to the environment by roughly 50 percent.[108] We also project in our baseline that annual total emissions from fertilization will grow to 1,741 Mt CO_2e by 2050, an increase of 35 percent over 2010 levels.[109]

The Opportunity

Strategies for improving NUE typically focus on fertilizer management by farmers and these well-understood practices have an important role to play. But the scale of improvement required is so great that additional measures are necessary to exceed what farmers can achieve alone. We therefore focus also on measures to improve nitrogen fertilizer compounds themselves, as well as advances in breeding.

Better general agronomy and nutrient management

The traditional focus of fertilizer management has been characterized by the International Fertilizer Institute as the "Four Rs": the **r**ight source, at the **r**ight rate, at the **r**ight time, in the **r**ight place.[110] In effect, this means applying fertilizer at a rate that does not exceed what crops can use at a time when they can use it. As an example of improved timing, many farmers in the United States and Europe have split their nitrogen load into two applications. The right place means applying nitrogen to a plant's root zones. Some forms of nitrogen are injected into the soil to limit losses.

Despite these opportunities, improved NUE in the United States is probably due mostly to general improvements in agronomy. Data from the U.S. Department of Agriculture suggest that only 25 percent of cropland is fertilized in line with the "Four Rs" recommendations,[111] and that adoption of these recommended practices has not increased.[112] NUE improvements probably owe more to breeding crops with higher yields, which has simultaneously increased their nitrogen uptake efficiency.[113] In addition, there has been an overall increase in management intensity, including weed and pest control, optimal seeding rates, and improved irrigation practices. These changes have led to greater yield stability, which increases NUE because there is a greater likelihood that the nitrogen farmers apply will be used by the growing crop.

Manure management is also relevant because the concentration of livestock production today in many parts of the world leads to the "dumping" of excess fertilizer on nearby farm fields, much of which escapes to the environment. In Europe, the Nitrates Directive of 1991 has restricted the quantity of manure nitrogen applied per hectare. Despite some implementation exceptions, the directive has played a significant role in the improvements in some European countries, such as the Netherlands and Denmark, which apply a large quantity of manure to crop fields. The limits have often required transport of excess manure to where it can be well used.[114]

These experiences suggest that some technical potential exists everywhere to increase NUE without any major technological breakthroughs. The largest opportunities exist in China and India, where nitrogen overuse is high[115] (Box 27-1).

The United States and Europe also have potential to increase their NUE through more sophisticated "precision" agriculture. Many farmers already use precision agriculture techniques, which allow them to deliver different quantities of nitrogen to different portions of fields. Yet the information about precisely how much to deliver in different portions of fields is less developed. Researchers and industry are cooperating on some projects to develop more detailed and consistent data for analyzing how to adjust rates and application times in the corn belt, which should help to tailor recommendations more precisely.[116]

Alternative nitrogen fertilizer compounds

We project growth of more than 50 percent in the amount of crops that will need to be fertilized by 2050. This means that even if changes in farming practices using existing technologies were able to improve NUE globally by about 50 percent over the same period—a large ambition—the world would still need to use roughly the same amount of fertilizer that it does today. Because even greater increases in NUE will be required to reduce nitrous oxide emissions and other forms of nitrogen pollution, we believe that technological advances are also needed. We believe that significant opportunities exist to increase the use of fertilizer additives that can control the release of nitrogen into the environment and develop this whole class of technologies further.

Appreciating the importance of such compounds requires an appreciation of how important timing is to the efficient use of nitrogen. Most nitrogen fertilizer is applied as ammonium or a form of nitrogen (such as urea or ammonia) that quickly converts to ammonium in soils. Ammonium is relatively immobile in soils, but microorganisms convert it easily into nitrate. It is nitrate that is highly soluble in water and easily runs off, and it is the breakdown of nitrate when soils are waterlogged that leads to emissions of nitrous oxide.

If economics did not matter, farming could achieve high levels of nitrogen use efficiency by frequent applications of just enough fertilizer to feed crops for a few days. Crops generally need little nitrogen early in the growing season, large quantities of nitrogen at peak growth periods, and then little nitrogen thereafter.[117] Chen et al. (2011) describe a series of experiments in China that combined detailed crop modeling of maize by region to determine the best crop varieties and planting dates, and the likely nitrogen needs of the crop over the course of its growth. Researchers then fertilized the maize five times over the course of the year with the estimated quantities needed for that part of the growth cycle. The experiment doubled yields with no increase in nitrogen quantities and nearly eliminated nitrogen surplus. If farmers everywhere were willing and able to apply fertilizer many times during a cropping season and to devote equivalent scientific effort to estimating plant needs, they could probably achieve very high NUEs as well.

BOX 27-1 | Improving nitrogen management in China

In 2011, farmers in China applied 51 percent more nitrogen to each hectare of maize than farmers in the United States, yet yields were 18 percent lower.[a] Most farmers in China could probably cut their nitrogen application rates without any negative effect on yields, and many farmers apply so much nitrogen that reducing rates would increase yields.[b] In addition, while the amount of manure produced in China increased fourfold from 1949 to 2005, the proportion applied to agricultural soils fell from almost all the manure to slightly more than half, which means that nutrients in this manure are being dumped elsewhere where they cannot be used.[c] A partnership of researchers from China and the United Kingdom has comprehensively investigated opportunities to reduce fertilizer use or better use manure while maintaining yields. In a summary, these researchers stated that by using simple nitrogen management practices, China could reduce fertilizer use—without altering yields—enough to reduce total Chinese GHG emissions by 2 percent.[d]

A first level of progress can probably be achieved mainly by working closely with farmers to educate them about nitrogen management. A group of scientists in China undertook such an effort without substantial government support by developing a multiorganization collaboration of more than 1,000 researchers, working with extension agents and agribusiness to reach 21 million farmers managing 38 million hectares (Mha).[e] Their efforts increased yields on average by roughly 11 percent, and decreased nitrogen application by 15–18 percent, depending on the crop. Despite an elaborate network of extension agents (people assigned to help farmers), China's agricultural extension system is known to be ineffective, and this collaborative effort delivered more compelling results.

Notes and sources:
a. Li et al. (2014).
b. A national meta-analysis found that decreasing N input rate by 28 percent (national average) would on average slightly increase yields (Xia et al. 2016), and a study in Shaanxi Province found that nitrogen use in maize and wheat could be reduced by 70 percent and 20 percent, respectively, without changing or only slightly decreasing yield (Zhang et al. 2015a).
c. Li et al. (2014).
d. SAIN (2011).
e. Cui et al. (2018).

Such a solution unfortunately is not practical, given that applying nitrogen so frequently is expensive.

Without some cost-effective measures to keep nitrogen on the farm field until crops can absorb them, NUE improvements will be limited. And to the extent that soils hold nitrogen in the form of nitrate, some of that nitrate will probably be converted to nitrous oxide after rainfall that saturates soils, even briefly.

Fortunately, compounds generally known as "enhanced efficiency fertilizers" (EEFs) can keep nitrogen in the soil available to crops longer by delaying the chemical progression to nitrous oxide. One approach involves coatings or other compounds that protect the fertilizer from dissolving in water. Another is the use of urease inhibitors, which inhibit the conversion of urea fertilizer to ammonia. Although ammonia is not a GHG, it is a volatile gas that can be lost to the atmosphere, reducing NUE and contributing to air quality problems. As ammonia is also an intermediate stage in the production of nitrate, these inhibitors can also reduce nitrous oxide emissions. The third group of compounds is nitrification inhibitors that slow the conversion of ammonium to nitrite, and from nitrite to nitrate. The International Fertilizer Institute lists seven patented nitrification inhibitors as of 2010.[118]

All of these compounds can increase NUE and reduce nitrous oxide by delaying the conversion processes by which nitrogen is turned into the forms in which it easily escapes (ammonia and nitrate). Despite great variation in results from field to field and year to year—probably heavily influenced by weather patterns—the great majority of studies have found, on average, substantial reductions in nitrogen losses to the environment when using any of the three types of compounds.[119]

Metastudies have also found that nitrification inhibitors and polymer-coated fertilizers on average reduced nitrous oxide emissions by between 35 and 40 percent.[120] There are two main reasons to believe that controlled-release fertilizers can become still more effective. One is simply the lack of research. One report estimates that the entire global research and development budget of the fertilizer industry for all purposes is only around $100 million per year, equal to 0.1–0.2 percent of its revenue.[121] By comparison, pharmaceutical companies and seed industries devote 10–20 percent of their revenues to research.[122] Probably only a fraction of this fertilizer R&D spending goes into EEFs. As a result, little funding has been made available by fertilizer companies to pursue new, better, and cheaper EEFs or to demonstrate where existing products will work best.

A second reason lies in the large variation in effectiveness of different compounds in different agronomic conditions.[123] Although some variability is likely inevitable because of variable weather patterns, compounds can respond differently to these patterns, as well as to different crops and soils. Better understanding of this variability should enable more effective and efficient use of compounds that delay the conversion of nitrogen in other forms into nitrate. There is no reason that fertilizer compounds, with different types and quantities of EEF compounds, could not be tailored to different conditions.

Because of their potential to reduce nitrous oxide emissions, nitrification inhibitors are often included in studies that examine cost-effective steps for climate mitigation.[124] For example, applying nitrification inhibitors to average corn fields in the United States might have a gross cost of around $50 per ton of CO_2e reduced.[125] But the evidence is growing that these compounds can have substantial economic benefits that at a minimum greatly reduce the net costs.

One potential source of economic savings is reducing nitrogen application while maintaining yields. Many studies do not test whether these compounds allow lower overall fertilizer use. Accordingly, one scientific review in 2009 concluded that there was no good evidence that inhibitors reduce the amount of fertilizer needed and therefore no good evidence that lower fertilizer costs offset the cost of the inhibitors.[126] However, other studies have found that these kinds of compounds make it possible to apply substantially less nitrogen while maintaining or boosting yields.[127] One such metastudy found that controlled-release fertilizers on average increased NUE by 13 percent.[128] Based only on this reduced need for fertilizer, one European study estimated that reduced fertilizer application would in general fully offset the costs of inhibitors.[129]

Increases in yield are also possible. A recent meta-analysis of nitrification inhibitors for farms applying nitrogen at recommended rates observed wide variability in yield effects but found average yield increases of 7.5 percent—with bigger increases in irrigated fields.[130] Another meta-analysis found average yield increases of 9 percent for grains, 5 percent for vegetables, and 14–15 percent for hays and straws.[131] If these kinds of yield gains are real, using nitrification inhibitors should be profitable. For example, one study estimated an additional cost of only $26 per hectare for good U.S. corn fields, and a yield gain equal to $164 per hectare.[132] The potential to increase yield, however, probably depends on how much nitrogen farmers are already applying. Where they apply too much fertilizer, an inhibitor is less likely to boost yields, so the main potential savings are probably from reduced use of fertilizer.

Given this potential for positive responses, McKinsey & Company has gone so far as to assume that these compounds save money overall, which leads to "negative costs" for reducing nitrous oxide through their use.[133] Yet one global marketing company estimated sales of controlled-release fertilizers to be only around 2 percent of global sales of nitrogen fertilizers in 2012–14.[134] If these compounds are profitable, then why do farmers use them so little?

Much of the explanation probably lies in the high variation and, therefore, uncertainty in the costs and benefits farmers will face.[135] For example, while one recent meta-analysis found increased yields on cereal crops, another found increased yields only on forage and vegetable crops, but not cereals.[136] Given this uncertainty, compounds are marketed to those farmers who face the greatest threat of losing nitrogen before crops can use it—such as those who apply fertilizer for the next year's crop in the fall, or those who farm on sandy soils. Despite the promise of this technology, increased use probably depends on regulations that not only directly require more use but also encourage development of information about when and where these compounds work best. Such a regulatory push is probably also necessary to persuade the fertilizer industry to explore the full potential development of these technologies.

Breeding opportunities

Chapter 12 discussed the promising option of deliberately breeding crops to utilize nitrogen more efficiently, as well as the increases in NUE that probably occur when breeding for increased yields alone. Taking a more radical step, and therefore with less chance of success, some breeders are trying to breed major grains to fix their own nitrogen.[137] Although this effort has received some publicity, the minimal literature on breeding to increase NUE—even at the level of discussion—suggests that research efforts are small.

Biological nitrification inhibition (BNI) for crops, similar to that for pasture grasses discussed earlier, provides another major opportunity. Just as researchers found that the *Brachiaria humidicola* grass exudes a chemical that inhibits nitrification, so they have found that each of the world's major grains, including wheat, maize, rice, and sorghum, has either wild or cultivated varieties with some level of BNI. A research partnership is under way to increase the production of the natural inhibitor sorgoleone in sorghum, and a BNI sorghum will probably be available within five years.[138] Research is also under way to transfer the chromosome region that controls BNI function from wild wheat strains into modern elite wheat varieties.[139]

As these researchers point out, BNI has potential advantages over chemical additives because BNI would come as an integral part of the plant and require no additional labor. In addition, the biology of plants has evolved to exude these inhibitors precisely into the parts of soils where nitrogen builds up and to continue to do so as plants grow. As a result, they can potentially achieve more inhibition than chemical inhibitors, which to date can last no more than a few weeks.

Improving balance among multiple nutrients

For most of the world's farmers, fertilization focuses on the macronutrients nitrogen, phosphorus, and potassium and ignores additional nutrients that can be both deficient and important to crop growth, such as sulfur, calcium, iron, zinc, and nickel. Unfortunately, the needs for these micronutrients are poorly understood, and the quantity of micronutrients needed may depend on the availability of other micronutrients.[140] Soil and root interactions are poorly understood, especially

complex microbial influences. Greater knowledge would probably enable improved breeding of crops and increased "inoculation" of soils by spreading microorganisms that help roots fix nutrients. Seed coatings with either micronutrients or one of the major nutrients have shown promise in some cases. In other situations, the best opportunity may involve directly spraying micronutrients onto the crops.

In all cases, more efficient fertilization has the potential to increase NUE and reduce emissions by leading to greater crop growth and more efficient use of the principal, potentially polluting, macronutrients nitrogen and phosphorus. But this whole field of knowledge receives limited research funding.

Estimating the opportunity

Although the evidence suggests that some improvement in NUE and consequent reduced nitrous oxide emissions would be cheap or even profitable, there is no sound basis for estimating what level of NUE is economically achievable or cost-effective. Zhang et al. (2015b) developed global NUE targets for major crop categories, which would raise the global average efficiency for all crops from 42 percent to 68 percent.[141] The 68 percent target includes NUEs of 85 percent for soybeans, 60 percent for rice, 40 percent for sugar crops and fruits and vegetables, and 70 percent for all other crops. In the GlobAgri-WRR model, we developed four scenarios in which farms in each of the world's regions close the gap between present performance and the goals of Zhang et al. (2015b) by 25 percent, 50 percent, 75 percent, and 100 percent.

Table 27-1 shows the results. Although all NUE progress contributes to significant emissions reductions, only achieving a global average NUE of 71 percent—slightly above the target in Zhang et al. (2015b)—would keep fertilizer emissions close to their 2010 levels. An NUE of 71 percent would reduce 2050 emissions by more than 600 Mt, roughly a 35 percent reduction. Yet even under this most optimistic scenario, fertilizer emissions would still remain above 1.1 Gt per year in 2050—more than one-quarter of our target for total agricultural production emissions of 4 Gt per year.

Table 27-1 | Global effects of scenarios of improved nitrogen use efficiency on agricultural greenhouse gas emissions

SCENARIO	GLOBAL AVERAGE NITROGEN USE EFFICIENCY (PERCENT)	EMISSIONS FROM SOIL FERTILIZATION[a] (MT CO_2E)	TOTAL PRODUCTION EMISSIONS (MT CO_2E)	PRODUCTION EMISSIONS GHG MITIGATION GAP (GT CO_2E)
2010	**46**	**1,289**	**6,769**	**—**
No productivity gains after 2010		1,758	11,251	7.3 (2.2)
2050 BASELINE	**48**	**1,741**	**9,023**	**5.0**
25% NUE gap closure *(Coordinated Effort)*	56	1,459	8,741	4.7 (-0.3)
50% NUE gap closure *(Highly Ambitious)*	62	1,306	8,588	4.6 (-0.4)
75% NUE gap closure (*Breakthrough Technologies)*	67	1,205	8,487	4.5 (-0.5)
Meets high NUE target[b]	71	1,130	8,412	4.4 (-0.6)

Notes:
a. "Emissions from soil fertilization" includes emissions from the energy used to produce and transport fertilizer.
b. Defined in Zhang et al. (2015b) as 70 percent for most crops, 85 percent for soybeans, 60 percent for rice, and 40 percent for sugar, fruits, and vegetables).
Numbers not summed correctly are due to rounding. Numbers shown in parentheses are changes relative to 2050 baseline.
Source: GlobAgri-WRR model.

BOX 27-2 | Possible refinements of nitrous oxide emission rates from fertilizers and their significance for nitrogen use efficiency (NUE)

Nitrogen use efficiencies may play an even more prominent role in determining global GHG emissions than our model calculates. GlobAgri-WRR uses a "default" emission standard adopted by the IPCC, which assumes that nearly all nitrogen deliberately applied to cropland, and all fertilizer applied to grassland, generates the same quantity of nitrous oxide per kilogram of nitrogen. The percentage in Tier 1 calculations works out to 1.45 percent of all nitrogen applied. As a result, 10 percent more nitrogen applied to farm fields means 10 percent more nitrous oxide. There is also a higher, fixed IPCC Tier 1 rate of 2 percent for nitrogen excreted in manure and urine by grazing animals, and that too is the same on all fields. But estimating nitrous oxide emission rates is challenging because the bulk of a field's emissions often will occur over only a few hours on one or a few days per year. The resulting data have enormous variation. In recent years, evidence has been growing that these estimates are too simple, which has important implications for mitigation strategies.

First, data are accumulating that emission rates likely overestimate emissions in drier regions, such as Australia and much of Africa,[a] but also likely underestimate emissions from wetter regions, at least on farms that use large quantities of nitrogen. Some of these underestimates may result from an underestimate of indirect emissions when nitrogen runs off into streams.[b] As soils around the world become increasingly saturated with nitrogen, emission rates may also increase.[c] These findings make intuitive sense because nitrous oxide should be higher where soils are more likely to become saturated and where there is more nitrogen available to the microorganisms that release nitrous oxide.

Second, there is a good chance that nitrous oxide emissions will increase as yields grow because, even with constant NUE, higher yields mean a larger nitrogen surplus per hectare. To use a simple numerical example, if crops remove half of the applied nitrogen and the rest is surplus, then doubling the yield while maintaining the same NUE will double the surplus. Unfortunately, evidence is increasing that the greater the surplus of nitrogen, the higher the rate at which nitrogen turns into nitrous oxide.

One meta-analysis of data from several studies indicated low nitrous oxide emissions at high rates of NUE but high exponential growth in emissions thereafter as NUE rates decline: emission rates could potentially approach 10 percent of all applied nitrogen rather than the 1 percent used by the IPCC.[d] Two other meta-analyses found a slower, but still exponential growth rate tied to application rates,[e] which should be generally correlated with surpluses. These results tally with several experimental field trials in different countries.[f]

These studies have several policy implications, and are cause for both optimism and pessimism:

- The studies suggest that nitrogen emission rates may vary significantly both from country to country and among types of farms within a country. Once scientists can define these conditions better, mitigation efforts can focus on the high-emission sources.
- The data suggest that the problem is more acute in wetter regions that use abundant fertilizer, such as North America, Europe, and China. Because of the technical sophistication of agriculture in these regions, they are better positioned to use advanced technology to apply nitrogen more efficiently.[g] The studies also suggest that increasing nitrogen use in Africa, which will result in declining NUE, might not result in nitrous oxide emissions as high as the levels we estimate using IPCC default emission rates.
- Global accounting rules may lead to a global underestimation of emissions. Under approved guidelines by the UN Framework Convention on Climate Change, countries are allowed to use lower emission rates if they can document and justify them. As a result, countries with drier climates have an incentive to document their lower emissions rates, while countries with higher actual emissions will lack this incentive and may instead adhere to IPCC methods that underestimate emissions. If science bears out these patterns, the IPCC should adjust its default emissions methods and countries should accept those changes.
- These data make increasing NUE even more important. On the one hand, as yields grow, just maintaining the same NUE means that surpluses of nitrogen per hectare will keep growing as yields increase. To illustrate, an NUE of 50 percent means that 50 percent of applied nitrogen is surplus to crop requirements. As a result, fertilizing a hectare that yields 10 tons of maize versus one that generates 5 tons will result in twice the nitrogen surplus per hectare. If the emissions rate is always 1 percent, as we and the IPCC assume, then emissions double, but if the emissions rate were to jump from 1 to 2 percent with the higher surplus, then the level of emissions would quadruple when the yield grows to 10 tons.
- Overall, if nitrogen surpluses dictate the rate of nitrous oxide emissions, then inefficient nitrogen use becomes even more harmful and highly efficient nitrogen use becomes even more beneficial.

Sources:
a. Hickman et al. (2014, 2015).
b. Turner et al. (2015).
c. Reay et al. (2012).
d. Van Groenigen et al. (2010).
e. Shcherbak et al. (2014); Hickman et al. (2015).
f. Hickman et al. (2015); McSwiney and Robertson (2005).
g. Gerber et al. (2016).



There are, however, several good reasons to believe these efficiencies underestimate the benefits of the measures we propose.

- First, nitrification inhibitors might be able to reduce nitrous oxide even more than improvements in average NUE by keeping nitrogen in the form of ammonium longer or perhaps at key times. Our analysis does not factor in additional benefits beyond the increases in NUE.
- Second, our analysis uses the simplest IPCC emission factors for emissions of nitrous oxide from farm fields. This emission factor applies the same emission rate to each kilogram of nitrogen regardless of how large the amount of nitrogen surplus is on the field and regardless of the amount not used by crops (Box 27-1). If farms achieved the higher efficiencies proposed in our model scenarios, even though the quantity of nitrogen used would still grow modestly compared to 2010, the surplus nitrogen not absorbed by crops would decline disproportionately—by approximately 50 to 80 Mt according to one study.[142] New science suggests that the emissions depend on the amount of this surplus nitrogen, as discussed in Box 27-2, and not the total amount of nitrogen. If correct, then emissions in our mitigation scenarios could decline much further.
- Third, science increasingly suggests that present systems are underestimating various indirect sources of nitrous oxide, which do not result from the farm soil itself but from the nitrogen after it is lost from the soil. One paper suggests that the major sources of loss from the U.S. corn belt could be occurring in the many drainage systems for farm fields plus the tiny streams that receive water flowing from them or from leaching of farm water through the ground.[143] Because large increases in NUE could disproportionately reduce these waterborne losses, they could also reduce nitrous oxide by more than we estimate.

Overall, some improved management with existing technologies could lead to meaningful progress. Major progress seems possible with use of enhanced efficiency fertilizers, and truly impressive progress may be possible with technological breakthroughs.

Recommended Strategies

The true scope of the nitrogen challenge by 2050 indicates that large improvements in both practices and technology are required. Our four recommendations reflect that challenge.

Establish flexible regulatory targets to push fertilizer companies to develop improved fertilizers

Our assessment is that nitrification inhibitors and related compounds hold great promise to increase NUE, boost yields, and reduce nitrogen runoff and nitrous oxide emissions in cost-effective ways. In some circumstances, farmers may experience increased profits. This potential exists on a variety of farms even with present technology, and the variability in performance suggests high potential both to make compounds better and cheaper and to target them where they are most effective. Yet this potential is going unrealized because compounds have variable and uncertain effects on different farms and crops, because farmer decisions do not need to reflect environmental costs, and because industry devotes too little research funding to inhibitor technology. A flexible regulatory approach therefore seems appropriate to encourage the industry to market more vigorously to the farms that would benefit the most with current inhibitor technologies, to improve understanding of optimal uses over space and time, and to improve the technology.

One approach is to mimic vehicle fuel efficiency standards, as elaborated in Kanter and Searchinger (2018). In the United States, as a result of fuel efficiency standards in place since the 1970s, auto manufacturers are responsible for increasing the fuel efficiency of their fleets over time. This obligation created the incentive to design the most efficient cars for consumers, and to improve fuel-efficiency technology over time.[144] It also probably encouraged innovation in marketing. The need to sell small, more fuel-efficient cars to average out their fleet efficiencies gave auto manufacturers an incentive to improve them and target consumers most likely to appreciate such cars.

A similar program might impose obligations on fertilizer companies to incorporate compounds into their mix of fertilizer sales to achieve increasing levels of nitrous oxide reductions over time. For example, a law might start with a requirement for 15 percent of sales to incorporate EEFs and steadily increase the requirement to 30 percent in 15 years. An alternative could vary the quantity of EEFs sold based on their effectiveness. Companies would have to demonstrate quantities sold and likely reductions based on how farmers use their product. This approach would allow companies to choose the types of compounds they sell and to target compounds where they would have the most impact. It would also encourage manufacturers to research where compounds would be most effective to support their sales efforts and give them incentives to improve their products and tailor them to different farming conditions.

To justify this kind of regulation, it is not necessary to downplay other nitrogen-reduction strategies. Nor do EEFs need to be effective for all farms or be used by all farmers. The evidence merely needs to show, as we believe it does, that EEFs have the technical and economic potential to play a larger part in a cost-effective nitrogen-management effort. Phasing in higher efficiency standards over time would allow companies to start by selling the least-expensive yet effective compounds to a small share of farms that existing science indicates would benefit the most.

The fertilizer production industry is highly concentrated, but its distribution system relies heavily on independent retailers and distributors. However, the U.S. Renewable Fuel Standard (RFS) illustrates how to address this complexity. The RFS requires that increasing quantities of renewable fuels be blended with gasoline or diesel over time and in this way is similar to our proposal for steadily increasing percentages of EEFs. As with the fertilizer industry, the fuel distribution network can be complex. The RFS deals with this complexity by assigning responsibility for meeting blending requirements to refiners or importers of oil. A fertilizer program could imitate this approach by applying requirements to producers and importers of fertilizers. However, the RFS program awards credits to producers of renewable fuels. Producers and importers meet their obligations by acquiring these credits from other producers, from other actors who blend further down the fuel chain, or from a credit market, which ensures that standards are met overall even if a particular blender falls short.[68] In this way, producers and importers of fuel do not have to produce renewable fuels themselves;

they just need to make sure that someone along the supply chain is doing so, and in an amount that meets the percentage requirement of the producer or importer. In the same way, fertilizer manufacturers or importers could meet their obligations without producing EEFs themselves and without having to track their own fertilizers by assuring that sufficient quantities of EEFs are sold somewhere.

India provides the closest example to date of this approach with its New Urea Policy, adopted in 2015.[145] It requires that fertilizer manufacturers coat all domestically produced urea with neem, a natural coating substance that delays nitrogen release over the course of the growing season.

Any country or subnational government could move this process along by adopting this kind of regulatory standard. For example, the state of California has led climate change efforts in the United States and is a natural candidate for pioneering this approach. Large food companies could also encourage this process through their own purchasing standards. For example, Walmart announced in 2013 that it would require its suppliers to submit plans to cut their nitrogen fertilizer use substantially.[146] Increasing use of advanced fertilizer compounds could play a valuable role in such plans.

Shift fertilizer subsidies into support for higher NUE

A wide range of economic research supports the view, predicted by basic economic theory, that farmers' fertilizer application rates reflect the ratio of fertilizer prices to crop prices in both developed and developing countries.[147] The price ratio helps explain differences in application rates across countries.[148] If subsidies artificially lower fertilizer prices to farmers, then farmers will use more fertilizer than they otherwise would.

In Africa, where farmers currently use little fertilizer, the case for and against fertilizer subsidies is complex (and we evaluate these arguments in Chapter 36). But in Asia, the case seems clear that fertilizer subsidies should be phased out. Economic studies have found that fertilizer subsidies in Asia contributed to agricultural growth and poverty reduction in the early years of policy implementation but that their effect declined thereafter.[149] Since the early years of subsidy programs, other efforts to raise agricultural productivity have had far greater impact. These efforts include agricultural R&D, roadbuilding, irrigation, and education. Reforms in tenure law and agricultural market liberalization have had even bigger effects.[150]

The evidence is strong that farmers in both China and India overuse fertilizer.[151] This overuse leads to particularly high emissions in China because much of the fertilizer in China is generated using energy from coal.[152] Fertilizer subsidies in China reached $18 billion in 2010 through various mechanisms.[153] In a bold step forward, China decided in 2015 to phase out the principal subsidies by the end of 2017, which had been artificially lowering prices for fertilizer manufacturers.[154]

Nitrogen fertilizer subsidies remain high in many other Asian countries, including India, Bangladesh, and Indonesia.[155] In India, fertilizer subsidies reduced domestic nitrogen prices to less than one-fifth of international prices from 2011 to 2014.[156] The annual cost of up to nearly $15 billion[157] constituted 5.6 percent of total government spending in 2011.[158] For many years, fertilizer subsidies have been particularly distorting because they more generously supported nitrogen than other nutrients, resulting in unbalanced fertilizer application. This structure has led to both reduced yields and highly inefficient use of nitrogen.[159]

The challenge of reforming fertilizer subsidies is mainly socioeconomic and political. All Asian countries with high fertilizer subsidies have large numbers of small farmers whose economic conditions are stressful and who benefit from fertilizer subsidies. Realistically, there is probably greater opportunity to reorient subsidies than to eliminate them.



We therefore recommend shifting subsidies from fertilizer toward NUE. Governments could start by shifting subsidies toward fertilizers that include nitrification inhibitors or other delayed-release compounds. Governments also should develop incentives to shift to application techniques that apply fertilizer more frequently and in balanced amounts.

Support critical research and development

Reaching long-term nitrogen management goals requires major innovations. Highly promising options include improved development and use of chemical EEFs and BNI. Less developed but also promising options include nitrogen-fixing cereals and crop breeding targeted to increase NUE. As we discuss in Chapter 12, funding for all these categories of research is minimal in relation to their importance and promise, and governments need to increase this funding.

At a more applied level, governments and the private sector need to pursue the kinds of detailed, site-specific agronomic analyses that can lead to more tailored application and use of fertilizers. The examples described above of researchers working with farmers in China or coming together to improve data in the U.S. corn belt illustrate the kinds of effort needed.

Fund demonstration projects of advanced technologies

Governments already support agricultural conservation efforts through national conservation funding and international aid projects. Outside of Africa, where fertilizer application rates are simply too low, the focus of such efforts should be on advanced technologies, such as use of inhibitors, or highly site-specific application levels. One option governments should pursue involves performance-based projects that reward producers, or fertilizer contractors, for achieving high levels of NUE.

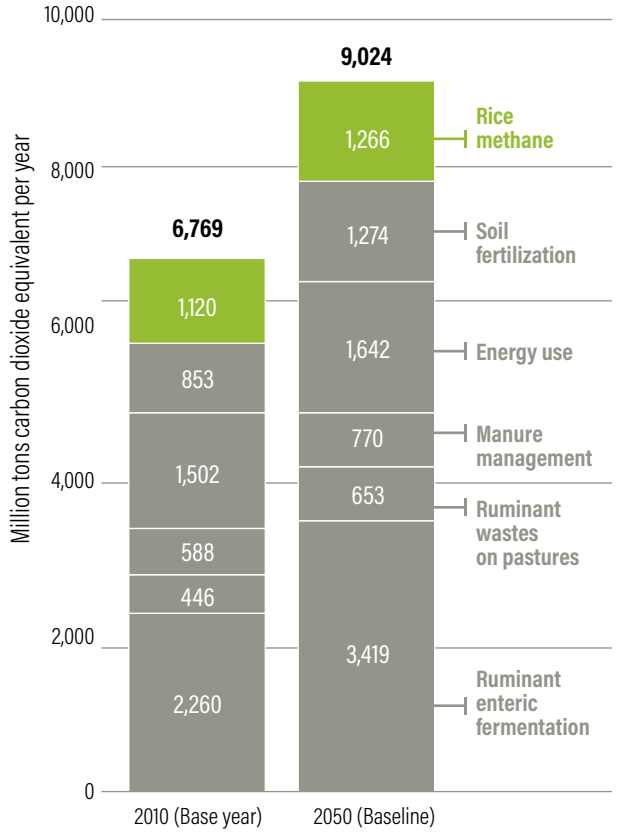


CHAPTER 28

MENU ITEM: ADOPT EMISSIONS-REDUCING RICE MANAGEMENT AND VARIETIES

Rice is one of the world's most important staple crops, but its production is a potent source of GHG emissions, primarily in the form of methane generated by flooded or "paddy" rice. This menu item focuses on strategies to reduce the GHG emissions produced by rice-growing and the potential of these strategies to increase rice yields and save water.

Figure 28-1 | Greenhouse gas emissions from agricultural production, 2010 and 2050



The Challenge

Rice is the largest staple crop for roughly half of the world's population.[160] Most rice is produced in flooded fields and, as in wetlands generally, flooding blocks oxygen penetration into the soil, which allows archaea that produce methane to thrive. Common estimates put paddy rice methane emissions at roughly 500 Mt CO_2e per year,[161] but adjusting for the IPCC's more recent estimates of the potency (global warming potential) of methane increases those estimates to 800 Mt CO_2e per year. In addition, paddy rice fields emit roughly 15 Mt CO_2e in the form of nitrous oxide.[162] The GlobAgri-WRR model estimates methane emissions from rice in 2010 at 1,120 Mt CO_2e,[163] using the more advanced methods for estimating methane rice emissions (so-called Tier 2 methods).

In short, paddy rice methane contributed at least 10 percent (and possibly more) of all global agriculture-related emissions in 2010 and approximately 2 percent of total human-generated GHG emissions. For most rice-growing countries in Southeast Asia, rice contributes around 50 percent of agricultural production GHG emissions and between 2.5 percent and 20 percent or more of total national emissions.[164]

Because the amount of methane emitted by rice cultivation depends more on the area of irrigated paddy rice land under production than on the amount of rice produced, boosting yields provides one way to reduce emissions per unit of production.[165] In 2014, farmers harvested rice on 163 Mha worldwide, an area roughly half the size of India. Ninety percent of production was in Asia.[166] Irrigated, flooded rice, which is responsible for the bulk of methane emissions, accounts for roughly half of total rice-growing area and 75 percent of the world's rice production.[167] Building on FAO projections, we project an increase in demand for rice of 32 percent between 2010 and 2050.[168] Using FAO projections for rice yields in 2050, we estimate some modest growth in paddy rice area, which means emissions will rise by roughly 150 Mt to 1,266 Mt of CO_2e in our baseline (Figure 28-1).

Unfortunately, the impacts of climate change, although uncertain, could decrease rice yields and increase GHG emissions from production. Some estimates of higher temperature effects on rice yields are harsh, on the order of an 8–10 percent decline in yield for every 1 degree Celsius increase in local temperature.[169] Millions of hectares of high-quality, low-lying rice lands in Asia could be affected by sea level rise, increasing the risks of salinity and flooding.[170] In addition, higher concentrations of carbon dioxide in the atmosphere may directly increase methane emissions by increasing the supply of carbon to the microorganisms that produce methane.[171] Although the science is evolving, one study estimated that the combination of lower yields and rising methane emissions could double the emissions per unit of rice by 2100.[172] This threat of growing emissions creates a powerful need to reduce rice emissions in ways that boost—or at least do not harm—yields and therefore hold down the need to expand rice-growing area.

The Opportunity

Four main strategies exist for mitigating GHG emissions from rice production: increase rice yields more rapidly, breed rice that produces less methane, improve management of rice straw, and reduce periods of flooding.

Increase yields more rapidly

The first strategy is to increase rice yields fast enough to reduce the necessary amount of future rice-growing area. FAO projects yields of 5.3 tons per hectare per year in 2050, which would be 23 percent higher than in 2010.[173] This yield growth is equivalent to only half of the annual absolute growth rate from 1962 to 2006, and the lower projection reflects judgments by experts that rice has decreasing potential to grow at higher yields. But if rice yields could grow at 62 percent of the annual rate that was achieved from 1962 to 2006, and reach 5.5 tons per hectare per year, rice-growing area would not need to expand.[174] An expert review on rice has found sufficiently high technical growth potential for rice yields to meet 2050 demand without land expansion. Fischer et al. (2014) estimated that the global potential yield for rice is 7.4 tons per hectare per year, well beyond the yield necessary to hold rice area constant.[175] Increasing yields beyond 5.5 tons per hectare per year could lead to an actual decrease in rice area and future emissions.

Breed lower-methane rice

Scientists have long known that some rice varieties emit less methane than others.[176] One 2017 paper showed that some high-yielding rice varieties already in use generate roughly 10 percent less methane than the average rice variety.[177]

More ambitiously, in 2015, a group of researchers reported developing a new breed of rice that generates only 10 percent or less of the methane emissions of normal rice under controlled conditions in small pots during parts of the rice-growing seasons.[178] The researchers had added a barley gene, which had the effect of transferring growth from roots to granules, resulting in higher (but starchier) yields and providing less feeding opportunities for methane-producing archaea in the roots. The results were promising, but there are also reasons for caution. This 90 percent reduction occurred only during early parts of the rice-growing season and therefore would not alter the methane emissions that occur later. The researchers have added the gene to only one variety of rice so far. And field experiments would be necessary to determine both how well rice plants do with more limited root growth and how methane emissions react under broader, real-world field conditions.

Minimal efforts are devoted to deliberately breeding low-methane rice varieties and encouraging their wider use. Overall, research results suggest that a deliberate effort to do so should be able to reduce methane emissions.

Remove rice straw

Rice straw is the nongrain portion of rice plants. Methane emissions increase when farmers add fresh (noncomposted) rice straw to flooded fields, which increases the carbon available to produce methane, particularly if farmers do not plow the straw under before planting. Yet burning, a common alternative for rice straw in some regions, also creates methane and other GHGs as well as local air pollution. Strategies to reduce emissions include incorporating rice straw into fields well before the new production seasons start. Another option is to remove rice straw from fields to use for other productive purposes, such as growing mushrooms, generating energy, or creating biochar.[179]

Reduce flood periods

Various practices can reduce or interrupt periods of flooding. The longer rice remains flooded, the more methane-producing archaea grow, and the more methane they generate. Decreasing the duration of flooding therefore reduces methane production and emissions.[180] The drawdown of water in rice paddies is accomplished by temporarily halting irrigation, allowing water levels to subside through evapotranspiration, percolation, and seepage. Interrupting flooding even with occasional drawdowns has a dual effect: it quickly drives down the population of methane-producing archaea, and it stimulates the breakdown of methane by bacteria. Although the reduction in methane emissions is not necessarily proportional to the duration of the drawdown, studies have found that almost any means of reducing or interrupting this flooding reduces methane emissions.[181] Even reducing flooding during the off-season—as many Chinese farmers do—can reduce emissions.

Systems for reducing flooding and emissions during the crop-growing season fall into four categories:

- **Dry seeding.** Most paddy rice production in Asia follows the traditional pattern of transplanting seedlings grown in nursery areas into already flooded paddies. But direct seeding of rice into dry fields is spreading in Asia and probably now accounts for one-quarter of all rice production in the region.[182] Farmers in the United States use direct seeding because it requires less labor.[183] Direct seeding can be practiced in flooded fields ("wet seeding") or by drilling seeds into dry fields ("dry seeding"). Wet seeding in flooded fields is unlikely to reduce methane emissions.[184] But dry seeding reduces emissions because it shortens the flooding period by roughly a month.[185]
- **Single midseason water drawdown.** Studies have shown that a single drawdown during the crop production season, sufficient to allow oxygen to penetrate the soils, substantially lowers GHG emissions. Typically, this kind of drawdown must occur for 5–10 days to generate methane benefits.[186] Most farmers in China, Japan, and South Korea already practice this drawdown to increase yields.
- **Alternate wetting and drying (AWD).** This practice involves repeatedly flooding a farm field, typically to a water depth of around 5 centimeters, allowing the field to dry until the upper soil layer starts to dry out (typically when the water level drops to around 15 centimeters below the soil surface), and then reflooding the field. This cycle can continue from 20 days after sowing until two weeks before flowering.[187] This approach is also known as "controlled irrigation" or "multiple irrigation," depending on the country and the research context. Because each drying cycle sets back the generation of methane-producing bacteria, AWD achieves even larger reductions in methane emissions than a single drawdown. AWD can be practiced along a continuum of less to more frequent drawdowns.
- **Aerobic rice production.** Like AWD, this system involves adding irrigation water only when needed. It avoids standing water, aiming instead to keep soils moist. This system can drastically reduce—or nearly eliminate—methane production. In general, however, aerobic rice production has lower yields than rice produced through traditional methods or the three methods listed above. Still, as the case study below shows, some farmers in China are maintaining high yields by constructing raised beds and ditches, which limit standing water to furrows.

Effectiveness of reducing flood periods

All reductions in flooding can reduce methane emissions. Various studies have found that dry seeding can lead to reductions in GHG emissions of 30 percent or more.[188] IPCC guidance provides that a single drawdown will reduce emissions that would otherwise occur by 40 percent, and multiple drawdowns by 48 percent.[189] However, these figures are global averages. Evidence from the U.S. state of Arkansas indicates that AWD could reduce emissions by as much as 90 percent.[190] There is also evidence that combining different water-saving approaches can have additive benefits for mitigation. For example, studies combining dry seeding with AWD have found emissions reductions of 90 percent.[191]

One concern is that while drawdowns decrease methane emissions, they tend to increase emissions of nitrous oxide, another powerful GHG. Nitrous oxide emissions are generally low in continuously flooded rice systems. However, under water-saving strategies, nitrous oxide emissions tend to increase because alternating periods when oxygen is and is not present in soils maximizes the opportunities for nitrous oxide production. In general, studies that have measured nitrous oxide emissions under different water management regimes have found that increases in nitrous oxide have substantially less climate significance than the reductions in methane as long as excessive nitrogen is not introduced through high doses of fertilizer.[192] Reflecting this difference in impact, the IPCC guidelines do not account for increases in nitrous oxide emissions under water-saving techniques, and below we have chosen to follow this convention in our consideration of these techniques' GHG mitigation potential.

Significantly, one study using a more frequent sampling technique found very high emissions of nitrous oxide from three Indian rice farms that flooded their fields for only a few days at a time. The emissions were so high that the researchers suggested these brief flooding conditions could cause nitrous oxide emissions in excess of methane savings.[193] Overall, the farms in this study that contributed the high nitrous oxide emissions were flooded for only a small portion of the growing season, and the study did not present any continuously flooded farms as a control. This type of wetting and drying, lasting for short periods, contrasts with standard AWD, which has much longer cycles and which therefore maintains flooding much longer. When analyzing this form of AWD in contrast with continuous flooding, researchers have found that nitrous oxide emissions increase a little but not enough to cancel out savings from reduced methane.[194] The India study therefore does not cast doubts on the standard way of practicing AWD but it does raise concerns about whether such briefly flooded rice fields are common and whether all such fields contribute high nitrous oxide emissions. It therefore makes a case for efforts to replicate these findings on other farms and to analyze how many other farms may be flooded so briefly.

Because farmers do not directly benefit from reducing GHG emissions, emissions reductions alone do not motivate adoption of rice water management techniques. In contrast, many farmers directly benefit from saving water, which provides a potential incentive to reduce flooding. Rice production uses around 40 percent of the world's irrigation water,[195] and almost one-third of rice-growing areas face high levels of water stress.[196] AWD and dry seeding would lead to the largest reductions in water consumption because they involve the shortest inundation periods.

Yet current estimates of water savings are at the field level; they do not necessarily reflect water savings for a local area. Evidence suggests that most or perhaps nearly all of the water savings will result from reduced percolation,[197] which implies that some of the irrigation water saved by an individual field would otherwise have recharged groundwater or been used further downstream.[198] However, in periods when surface soils are allowed to dry out, evaporation from soils should decrease, which means that reduced flooding should also make some more water available at the system level. Further analysis in each district is necessary to determine the extent to which field-level water savings translate into savings for the district or aquifer.

Evidence of the effect of these water management practices on rice yields is mixed. Many early studies found yield declines from AWD.[199] But as AWD becomes more widely practiced, studies in Asia typically found yield gains, including in the Philippines,[200] Vietnam,[201] and Bangladesh.[202] Studies in India have found yield gains from AWD when practiced as part of a broader rice production system known as the "System of Rice Intensification."[203] In China, an estimated 80 percent of farmers perform a single midseason drawdown for 7–10 days because they have found that doing so increases crop yields.

Determining the precise reason for these yield gains requires further investigation, but there are at least three possible explanations:[204]

- Better resistance to lodging (bending over) of stems, attributable to better anchoring of well-developed roots or sturdier stems.
- More profuse early rice tillering (additional shoots), while midseason drawdowns suppress unproductive late tillering, which consumes the plant's energy while producing few or no rice grains.
- Less susceptibility to disease in some cases (although some studies have found greater susceptibility to disease and weeds).

Recent studies in the United States have found that AWD has no effect on yields as long as soils retained an acceptable level of moisture at all times. Studies also indicate that yields could drop dramatically if soil was allowed to dry too much at any one time. U.S. yields are nearly universally high, indicating a persistently high quality of management, which may help explain why changes in water management have not boosted yields.

Unfortunately, just because some of these water management practices are possible does not mean they are feasible everywhere or all the time. For example, to be able to practice AWD, farmers realistically need a number of physical conditions

to be met. They require well-leveled fields to avoid pockets that dry excessively. They must also be able to manage their water reliably, which means they must be able to drain their fields effectively and then they must also have a reliable source of water to rewet their fields as soon as needed. But most rice-growing regions have distinct wet and dry seasons. In the wet season, farmers may not be able to drain their fields adequately. In the dry season, only some irrigation systems can provide water reliably enough to encourage farmers to practice AWD.

In a series of case studies, we highlight what is known and not known about the opportunities and challenges of using some form of water management to reduce methane emissions during rice production. The case studies are drawn from key rice-producing areas in India, the Philippines, the United States, and China.

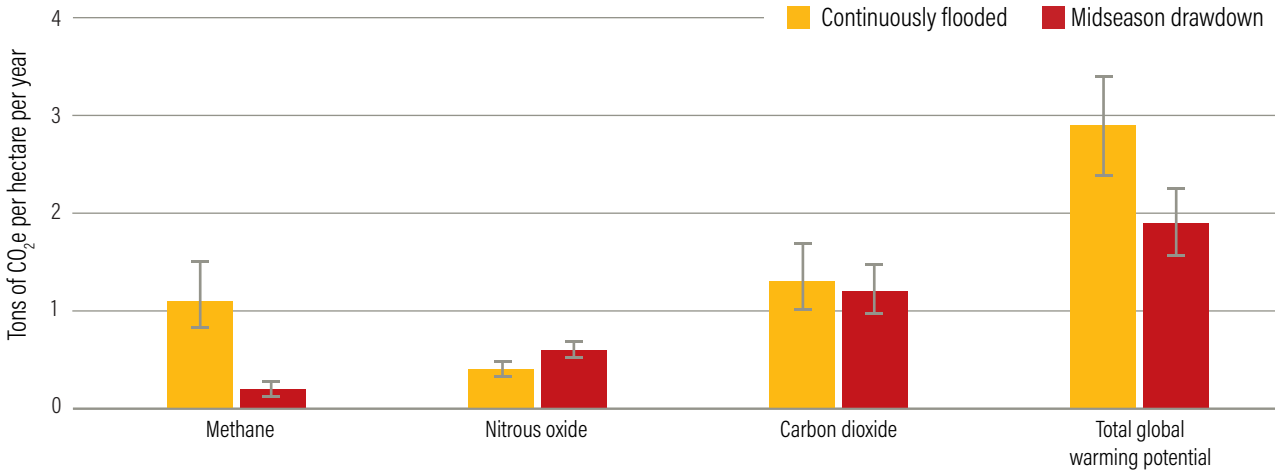
INDIA

India produces more rice than any country but China, and the states of Tamil Nadu in the south and Punjab in the north illustrate the opportunities and challenges for water management. Rice is the dominant crop in both states. Small farmers (working less than 2 hectares [ha]) farm half of the land in Tamil Nadu and one-third in Punjab and constitute the majority of farmers. Farms of 2 to 10 ha make up the majority of the remainder in both states. Both states also experience great water scarcity, withdrawing roughly 40 percent more water than rainfall replenishes each year. Farmers mine groundwater to meet their needs, and water tables are falling. In parts of Punjab, water tables have been falling by up to one meter per year, increasing pumping costs severalfold, and leading to contamination of soils with salt and wells with arsenic. Unable to conceive of an alternative solution, a recently released government plan proposed to reduce rice farming in Punjab by more than 40 percent.[205]

Researchers have performed at least a few studies of AWD or midseason drawdowns[206] in each region and have found substantial GHG emission reductions, yield gains, and water savings at the farm level (Figure 28-2).[207] Based on these water-saving and production benefits, government policy in both regions has promoted the System of Rice Intensification (SRI), which includes many practices of which one is, in effect, AWD. Although many farmers in Tamil Nadu and Punjab have adopted some components of SRI, few have adopted some kind of midseason drawdown.

The technical potential to engage in AWD, or even one midseason drawdown, varies in both regions. Because of porous soils, drainage is possible even during the wet seasons. However, many farmers

Figure 28-2 | Midseason drawdown reduces greenhouse gas emissions from rice production in Punjab by one-third



Note: Solid bars show average statewide emissions. Error bars represent one standard deviation.
Source: Pathak et al. (2012).

rely exclusively on surface water irrigation networks, which are too unreliable in both regions to practice wetting and drying. Somewhat more than half the farmers in Tamil Nadu and most farmers in Punjab also pump groundwater.[208] These farmers could therefore time their irrigations to perform AWD. Many farmers in Tamil Nadu also receive irrigation water from large earthen pits used to store water from the rainy season.[209] The potential probably exists to time water deliveries from these pits to allow AWD, although designing such a system would be more complicated than just turning pumps on and off. For many of these farms, additional leveling would also be necessary to ensure that drying the lower portions of fields does not lead to excessive drying of higher areas.

Dry seeding of rice is also starting to emerge as an alternative production system in Punjab, though it was practiced on only 5,000 ha in 2012.[210] Some studies have found GHG benefits and large irrigation savings at the field level.[211] One study found modest declines or increases in yields depending on the variety of rice used,[212] but follow-up studies found that these yield declines occurred where farmers did not follow recommended regimens of fertilizer and pesticide use.

Despite the potential for many farmers to practice AWD, two factors greatly limit their incentive to do so. First, farmers currently enjoy essentially free water. Second, governments heavily subsidize the electricity used to run pumps in both states. Unless it is proven to increase yields substantially, farmers have little individual incentive to implement some form of water management.

PHILIPPINES

The Philippines ranks eighth in global annual rice production, with around 4.4 Mha in production in 2010.[213] It is also the world's largest rice-importing country. Roughly 70 percent of the Philippines' total rice area is irrigated, but it produces relatively low yields of around 3.3 t/ha.[214] As in India, a few research studies in the country have found substantial reductions of methane emissions from midseason drawdowns, although there are no studies yet of AWD.[215] Yet few rice farmers engage either in drawdowns or dry seeding. One limitation is physical. One rice-growing season in the Philippines occurs during periods of heavy rainfall, which are heavy enough to limit the potential of most farms to dry their fields unless they employ drainage systems that are not now common. It is possible that one midseason drawdown might be possible on some of these fields, but that requires further analysis. Dry-season irrigation limitations are also important. Nationally, 86 percent of irrigation water comes from surface water irrigation, primarily rivers. The water supply is typically too unreliable for farmers to have confidence that they could replenish fields if they drain them. Two experiences, however, show some potential.

Roughly one-quarter of all rice farms use pumps to access groundwater, typically those at the last stage of surface water irrigation systems, where water deliveries are most unreliable.[216] These farmers can face high pumping costs. According to one study, half of all such farmers targeted by government initiatives to adopt AWD did so.[217] An analysis of an initiative in Central Luzon that targeted farmers with pumps found no statistically significant impact on yields under AWD. It also found no change in labor costs, which also suggested no increase in weeding problems.[218] This study also found that farmers employing AWD reduced their hours of irrigation by 38 percent[219] (while other studies found water savings of 15–30 percent).[220]

In general, these studies have confirmed farmers' willingness to switch to AWD where the costs of pumping water are high but not where costs are low.[221] Beyond physical limitations of surface-water irrigation schemes, farmers currently would also have little incentive to adopt AWD because they typically pay a fixed irrigation fee per hectare, usually about $50–$70 per season, and therefore have little financial incentive to use irrigation water judiciously. Creating incentives for AWD would thus require changing payment systems.

An irrigation project on the island of Bohol in the Visayas illustrates another potential model for some areas. In 2005 the National Irrigation Administration constructed a new dam with Japanese assistance to address declining and unreliable water supply. This new dam generated a far more reliable source of irrigation water; to optimize its use, the administration imposed an AWD irrigation schedule in 2006. Each farmer has irrigation water for three days, then none for the next 10 to 12 days. The project allowed farmers to cultivate in a manner that resulted in overall yield increases of 11–13

percent, an increase of 16 percent in irrigated land, and two rice crops instead of one in some parts of the island.[222] This project suggests how irrigation improvements could be tied to AWD for both GHG benefits and water savings.

UNITED STATES

The United States produces only 1.1 percent of the world's paddy rice and harvests only around 0.6 percent of the world's rice area.[223] Nevertheless, it has high yields of more than 8 tons per hectare and contributes 10 percent of internationally traded rice.[224] Six states produce nearly all U.S. rice: Arkansas, California, Louisiana, Missouri, Mississippi, and Texas, with half of production from Arkansas alone. In both the southern United States and California, recent studies have confirmed large GHG reductions via AWD of 50 percent or more.[225] In California, a study found emissions reductions of 90 percent when AWD was combined with dry seeding.[226] Rice farmers already mostly dry seed rice in Arkansas but not in California, where one study found nearly 50 percent reductions in methane emissions from dry seeding.[227]

In theory, AWD could prove attractive in both states because both suffer from severe water shortages and falling aquifer levels. One Arkansas study found increases in water use efficiency from AWD of 22 percent at the field level.[228] However, in California, AWD could lead to higher rates of water loss into groundwater because soils are heavy clay, which allows little percolation when flooded but cracks when dried.

Growing season rainfall is sufficiently low in Arkansas that farmers can dry their fields, and farmers are able to use pumps or on-farm reservoirs—filled in the winter—that provide sufficient and reliable water supplies. The main physical limitation in Arkansas is the size of fields. Unlike the small rice fields of Asia, single rice fields in the Arkansas are typically between 20 and 50 ha, with some much larger. Most are carefully leveled, which makes them promising for AWD. But because of their size, farmers usually divide fields into separate basins, separated by levees and weirs to control water heights and to allow water to move from one basin to another in a controlled fashion. To provide the level of water management for AWD, farmers would probably have to make adjustments to be able to deliver water separately to each separate part of the field.

Opportunities for AWD adoption are considerably lower in California. Because the state's Mediterranean climate generates little to no rainfall during the summer growing season, farmers rely on water deliveries from large, regionally managed water systems fed heavily by snowmelt and reliant on gravity. Farmers therefore do not have direct control over their water, and California's irrigation systems are generally unable to supply water quickly enough to all farmers at the time it is needed. Dry seeding probably provides the best option for water saving. Since dry seeding can increase the need for weed control, additional incentives would probably be necessary to persuade farmers to adopt the practice.

The other main concern is potential impacts on yield. Unlike in other countries, there is no evidence from U.S. tests that AWD would increase yields, and some earlier studies suggested yield declines. Meanwhile, there is some risk of lower yields if farmers overdrain fields.[229] The fact that Chinese and Japanese farms experience yield gains from at least one midseason drawdown but U.S. farmers do not presents a scientific puzzle.

Overall, it would appear that most Arkansas farmers, with reasonable adjustments, could implement AWD, while dry seeding should be an option for most California farmers. As in other countries, essentially free water limits their incentives to do so even while there might be collective benefits to farmers through water savings from broad adoption of these practices.

CHINA

Farmers in China harvest almost 20 percent of the world's rice fields by area and produce almost 30 percent of the world's rice.[230] The vast majority of China's farmers practice at least one midseason drawdown. Although most rice is grown on well-irrigated flatlands, much is still grown in hill environments, including two-thirds of Sichuan Province's 3 Mha of rice. The hilly terrain limits yields, increasing GHG emissions per ton of rice. Although farmers have long practiced intermittent flooding to reduce water consumption—with the side benefit of reducing methane—farmers also tend to keep fields flooded in the winter to ensure that water is available in the spring, when droughts are

frequent. This maintenance of standing water in the winter increases emissions.

One new technique used in Sichuan relies on plastic covering as mulch. As shown in Figure 28-3, farmers construct a series of furrows and raised beds, cover the beds with long strips of thin plastic film 1.5 to 2 meters wide, punch holes in the film, and transplant rice into the holes. Farmers maintain water in the furrow for approximately 1.5 months after transplanting seedlings but no water on the bed surface, and furrows themselves are drained for around two weeks in the middle of the season to inhibit late-emerging unproductive tillers, to remove toxic substances, and to improve root activity.

Research has found that plastic film mulching reduces GHG emissions by maintaining higher oxygen content in the rice bed, thereby inhibiting methane-producing bacteria.[231] Counting all sources of emissions, these studies suggest GHG emissions reductions of roughly 50 percent per hectare, and 55–60 percent per ton of rice, and even more if farmers use nitrification inhibitors.[232] Studies have also found yield and water benefits. In controlled comparison studies, plastic film mulching tends to improve yields by 5 to 20 percent, probably by raising temperatures.[233] Scientists have reported water savings per hectare of 58–84 percent and increased water use efficiency of 70–106 percent when factoring in the benefits of increased yields.[234] Economic studies have also found economic benefits through decreased costs of fertilizer, pesticides, weeding, and yield gains.[235]

In lowland parts of Sichuan Province, the use of plastic does not boost rice yields because soils are warm enough that they do not benefit from the increased warming, but a similar cultivation method has been developed without the film. Called either "ridge-ditch cultivation" or "aerobic cultivation,"[236] it too involves construction of raised beds and then maintenance of water in the furrows but not on the bed surface. As with plastic film mulching, studies have found that ridge-ditch

Figure 28-3 | New rice-growing techniques in Sichuan Province use furrows, raised beds, and plastic covering as mulch



Image source: Jing Ma.

cultivation significantly reduces methane emissions from paddy fields.[237] Studies also have found that this practice can enhance water use efficiency, improve topsoil temperature and soil aeration, reduce the amount of toxic substances, enhance soil microbial activities, and therefore promote soil nutrient transformation.[238] By improving soil conditions, ridge-ditch cultivation has also been measured to improve rice grain yields by 12.3 percent to 45.8 percent in comparison with traditional cultivation systems.[239]

Despite the promising results, these practices occur in only a small fraction of suitable rice-growing areas in the province. One reason is that these practices require more intensive labor during rice transplanting. Purchasing the plastic film also adds to production costs.

Model Results: Mitigation Potential

We used GlobAgri-WRR to explore six rice mitigation scenarios plus a number of variants:

- Mitigation scenario 1 includes rates of crop yield gains from 2010 to 2050 that are 20 percent higher than projected by FAO, which reduces the area under cultivation and therefore methane emissions. Instead of projecting increases from a global average of 4.3 tons of rice per hectare in 2010 to 5.3 tons in 2050 in our baseline scenario, we project that yields will grow to reach 6.4 tons per hectare. This growth would reduce rice area by 27 Mha compared to the area in our baseline.
- Mitigation scenario 2 involves a 10 percent reduction in methane emissions from rice production "across the board" due to improved breeding.
- Mitigation scenario 3 involves adoption of water drawdowns. In our baseline, we estimate that 90 percent of irrigated rice farms in China, Korea, and Japan already employ a midseason drawdown and 10 percent use continuous flooding, but we estimate that outside of these three countries, 90 percent of farms use continuous flooding.
  - In mitigation option 3a, we estimate that only 50 percent of farms outside of China, Korea, and Japan use continuous flooding, 25 percent employ one midseason drawdown, and 25 percent employ multiple drawdowns.
  - In mitigation option 3b, we assume that 90 percent of all irrigated farms outside of these three countries employ multiple drawdowns.
- Mitigation scenario 4 involves shifts in rice straw management so that rice straw is removed or mulched in some manner outside of the growing season. In some areas with double or triple cropping, a new rice crop is planted within a few days of the last rice crop. In those situations, we assume farmers have no time to remove their rice straw.
  - In mitigation option 4a, we assume half of all farms that are not growing a new rice crop in such a short time switch to out-of-season straw management.
  - In mitigation option 4b, 100 percent of all such farms employ out-of-season straw management.
- Mitigation scenario 5 combines options 3a and 4a, simulating a combination of low water-level drawdowns and a low level of straw mitigation.
- Mitigation scenario 6 combines faster growth in yields to 6.4 tons per hectare per year, a 10 percent across-the-board reduction in emissions due to plant breeding, and our first-level improvements in water and straw management (options 1, 2, 3a, and 4a).

Table 28-1 shows the results. Each of the mitigation options achieves substantial GHG emissions reductions relative to the baseline in 2050. Most options close the total GHG mitigation gap by between 1 and 3 percent, but scenario 6—which also includes yield gains and thus avoids future land conversion and associated emissions—closes this gap even more. Scenario 6, which puts together different forms of mitigation at plausible levels, would cut rice-production emissions by nearly 40 percent, close the production emissions GHG mitigation gap by 10 percent, and close the total GHG mitigation gap by 7 percent.

Table 28-1 | Global effects of scenarios of improved rice management on agricultural greenhouse gas emissions

SCENARIO	DESCRIPTION	METHANE EMISSIONS FROM RICE PRODUCTION (MT CO_2E)	TOTAL PRODUCTION EMISSIONS (MT CO_2E)	PRODUCTION EMISSIONS GHG MITIGATION GAP (GT CO_2E)
2010		**1,120**	**6,769**	**—**
No productivity gains after 2010		1,696	11,251	7.3 (2.2)
2050 BASELINE		**1,266**	**9,023**	**5.0**
1: 20% yield gains	Global rice yields reach 6.4 tons/hectare instead of 5.3 tons/hectare in 2050 (and 4.3 tons/hectare in 2010)	1,055	8,806	4.8 (-0.2)
2: new low-methane rice breeds	10% across the board reduction in rice methane due to new breed varieties	1,139	8,896	4.9 (-0.1)
3a: 50% water management	In countries that do not already employ drawdowns, half switch to midseason drawdown(s) or AWD	1,111	8,869	4.9 (-0.2)
3b: 90% water management	In countries that do not already employ drawdowns, 90% switch to midseason drawdowns or AWD	960	8,717	4.7 (-0.3)
4a: 50% off-season straw management	Roughly half of all farms manage rice straw out of season in all seasons where that is possible	1,170	8,927	4.9 (-0.1)
4b: 100% off-season straw management	All farms manage rice straw out of season in all seasons where that is possible	1,075	8,832	4.8 (-0.2)
5: 50% water management + 50% off-season straw management *(Coordinated Effort, Highly Ambitious)*	Combination of scenarios 3a and 4a	1,032	8,789	4.8 (-0.2)
6: Combined *(Breakthrough Technologies)*	Combination of scenarios 1, 2, 3a, and 4a	774	8,526	4.5 (-0.5)

Notes: Numbers not summed correctly are due to rounding. Numbers shown in parentheses are changes relative to 2050 baseline.
Source: GlobAgri-WRR model.



Recommended Strategies

From a purely technical perspective that ignores economic cost, available research suggests a high potential for mitigating GHG emissions from rice production. For example, although our case studies revealed a number of technical obstacles to employing midseason drawdowns on all farms, most farms could implement dry-seeding, many farms could implement water drawdowns today, and the obstacles facing other farms seem reasonable to overcome (such as the need for more level rice paddies in India or for more field pipes for distributing irrigation water in Arkansas). Faster yield gains are technically feasible and could do much to mitigate emissions. The most speculative mitigation option involves breeding low-methane rice varieties. But lower-methane varieties already exist, and science suggests real potential from more extensive breeding.

The mitigation options all have significant potential to provide economic returns through higher yields and reduced water consumption, which provides benefits even if subsidies presently keep many farmers from realizing them, but these options also have unknown costs. The lack of detailed analyses of mitigation costs and benefits in specific rice-producing areas makes our estimates somewhat speculative. Unfortunately, we are aware of no coordinated national, let alone international, projects to mitigate emissions and to systematically improve our understanding of how to do so.

Based on these assessments, we offer the following recommendations:

Development agencies and national governments should fund a coordinated series of rice emissions mitigation projects that focus on synergies with water savings and yield improvements. Among criteria, projects should be chosen because of their potential for synergies and to test synergistic mitigation options in a range of different rice-growing settings.

Development agencies and national governments should similarly support coordinated technical support, research, and assessment of such projects through an international, collaborative technical team. Such an effort would help maximize impacts per dollar, assess results, and steadily improve technical understanding of how to pursue rice mitigation over time. The team should incorporate experts with a range of expertise, including knowledge of rice emissions and plant breeding, hydrology, irrigation management, and economics. The team should ensure that projects generate information not only on project design but also on yield, disease management, water conservation, and cost implications of various production options.

Governments should reform water and energy subsidies that distort mitigation goals and structure incentives and rules to encourage mitigation. Farmers practicing improved water management techniques typically do so because they anticipate yield gains, reduced pumping costs, and—in the case of dry-seeding—sometimes reduced labor costs. However, subsidies for water and energy distort these incentives. Subsidies to small farmers can be provided in ways that do not encourage excess water use. At a minimum, in areas where rice farming is already threatened by insufficient water supplies, water allocation systems should reward farmers who use water more efficiently by giving them priority access when water is short.

Crop breeding institutions should prioritize breeding of low-methane crop varieties. As discussed in Chapter 12, breeding for environmental goals can complement the primary breeding goal of increasing yields—or at least maintaining yields in the face of climate change. This should involve immediate efforts to cross-breed low-methane varieties with those that produce the highest local yields. Governments and international aid agencies should support large-scale pilot efforts to explore new varieties that produce lower amounts of methane.

International institutions should offer a prize for low-methane rice. The Green Climate Fund or another international funder should create a prize for a variety of rice that comes into widespread usage and reduces methane emissions in real-world conditions by 50 percent or more.

For more detail about this menu item, see "Wetting and Drying: Opportunities and Challenges for Rice Management," a working paper supporting this World Resources Report available at www.SustainableFoodFuture.org.

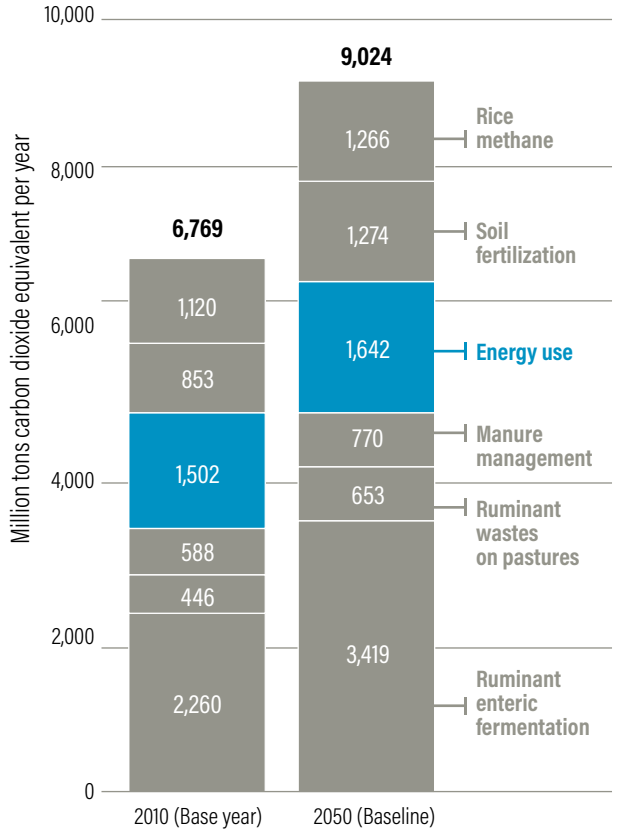


CHAPTER 29

MENU ITEM: INCREASE AGRICULTURAL ENERGY EFFICIENCY AND SHIFT TO NONFOSSIL ENERGY SOURCES

Agriculture uses energy to produce and transport inputs such as fertilizer and animal feeds, to heat and cool farm buildings, and to run on-farm vehicles and machinery. This menu item focuses on increasing energy efficiency in agriculture and shifting to low-carbon energy sources to reduce emissions.

Figure 29-1 | Greenhouse gas emissions from agricultural production, 2010 and 2050



The Challenge

We estimate that total GHG emissions related to energy use in agriculture will be 1,642 Mt CO_2e in 2050 (Figure 29-1). Of these emissions, 1,062 Mt result from on-farm energy use, 408 Mt result from manufacturing and transporting nitrogen fertilizers, and 172 Mt result from manufacturing and transporting all other inputs of nutrients and pesticides. (These total estimates of energy use emissions are somewhat higher than previous estimates in our *Creating a Sustainable Food Future* series[240] because they incorporate newer, higher estimates of on-farm energy use by FAO.)[241]

Overall, these emissions are only about 9 percent higher than in 2010, but our estimate is based in part on difficult projections. As poorer countries develop, they are likely to adopt more mechanization, and even developed countries may use more machinery than they do today. At the same time, there is likely to be some growth in efficiency of energy use, probably modest in tractors[242] but higher in other applications. In our baseline scenario, on-farm emissions stay the same because we assume that a 25 percent growth in energy use efficiency on farm cancels out a 25 percent growth in the level of energy use. The baseline also factors in a slightly smaller 23 percent increase in the energy efficiency of nitrogen production at fertilizer plants. This projection is based on a time lag that can be observed in the past: it takes 30 years for the average efficiency of all fertilizer plants to improve to the point where it matches the efficiency of the most efficient plants at the beginning of the 30-year period.[243] Yet, even under these generally optimistic assumptions, emissions from agricultural energy use in 2050 would amount to 1.6 Gt, filling 40 percent of our target budget for total agricultural production emissions (4 Gt CO_2e). Efforts to reduce these emissions are necessary.

The Opportunity

The opportunities to reduce emissions from energy use in agriculture mostly match the opportunities to reduce emissions from energy use in other economic sectors, which are the subject of many other studies.[244] They center on energy efficiency measures and on shifts from fossil-based energy feedstocks to zero-emission feedstocks such as solar, wind, and—in some studies—nuclear power.

Energy efficiency

One mitigation opportunity involves improvements in energy efficiency. Although we have found few studies of this potential in agriculture, one Indian study from 2013, for example, found potential to improve the energy efficiency of irrigation pumps by 40 percent.[245] Another study of cassava drying found potential for doubling efficiency.[246] More broadly, studies identify significant potential increases in energy efficiency in the aviation, maritime, and manufacturing sectors, and we doubt that agriculture is fundamentally different.[247] Although little explored, potential for efficiency gains in agriculture is likely larger than we have assumed in our baseline.

Renewable energy sources

Energy efficiency measures alone will not be sufficient to address climate change, and further mitigation will have to be achieved through shifts in energy supply. Electricity provides probably the easiest way to switch to low-carbon energy sources. Electricity accounts for approximately 40 percent of the roughly 1.2 Gt of baseline energy emissions in 2050 that result from on-farm energy use and manufacturing of inputs other than nitrogen fertilizers.[248] Another 25 percent of emissions from on-farm energy use and manufacturing involves direct on-farm use of coal for heat.[249] To reduce these emissions, farms need to shift to solar heat supplies or to electricity powered by low-carbon sources, such as solar or wind. The challenges and opportunities involved in energy shifts are likely to mirror those of shifting to low-carbon energy sources in other sectors. However, agriculture might enjoy an advantage in that farms generally have land available to generate their own solar or wind energy.

A greater challenge is the need to replace diesel fuel, which generates around one-third of agriculture-related energy use emissions. Agriculture uses diesel fuel for tractors and other farm equipment, and for some heavy machinery used in mining phosphate and potash. Battery-powered equipment may be a partial solution, but some of these end uses require such concentrated power that they will be difficult to electrify. Some experts view them as primary targets for biofuels. Because the capacity to produce truly low-carbon biofuels is limited (Chapter 7), we see less potential, although powering heavy equipment would be a good use of biofuels supplied by truly "additional" biomass. Another alternative might be the use of fuel cells powered by renewably generated hydrogen, or synthetic, carbon-based fuels made from renewable energy. However, the economical deployment of such fuels will require technological enhancement.[250]

Nitrogen fertilizer manufacturing

Dramatically reducing emissions from nitrogen fertilizer manufacturing presents a particular challenge. We estimate that the production process for fertilizer will emit 408 Mt CO_2e in 2050, an increase from 359 Mt CO_2e in 2010. Nitrogen fertilizer production generates high emissions because the Haber-Bosch process requires high temperatures, high pressures, and therefore high energy levels to break the double nitrogen atom bond of nitrogen gas into nitrogen atoms that can be bound in various fertilizer compounds.

One opportunity involves making this process more efficient. Modern production facilities use 36 gigajoules (GJ) of energy per ton of nitrogen fixed, but this is already roughly three times more efficient than the original Haber-Bosch method.[251] Most of the improvement has been in the "upstream" supply of hydrogen and nitrogen to the synthesis process,[252]and further improvements seem plausible because different fertilizer manufacturing plants have different efficiencies. Plants with the lowest energy requirements are roughly 25 percent more efficient than the global average.

China provides a special opportunity because it produces roughly one-quarter of the world's fertilizer[253] but uses 15 percent more energy than the global average and 35 percent more than the most efficient plants.[254] China also uses coal mined in ways that produce disproportionate emissions. One study estimated that China could reduce its emissions from nitrogen production by 30 percent just by moving to global average manufacturing standards for nitrogen.[255] Our 2050 baseline already incorporates 23 percent reductions in the global average fertilizer manufacturing emissions rate, bringing energy use down from an average of 36.6 to 28.0 GJ per ton of nitrogen fertilizer, which is the standard for the most efficient plants today. The theoretical limit to the efficiency in modern production systems is 20 GJ per ton of nitrogen fertilizer, and we hypothesize that it might be possible to reduce energy use to 24 GJ in real conditions still using the Haber-Bosch method.

In addition to efficiency measures, a wide variety of technologies will need to be deployed. The most straightforward opportunity involves a shift to producing fertilizer with electricity generated from solar or wind energy. The principal requirement would be to use solar or wind power to produce hydrogen, which is used in the production of ammonia. Hydrogen production in conventional ammonia plants accounts for approximately 85 percent of the energy requirements for nitrogen fertilizer production.[256] Given this heavy energy use to produce hydrogen, it might be practicable to retrofit existing ammonia production facilities

with "bolt-on" facilities for supplying hydrogen and ammonia.[257] Long-established "electrolyzer" technologies exist to make hydrogen from electricity, but their use to produce relatively cost-effective low-carbon hydrogen is impeded by the higher costs of low-carbon electricity, by inefficiencies in converting that electricity into hydrogen fuel, and by the costs of the electrolyzers themselves. Substantial research therefore focuses on improving efficiencies and reducing these costs, as well as on designing systems that can utilize cheap, intermittent solar or wind power. None of the barriers seem insurmountable.[258] In addition, research is ongoing into ways to use solar radiation directly to generate hydrogen without first generating electricity,[259] and these approaches have the potential to be cheaper and more efficient. Two prototype solar fertilizer plants are being built in Australia.[260]

Mitigation Potential

As with crop yields and livestock systems, our baseline factors in an increase in energy efficiency of 24 percent per unit of agricultural output—sufficient to cancel out the effects of increased mechanization—and this increase will already require significant effort. We therefore treat our baseline also as our Coordinated Effort scenario.

Our Highly Ambitious scenario contemplates a 50 percent reduction in emissions per unit of output, with the exception of nitrogen fertilizer production, where we project slightly lower efficiency gains of 45 percent, which represents the limits of the Haber-Bosch system.

Our Breakthrough Technologies scenario reduces emissions by 75 percent from the baseline level of efficiency and applies to emissions from all energy uses including production of nitrogen fertilizers. Such a significant reduction would require deployment of breakthrough technologies in both heavy machinery use and production of nitrogen from renewable sources of energy.

Model results are shown in Table 29-1. Our Highly Ambitious and Breakthrough Technologies scenarios reduce the production emissions GHG mitigation gap by 8 to 18 percent and reduce energy emissions from nitrogen production and transportation by 14 to 67 percent.

Recommended Strategies

For the most part, strategies for reducing energy emissions in agriculture are the same as those for reducing energy emissions more generally across all economic sectors. They involve measures that increase the price of fossil-based energy sources (e.g., carbon taxes, GHG cap-and-trade systems), measures that lower the price of zero-emissions sources (e.g., incentives to purchase equipment that generates or uses zero-emissions energy), and technical and financial support for research. Because these issues are large and the subject of a vast amount of academic literature, we do not discuss them further here. However, we offer three specific recommendations related to agriculture:

Integrate low-carbon energy sources into all government agricultural investment programs and projects. On-farm renewable energy programs already exist to encourage alternatives to fossil fuels. Opportunities include low-carbon technology systems for aquaculture,[261] "passive solar" food storage,[262] solar- and wind-powered irrigation pumps,[263] and manure digesters.[264] Efforts to reduce energy emissions from farms should be built into national government agriculture projects and international aid projects and should be a focus of dealings between larger food companies and their suppliers.

Invest in research into low-carbon fertilizer production and build pilot facilities. The world's research agencies that are now funding energy innovations should invest heavily in research to develop production of nitrogen from renewable electricity. Much of that work could be linked to work now being done on developing hydrogen fuel produced by solar and wind power. Because these facilities will operate for two decades or more, moving the technologies forward quickly is necessary to avoid locking in highly polluting technologies for decades.

Apply carbon pricing or regulation to fertilizer. Governments should apply the same taxes or other regulations on emissions from manufacturing facilities to fertilizer production. Europe has included fertilizer manufacturing in its emissions trading system. As in the case of aircraft manufacturers, in initial years fertilizer manufacturers may need to purchase offsets, but this approach would create incentives to engage in their own R&D and to shift toward low-carbon fertilizer production.

Table 29-1 | Global effects of scenarios of agricultural energy use reduction on agricultural greenhouse gas emissions

SCENARIO	DESCRIPTION	TOTAL EMISSIONS FROM ENERGY USE IN AGRICULTURE (MT CO_2E)	PORTION OF ENERGY EMISSIONS FROM NITROGEN PRODUCTION AND TRANSPORTATION (MT CO_2E)	TOTAL PRODUCTION EMISSIONS (MT CO_2E)	PRODUCTION EMISSIONS GHG MITIGATION GAP (GT CO_2E)
2010		**1,502**	**359**	**6,769**	**—**
No productivity gains after 2010		1,982	374[a]	11,251	7.3 (2.2)
2050 BASELINE and Coordinated Effort	25% reduction in energy emissions per unit of agricultural output in 2050 relative to 2010 but energy use for nitrogen fertilizer manufacturing reduced from 36.6 to 28.0 GJ per ton.	**1,641**	**408**	**9,023**	**5.0**
50% Energy Emissions Reduction *(Highly Ambitious)*	50% across the board emissions reductions per unit of agricultural output. For nitrogen, the reduction is 45%, which achieves the thermodynamic limit of the Haber-Bosch process.	1,280	349	8,661	4.7 (-0.4)
75% Energy Emissions Reduction *(Breakthrough Technologies)*	75% reductions in energy emissions per unit of agricultural output across the board, including nitrogen production.	762	134	8,143	4.1 (-0.9)

Notes:

a. Emissions in the "no productivity gains" scenario are lower than our baseline scenario because lower livestock productivity leads to production of more manure, which partially substitutes for fertilizer.

Numbers not summed correctly are due to rounding. Numbers shown in parentheses are changes relative to 2050 baseline. Coordinated Effort scenario assumes no reduction in emissions from energy use relative to levels projected in the 2050 baseline.

Source: GlobAgri-WRR model.



CHAPTER 30

MENU ITEM: FOCUS ON REALISTIC OPTIONS TO SEQUESTER CARBON IN AGRICULTURAL SOILS

Some researchers are optimistic about the potential for large-scale sequestration of carbon in agricultural soils. Other researchers are more skeptical. This chapter analyzes both optimistic and more pessimistic claims and concludes that the realistic potential for sequestering carbon in agricultural soils is limited and that efforts should focus on sequestration as a cobenefit of boosting productivity, with a goal to stabilize soil carbon.

The Sequestration Debate

Many strategies for agricultural GHG mitigation have focused less on directly reducing agricultural emissions and more on offsetting them by sequestering more carbon in soils or trees on agricultural land.[265] The 2007 integrated assessment of the IPCC, the so-called AR4, estimated that various forms of carbon sequestration on agricultural land provided 80–90 percent of the global technical and economic potential for agricultural emissions mitigation.[266] The subsequent assessment, the AR5, in 2014 reproduced this figure.[267] The analysis that went into this figure has remarkable staying power: a 2017 paper in *Nature* quantifying estimates of the mitigation potential for soils in agriculture is based on essentially the same modeling analysis that generated the AR4.[268] Today, there is also a major international initiative with the stated goal of increasing global soil carbon by 4 percent per year, which would remove more than 4 Gt of carbon dioxide from the atmosphere each year.[269]

Some of these climate mitigation strategies focus on restoring agricultural land to forests or other natural vegetation. We explore these strategies in Chapter 20 and conclude that some important options exist to reforest both marginal and realistically unimprovable agricultural land, and that restoring drained peatlands should be a priority. Much larger-scale reforestation depends on—and must wait for—a high level of success in implementing the strategies described in this report.

The claim of large potential to store carbon in soils gained wide attention with publication of a paper in *Science* in 2004.[270] As this paper argued, use of land for cropland has undoubtedly led to great carbon loss, which is probably on the order of 25 percent of the carbon within the top meter of soil.[271] Loss rates, however, vary greatly and are probably due in part to management. At least some management practices can undoubtedly increase carbon in soils, such as adding manure, mulch, or more crop residues. There is also no doubt that many grasslands have lost carbon and could store more.

Claims of achievable carbon sequestration rates per hectare vary,[272] but, if all of the world's agricultural lands could sequester 0.5 tons of carbon per year, then the world could achieve something on the order of 2.5 Gt of carbon storage each year (roughly equal to 9 Gt of carbon dioxide, almost 20 percent of annual anthropogenic emissions from all sources).[273] Supporters of such soil carbon sequestration efforts also cite multiple cobenefits, such as aiding productivity and helping soils hold water and resist droughts, which would increase resilience to the rainfall variability likely to result from climate change. Many researchers have continued to make the case for large soil carbon sequestration potential using approaches that are, in effect, based on the physical potential of agricultural soils to store more carbon and the fact that a variety of practices can in theory increase soil carbon.[274]

In response to these claims, a number of other researchers have published articles expressing strong disagreement.[275] Our analysis of these claims leads us generally to side with the doubters. We believe that the realistic potential for soil carbon sequestration is far more limited than has been claimed and that before soil carbon sequestration can be treated as an offset for other emissions, it needs to be used to stabilize current global soil carbon stocks.



The Challenge

There are only two ways to boost soil carbon. One is to add more carbon to soils, and the other is to lose less. Losing less primarily means trying to manage soils so that microorganisms are less effective at consuming carbon and respiring it back into the atmosphere. We agree with the observations of others that carbon sequestration claims based on adding more carbon have frequently double-counted carbon sources, and that there are serious scientific, technical, and economic doubts about the ability to manage soils to starve microorganisms.

Building soil carbon with manure, mulch, and crop residues

Farmers can build soil carbon by cutting up parts of trees and shrubs and adding the mulch to soils, by adding manure, and by leaving more crop residues in the soil.[276] Yet in each case, the primary effect is to divert carbon from some other storage location or use to storage in soil. Pruning and mulching trees only shifts carbon from above-ground to below-ground storage—unless the trees were going to be pruned and burned. (As discussed in Chapter 7 on bioenergy, even though trees might eventually grow back, cutting down trees to use them for energy will increase carbon in the atmosphere for decades, and cutting wood to add to soils is likely to do so as well.)[277] Cows produce a given quantity of manure, so using manure on one farm usually means using less in another place. Although some crop residues are burned, most that are not already left on the soils are used for animal feed or household energy, so their use as mulch has both economic and carbon costs because their replacement as fuel or feed also causes emissions.[278]

Available carbon is finite, and any calculation of the sequestration benefits when carbon sources are used as a soil amendment in one location must count the costs of not using that carbon for another purpose or for soil amendment in another location. This calculation is typically ignored by the more optimistic carbon sequestration analyses.

There are some sources of wasted or inefficiently used carbon, such as organic municipal waste now landfilled, that could be added to soils. In China much manure is discharged directly into streams,[279] so diverting this manure onto farm fields would avoid pollution and sequester additional carbon in soils.

Another potential source of soil carbon is crop residues that are currently burned. These arise in some cropping systems including sugarcane harvested by hand, rice straw in much of India, and many cereals in northeastern China.[280] Crop residues are burned for a variety of reasons: to get rid of bulky wastes; to make it easier to harvest some crops, particularly sugarcane; to control pests; and sometimes to improve the pH of soils. The need to burn residues can be reduced by mechanization and pesticide use. For example, in Brazil, the shift to mechanized harvesting of sugarcane has greatly reduced burning of sugarcane leaves and appears to contribute to higher soil carbon compared to burned systems.[281]

The potential soil carbon gains from further residue incorporation are limited, however, if only because only around 10 percent of crop residues are burned.[282] According to FAO estimates for 2016, these residues globally amounted to only 381 Mt of dry matter, which therefore probably contain 190 Mt of carbon. The amount of carbon in residues incorporated into soil probably depends heavily on availability of nitrogen, but may be around 10 percent in nitrogen-rich environments.[283] Therefore, elimination of all residue burning and incorporation of all residues into soils would result in soil absorption of only about 19 Mt of carbon, equivalent to roughly 70 Mt of carbon dioxide per year, or less than 1 percent of likely agricultural production emissions in 2050.

Even increasing these estimates severalfold would create soil carbon gains on cropland of only a small fraction of the more enthusiastic estimates. It would also require overcoming the many practical challenges faced by farmers who burn residues to control pests and reduce soil acidity, and who lack mechanized means to mulch residues.

Crop residues are also commonly targeted as feedstocks for biofuels. We are sympathetic to the use of residues as a soil amendment primarily because of likely benefits for soil fertility, which include not just increased carbon content but other improved soil properties.[284] Yet this use reduces the potential for biofuels even more than we analyze in Chapter 7.

Overall, there is probably some potential to add otherwise underutilized organic material to soils, but the quantities are limited and there are real obstacles.

Reducing carbon losses through changes in tillage practices

In the normal course of farming, crop roots and residues left in the field help replenish carbon released into the atmosphere by soil microbes. Much hope has rested on "no-till" techniques that drill seeds into the ground without turning over the soil. Because the original plowing of grassland or of cut-over forests contributed to the loss of soil carbon, the plausible theory has been that reducing annual soil turnover should expose less of that soil carbon to decomposition by microbes. Many field studies initially appeared to support this view.[285] But in 2007, a scientific debate broke out when some researchers pointed out that past studies focused only on shallow soil measurements, often the top 10–30 centimeters, and that studies measuring soils to a depth of a full meter showed no consistent pattern of change in soil carbon.[286] In effect, analyses measuring carbon only at shallow depths ignored a variety of potential ways in which tillage could transfer more carbon deeper into the soil, so even if no-till practices increase carbon in the top layer of soil, that might be offset by reduced carbon at lower depths.[287] Scientists defending no-till argued in return that the statistical variability in measuring soil carbon changes at depth blocked any solid conclusion that soil carbon gains had not occurred,[288] but the proper inference is that we do not really know.[289] A consensus appears to be emerging that results are highly variable. In some areas, no-till appears to have no effect on soil carbon, and in other areas it appears to have a small effect of perhaps 0.3–0.4 tons of carbon/hectare/year (tC/ha/yr) (assuming continuous use).[290]

No-till has probably been most widely adopted in Brazil where, in 2012, the practice reached 29 Mha,[291] roughly half of all cultivated land. High adoption rates in Brazil probably reflect the high risk of soil erosion due to intense storms and the discovery of some additional agronomic benefits; for example, reductions in soil acidity. Brazil also

widely cultivates glyphosate-resistant soybeans, so farmers can use glyphosate to control weeds without the need for tillage. No-till in Brazil tends to persist year after year. A number of studies have shown that the consistent practice of no-till—at least of recently cleared areas in the Cerrado—has maintained soil carbon levels comparable to those of soils under natural vegetation, while areas under conventional tillage have lost carbon.[292]

Where no-till generates small carbon gains, it still faces many practical challenges.

No-till agriculture is hard to maintain over time. Outside of Brazil, even where no-till is practiced, periodic plowing still commonly occurs to control weeds, deal with soil compaction or meet other agronomic needs.[293] There are virtually no data about how many farms employ truly long-term no-till, meaning no-till practiced for 10 or 20 years, but the data show that continuous no-till even for 10 years is infrequent. For example, in one complicated analysis of Iowa using data from the 1990s, the authors estimated that the probability of no-till persisting for even two consecutive years was only 8 percent, with the vast majority of farmers practicing no-till for a single year.[294] A study by the U.S. Department of Agriculture using more recent data estimated that only 13 percent of cropland in the Upper Mississippi River basin was in no-till for three consecutive years, the maximum period for which data could be assessed.[295] Regular or even occasional plowing probably causes much or all of any soil carbon gains to be lost, although there is some uncertainty because the data are so limited.[296]

Nitrous oxide emissions may increase. There is evidence that if practiced for only a few years, no-till may increase nitrous oxide emissions by temporarily saturating some portion of soils immediately after rainfall, leading to the low oxygen conditions that encourage nitrous oxide formation. This nitrous oxide can cancel out the benefits even of large carbon gains.[297] However, there is also evidence that nitrous oxide emissions decline after 10 years of continuous no-till on those limited areas that practice no-till that consistently. These contrasting results heighten the importance of whether no-till cultivation is practiced persistently.

No-till may reduce yields or increase costs. For many farms, no-till probably decreases yields although effects are variable. No-till appears to result in lower yields on average in wetter climates but to boost yields on average in some drier climates if combined with other practices.[298] Again, a key point is that there is high variability, but the yield consequences of practicing no-till are obviously an obstacle to adoption in many areas. Projections of large potential global carbon gains do not address this issue.

Finally, as discussed in Chapter 13 on soil and water conservation, there can be other challenges to adopting no-till, particularly in developing countries. They include the increased need for herbicides, and sometimes additional labor.

To put these numbers in perspective, if we assume that even one-third of the world's croplands were cropped using no-till—a big assumption given adverse yield and other practicable challenges on much cropland—and if we further assume that no-till is persistent on half of these croplands and that there are no offsetting nitrous oxide emissions—more big assumptions— and that half of these lands sequester carbon at 0.4 tC/ha/yr while the others do not, then the total mitigation would be ~200 $MtCO_2$ per year globally. This level of mitigation would offset only around 2 percent of likely agricultural production emissions in 2050, which would be a small contribution from such expansive efforts and given such optimistic assumptions.

Sequestering carbon on grazing land

Early studies were optimistic about the potential to increase carbon on grazing land, often by reducing the number of grazing animals.[299] Subsequent analyses have shown that the impact of improved rangeland management practices on soil carbon is highly complex, site-specific, and hard to predict.[300] In some grasslands, reduced grazing leads to more soil carbon and in some places it leads to less. Stranger still, truly poor grazing practices that undermine grassland productivity may actually promote carbon sequestration in some savannas by favoring tree growth.[301] Even in New Zealand, where grasslands are intensively managed and carefully studied, there is a high level of scientific uncertainty over the soil carbon effect of different management practices.[302]



In some cases, the claimed gains from improved grassland management probably reflect the ongoing benefits of efforts to restore cropland to grazing land. For example, one paper with careful grassland measurements in the southeastern United States, which has been cited for showing the potential gains of "improved management on grazing lands," studied a site that had recently been converted from cropland to grassland.[303] Newly established grasslands appear capable of building soil carbon quickly, and as Smith (2014) points out, may continue to gain carbon, although in declining amounts, for 100 years.[304] However, like forests, they will eventually reach an equilibrium. Management appears capable of altering the rate at which they gain carbon, but the benefits that should be counted are only the increase in the rate, not the total gain, and this increased rate may not change the ultimate carbon stock the grassland will achieve.

This long-term recovery of carbon stocks is just one of many issues to be considered when assessing claims that improved grazing can result in "climate-neutral" beef, in which soil carbon gains would cancel out emissions from animals.[305] Some studies of European grazing lands directly measured soil carbon, with some reporting these lands gaining carbon and others losing it.[306] A recent large European research project used a form of air monitoring at 15 sites to measure carbon fluxes in and out of soil and vegetation and found net gains of 0.76 tC/ha/yr.[307] That is a large figure, representing perhaps three-quarters of the common estimate of carbon sequestration by grasslands that have been newly reestablished on cropland. It was surprising because science has generally shown that long-established grasslands typically reach an equilibrium in which they stop gaining carbon.[308]

Unfortunately, this argument does not prove that carbon gains were caused by the grazing operation and does not compare the consequences of grazing to the counterfactual of not grazing. Part of the explanation may be that many of these grasslands are still recovering from previous plowing, so the gain would occur whether these lands were grazed or not.[309] In subsequent papers, the European researchers and others explain the results using modeling; they attribute half of the carbon gain to reduced numbers of animals grazing—leaving more biomass to be returned to the soil—and half to climate change and the associated rise of carbon dioxide concentrations, which stimulated more plant growth.[310] Yet if the carbon gains are the result of climate change, they would happen anyway and should not be attributed to grazing operations. In fact, assigning carbon gains to the grazing land

ignores the far greater levels of carbon the land would sequester if it were allowed to return to forest, which would be the fate of the vast majority of European grazing lands if they were not grazed.[311]

In addition, moving toward less intensive grazing in Europe, even if it resulted in more carbon gains on European pasture lands, would probably lead to greater aggregate emissions globally if this shift resulted in reduced milk and meat production in Europe. Assuming the same level of global consumption, these efforts would necessitate increased production of milk and meat in regions where farming is less efficient (i.e., lower output and higher emissions per hectare), and would therefore likely trigger pastureland expansion in those regions.

We believe that a paper[312] claiming potential for "carbon-neutral" beef in the United States using only grazing land suffers from similar limitations. The authors estimated that carbon-neutral beef would require twice as much land per cow as the standard alternative using some feedlots, but they did not count the GHG emissions that would occur as more forests and savannas globally are converted to pasture. Even in an ideal situation of globally reduced agricultural land area, more grazing land would reduce the potential to sequester carbon through reforestation.

For reasons we discuss below, we believe that carbon gains on grazing land are possible but that early estimates of high potential cannot be justified.

Need for additional soil nitrogen

In 2011, Kirkby et al. pointed out that lack of nitrogen presents a major challenge to efforts to sequester carbon.[313] Soil organic matter is sequestered over the long term through microbial activity that requires 1 ton of nitrogen for roughly every 11 tons of carbon. By contrast, plant material on average has only 1 ton of nitrogen for every 100 tons of carbon. To sequester more carbon therefore requires more nitrogen, which Kirkby et al. (2011) calculated at around 80 kg of additional nitrogen for each ton of carbon. This additional nitrogen must be surplus to the amount used by plants.

In a 2017 comment, a number of other academics argued that this need for nitrogen made carbon sequestration an unrealistic climate mitigation strategy in light of both the practical challenges and environmental concerns associated with the additional nitrogen.[314] They calculated that achieving the goal of sequestering 1.2 Gt of carbon per year established by the 4 per 1000 Initiative[315] would require a 75 percent increase in the global application of nitrogen.

A number of academics known as champions for soil carbon sequestration wrote a response that only partially disagreed.[316] They did not challenge the need for vast amounts of nutrients to build soil carbon, and they agreed that trying to supply these nutrients through synthetic fertilizer would be too expensive and environmentally unwise. But they argued that regions with surplus nitrogen and other nutrients could supply the nutrients needed for soil carbon sequestration.

One major implication of this argument is that soil carbon sequestration at scale, sufficient to mitigate climate change, is enormously challenging at this time in sub-Saharan Africa. Much of the region is nutrient-deficient and is still far from being able to provide enough nitrogen even to grow crops. Building soil carbon would require nutrient additions that are high enough both to fully feed crops and to leave a surplus of nutrients to build soil carbon. This limitation does not undercut the importance of boosting soil carbon as part of the larger effort to improve yields and resilience in the region, but it does suggest that building soil carbon in this region to levels that would significantly affect carbon concentrations in the atmosphere is not feasible.

It remains highly uncertain how much even areas with nutrient surpluses could build soil carbon at scale without additional nitrogen applications. Nitrogen is released by soils or applied as fertilizer at particular times and in particular molecular forms. Microbes that turn plant carbon into stable carbon in humus probably cannot always take immediate advantage of all of this available nitrogen before it is lost from the field. A compelling study found that, if nitrogen is not available when carbon is added, soil microbes would break down existing soil organic matter in order to access the nitrogen embedded with it that would allow the microbes to feed on the new carbon source. This process would lead to a loss of soil carbon overall.[317] To build soil carbon by adding crop residues or other carbon sources (i.e., without deliberately adding more nitrogen), this study suggests that nitro-

gen from earlier fertilization must be freely available in soils or that it must be present in reasonable quantities as part of the added carbon material (as it is in manure or the residues of legumes).

The need for additional nutrients is a fundamental challenge to sequestering soil carbon and has received far less attention in the literature than it deserves. At the very least, it limits the capacity to sequester additional carbon in soils without the additional expense and the risk of further pollution (including GHG emissions) from additions of more nitrogen to the agricultural system.

Carbon gains or reduced losses?

Another important factor that is little discussed is the reasonable probability that the world is actually losing soil carbon today. The main goal (and likely effect) of efforts to sequester soil carbon may be to avoid further losses rather than to generate gains. One issue is that many of the studies claiming soil carbon benefits from different practices do not differentiate between actual soil carbon gains and reduced losses.[318] There are many technical reasons, including the availability of nitrogen, why it might be easier to reduce losses than to build additional carbon.

Current fluxes in agricultural soil carbon vary by region. For example, there are claims of relatively modest soil carbon gains overall in China,[319] conflicting estimates of soil carbon in the United States,[320] and estimates of soil carbon loss in Europe.[321] In general, global nitrogen studies provide the main reason to believe that carbon stocks on cropland are decreasing globally. Because nitrogen is needed to store carbon in soils, a loss of nitrogen from croplands implies that soils are losing carbon. Today, global studies that attempt to account for all inputs and outputs of nitrogen estimate that soils are losing tens of millions of tons of nitrogen.[322] In other words, even after accounting for all nitrogen that is applied to croplands, the amount of nitrogen that is removed by crops or lost to air or water indicates that, on balance, there is a net loss of nitrogen from soils. Although uncertain, if one estimate of nitrogen loss from croplands producing cereals is correct, then global soil carbon losses from these crops alone would account for 2.5 Gt of CO_2 emissions per year.[323]

Ton for ton, reducing the global loss of carbon is just as important for mitigating climate change as increasing global sinks, but standard global climate assessments do not assume any ongoing soil carbon losses on existing cropland, aside from peatlands. Because of the uncertainty, our model does not assume such losses either.[324] However, if these nitrogen budgeting studies are correct, then our projected emissions—and the projections of other modelers—are too optimistic. Additional management practices will be needed just to maintain soil carbon levels and reduce emissions to bring them into line with current projections.

Complexity of the soil carbon issue

Despite the complexity of the issues presented, our discussion still fails to communicate the full degree of uncertainty about nearly all features of soil carbon.

Accuracy of soil carbon measurements. Whether analyses are based on accurate measurements is itself a major issue. Today, it is commonly agreed that soil carbon measurements need to be taken at a depth of a full meter and adjusted to take account of the different density of soils at different depths to generate proper carbon content measurements. But vast quantities of soil data have not been collected in accordance with these practices. As a result, some meta-analyses exclude much data and end up relying on limited sources and still need to adjust for some inadequacies.[325] Many others simply rely on data measured to limited depth.[326]

Another big issue, rarely explicitly addressed, is how to define soil carbon. Much plant residue remains, at least for some time, in small pieces that will decompose as microbes turn it into more stable material. If some of this material is measured as soil carbon, there can be the appearance of large gains. At least one study that carefully considered this issue had to exclude much global soil carbon data because they not been gathered in ways that excluded larger residue particles.[327]

In addition, determining soil carbon changes over a few years is challenging because the amount of change is small by comparison with the total stock of carbon in the soil. Soils are heterogeneous and tillage practices can result in different surface configurations. Even when measurements are taken by scientists renowned for their care, different

measurement techniques can result in dramatically different estimates.[328]

Accumulation and retention of soil carbon. The processes that affect accumulation and retention of carbon in soil are also enormously complex. In 2013, a large group of prominent soil scientists published an article, "The Knowns, Known Unknowns and Unknowns of Sequestration of Soil Organic Carbon," whose dominant lesson was the scope of the known unknowns.[329] Although adding carbon and nitrogen are inherently critical to building soil carbon, in some cases each is known to decrease soil carbon by "priming" microorganisms to become more active and consume more of the previously stored carbon. As summarized in this study, it generally appears that soil carbon can more easily be sequestered in clay soils, but some studies show no correlation. Soil erosion could have a large effect on the global storage of carbon, but, because eroded soils may bury carbon elsewhere, researchers disagree about whether erosion, on average, leads to more or less carbon storage globally.

In addition to all the other challenges discussed above, these complexities suggest that carbon gains are likely to be site-specific. Most conclusions to date carry with them a significant level of uncertainty, and carrying out a strategy to boost soil carbon will be hard to implement and harder still to verify.

Summary of the Challenge

Since a prominent 2004 *Science* paper,[330] researchers estimating soil carbon sequestration potential have continued to emphasize the simple fact that many of the world's agricultural soils can technically store more carbon than they do today and that practices exist to enhance their carbon levels.[331] We believe that analysis is too simple because the ability of soils to store carbon is only one factor and generally not the principal limiting factor of sequestering more carbon in soils. (Banks have additional shelf space to store more money, and there are "practices" for making money, but that does not mean it is easy for the world to become richer.) The technical capacity of soils to store more carbon does not by itself resolve the technical, practical, and economic challenges of getting the carbon into the soil and keeping it there.

At best, studies estimating large soil carbon gains focus on technical potential, which is itself complex, and do not deal with the practical and economic challenges. To summarize, these challenges include the differential yield effects; the need to count only additional carbon and biomass (or to count only net gains if diverting this biomass from another use); the need for more nitrogen; the multiple practical challenges facing farmers who try to change tillage, crop rotations, and manure- and residue-management practices; and the fact that even short-term gains can quickly be lost through changes in management due to changing markets and farm conditions.

The Opportunity

Despite the challenges and uncertainties, it is obvious that some types of farming tend to result in more soil carbon than others (even if only because they lead to smaller losses) and that increased soil organic carbon has important agronomic benefits in addition to mitigating climate change. In many systems, it will be worthwhile to continue to push no-till farming forward to help reduce soil erosion and improve water retention. Except in rice systems, where retaining rice straw increases methane, it makes sense to try to retain on the land those crop residues that are currently burned or removed. Doing so would necessitate replacing crop residues used as livestock feeds with more nutritious fodders, which would benefit livestock production where farmers are able to generate those fodders (although that may require some additional land).

On the whole, however, we believe that the realistic potential to sequester carbon is to be found in approaches such as those described below that can plausibly generate economic gains independently and that do not sacrifice carbon storage in another location.

Boost crop and pasture productivity

Measures that increase cropland and pasture productivity (Course 2) have the potential to help build soil carbon. Increasing yields will also increase crop residues and root growth, which can contribute to boosting or maintaining soil carbon. Efforts to boost crop yields are responsible for the soil carbon gains on cropland in China (at least in the top soil layers) as discussed above, and they have either modestly boosted or reduced the losses of soil organic carbon in the United States.

The same is true for grazing land. In Brazil, for example, there is consistent evidence that soil carbon is higher under productively managed pasture than degraded pasture.[332] China has made extensive efforts to restore the productivity of overgrazed land and, although the performance is variable, the evidence is strong that many grazing lands have simultaneously sequestered more carbon.[333] There is some evidence that introducing legumes into grasslands can increase soil carbon through root effects to levels beyond those achievable with improvements in fertilization.[334] A new meta-analysis found small gains from largely unspecified "improved grazing" practices on existing grazing land.[335]

A more recent global modeling study suggests that optimizing grazing globally has the *technical* potential to sequester the equivalent of up to 0.6 Gt of carbon dioxide per year[336]—around 40 percent of the IPCC's 2007 estimate of carbon sequestration *economic* potential on grazing land.[337] Because achieving this potential would require improvements in grazing practices on billions of hectares of land, including the introduction of legumes (which presents problems because legumes are often selectively grazed by animals), it should be used mainly as a theoretical estimate. Yet it does highlight that increasing productivity can increase soil carbon.

Agroforestry

Agroforestry, discussed in more depth in Chapter 13, may provide a means of boosting soil carbon by increasing carbon uptake. Unlike annual crops, trees can grow year-round and therefore take advantage even of the drier season. They can also often tap into groundwater that annual crops cannot reach. Although farmers commonly clear trees to provide more light for their annual crops, trees can sometimes boost productivity. In tropical areas, shade from trees can be less of a problem than in temperate systems because sunlight is abundant, some crops need some shading, trees can increase humidity or add nutrients, and some trees lose their leaves during the growing seasons of some crops.

Trees, of course, also store carbon in vegetation. Although this chapter has focused on soil carbon because we deal elsewhere with reforesting agricultural land, agroforestry can provide opportunities to build vegetative carbon without reducing food production.

Despite potential benefits, we believe the practical potential of agroforestry at this time is too uncertain to estimate. Agroforestry can refer broadly to any form of agriculture incorporating the cultivation and conservation of trees. It can include any form of tree-based crops, such as rubber or cocoa. Growth in the agroforestry sector is obviously limited by demand for the outputs and, although converting annual crops to tree crops would sequester carbon, the annual crops would need to be replaced by cultivation elsewhere.

In some analyses, the term *agroforestry* is applied to any trees found on farms. Using this broad definition, one recent study estimated that growth of trees on farms globally sequestered an average of 0.75 Gt CO_2e each year between 2000 and 2010, predominantly on parcels of land that are mixed combinations of forest and agriculture.[338] Findings like this must be considered in the light of numerous data and mapping challenges. We believe that this paper is probably counting as agroforestry what is primarily reforestation of abandoned agricultural land.[339]

The potential true net carbon gains from agroforestry are those that result from incorporating trees and shrubs into existing productive systems without loss of yield, such as productive silvopastoral systems discussed in Chapter 11, and park systems in the Sahel in Chapter 13. Agricultural landscapes also often include land that is producing little or no food, such as some (but not all) field borders. Some studies focusing on such opportunities have estimated meaningful opportunities for carbon gains.[340] As we discuss in Chapter 13, much of the true technical potential to expand agroforestry remains

unclear and unexplored but we believe it has more potential than realized today.

Possibility for new scientific breakthroughs

Driving much of the interest in soil carbon is the basic fact that microbial decomposition of organic materials in soils and dead vegetation returns tens of gigatons of carbon to the atmosphere each year, while the amount of this carbon that is instead retained in soils varies greatly from one location to another. If changed land-management practices could retain even a small fraction of the carbon that microbes are now respiring, then the climate-mitigation impact could be significant. The conditions that influence the level of carbon retention turn out to be far more complex than thought only a decade ago. They depend significantly on soil structure and on a variety of biological and ecosystem conditions.[341] In forests, for example, research has shown that the presence or absence of one group of fungi has a major effect on levels of carbon storage.[342] New research could generate new mechanisms for increasing carbon storage. One research initiative, for instance, aims to breed plants whose roots produce more suberin, an organic compound highly resistant to breakdown.[343] The potential importance of soil carbon storage warrants research into the fundamental science of soil carbon storage and creative ways of increasing it.

Recommended Strategies

The challenges and uncertainties involved in boosting soil carbon do not imply a complete lack of opportunities to improve soil management, but the uncertainties are too high to project how much. We also believe the best evidence indicates that agricultural soils are losing carbon today—with total losses exceeding even the losses from peatlands, which are commonly counted as agricultural emissions. However, losses form nonpeatland soils are too uncertain to be reflected in our 2050 baseline. Although new science may change this impression in the future, we believe that the reasonable goal in the short and medium term should be to maintain global soil carbon. We therefore believe that improvements are necessary, but we count them only as maintaining global soil carbon, and we assume that such improvements occur in our baseline and all our mitigation scenarios.

The effort that societies can and will put into solving the food and climate challenge is not unlimited, and it should focus on the most promising options. In the case of carbon storage, we know that deforestation and other land-use changes are obvious targets. We could reduce gigatons of emissions by avoiding conversion of forests and other native landscapes and producing the food we need on existing agricultural land. Only 26 Mha of drained peatlands generate more than a gigaton of emissions, and we know those emissions can be stopped by rewetting the land. Based on these and the other promising opportunities we identify in this report, we do not believe that carbon sequestration in soils should receive much effort for climate mitigation purposes alone.

Instead, we believe that such efforts should follow a no-regrets strategy that focuses on boosting soil carbon either as a cobenefit of other actions taken for different purposes or when boosting soil carbon is critical to meeting other objectives. Such efforts include improving cropland and grazing land productivity, and appropriate development of agroforestry. No-till potentially offers other benefits, including yield gains in dry climates, reduced soil erosion, and other beneficial soil properties when practiced over the long-term. Where it is practicable to achieve truly continuous no-till beyond 10 years, reductions in nitrous oxide and yield advantages also appear achievable. Alternative animal feeds to replace crop residues will benefit livestock productivity, and any emissions reductions or soil carbon gains would be additional.[344]

In Chapter 13, we also highlight the urgent need to rebuild degraded soils in sub-Saharan Africa. This task does not represent an easy source of climate benefits—it is hard—but improving soils will be critical if Africa is to feed itself, reduce poverty, and reduce clearing of forests and savannas. Overall, we believe there are many potential opportunities for such synergies, and they should be the focus of efforts to sequester more carbon in soils.



CHAPTER 31

THE NEED FOR FLEXIBLE REGULATIONS

Among the many menu items discussed in Course 5, some common themes stand out. They include the need for greater production efficiencies and for innovation in technology and management systems. Another theme is the need for government regulations that require improved performance while allowing flexibility in implementation.

Why Regulations?

If there is no regulation—financial or otherwise—the world treats agricultural production emissions as though they are without cost. Farmers and agricultural companies have economic incentives to increase productivity, which will often have a side effect of reducing emissions, and many measures to reduce emissions will have other economic benefits, such as health benefits from reduced air pollution. Yet measures needed to solve climate change will not always be profitable to farmers, particularly when they involve technologies that are not fully developed.

Part of the need for regulation is to spur technological advances. In critical areas, our analysis shows that promising potential innovations exist to reduce emissions, including ruminant feed additives, new techniques for manure management, and different fertilizer compounds. Most of these options may—at least initially—involve additional costs, but they appear to be cost-effective relative to climate change mitigation strategies in other sectors. Many options would have large collateral benefits, such as reducing the water pollution, air pollution, and disease-bearing organisms associated with excess use of nutrients or poorly controlled livestock waste. Many might eventually more than pay for themselves as technologies evolve, including additives for enteric methane or nitrification inhibitors. Yet these technologies do not seem likely to evolve absent either strong incentives or some form of regulation designed to advance their development and deployment.

Regulatory requirements have advantages over purely incentive-based approaches because they encourage farms, like businesses generally, to find the cheapest ways of meeting new requirements. Voluntary incentives alone do not establish a level playing field, and first movers—those who act early to reduce environmental effects on their own—may suffer a competitive disadvantage when governments then subsidize efforts by those who chose to wait before acting. Regulations can also encourage the spread of cost-effective mitigation methods that farmers might otherwise ignore.

Subsidized regulations

Regulations can be advantageous even if governments choose to absorb much or all of the cost. In most of the world, regulation of agriculture has been limited either because of the political power of the agricultural community or a concern about economic impacts on farmers. Who pays the costs of environmental controls, however, is a separate question from whether to use regulations to encourage those controls. If governments reimburse the average costs of compliance, for example, farms could even make money if they find cheaper methods to meet the regulation. Over time, the costs should then come down.

Flexible regulations

Intelligent regulations can encourage innovation. In our discussion of new nitrogen fertilizer compounds, we suggest phasing in requirements for fertilizer companies to increase the market share of new compounds that increase fertilizer use efficiency (and thus reduce nitrous oxide emissions and nitrogen runoff). Preferably, such regulations would reward compounds that are more effective than others. This kind of approach would both allow and encourage companies to develop better and less expensive fertilizer compounds, gather the information to identify which farmers could most benefit from them, and market the better compounds to those farmers.

Shifting regulations to industry where feasible

One reason our recommendation for nitrogen fertilizer improvement could be effective is that the responsibility for regulatory compliance would rest with large entities. Such entities can better assemble the resources to push technologies forward and can spread the costs. Such entities can also select the most promising opportunities for improvement, such as those farms most likely to benefit from enhanced efficiency fertilizers, increasing the benefits of flexibility. For similar reasons, we recommend that requirements to improve manure management be applied to large pork businesses that control much of the pork production in the United States.

Creating future markets

Technologies have yet to be developed to control some types of emissions. In other cases, the technology has not yet been sufficiently proven to be effective and economical, as in the case, for example, with methane-inhibiting compounds for ruminant stomachs and inhibitors to control nitrous oxide from urine that can be fed to cattle. In these situations, governments can create incentives for industry to develop these techniques by committing in advance to require their use if they prove cost-effective. Innovative companies would invest in these new technologies to capture market share or otherwise gain a comparative advantage over competitors. For example, governments could commit to requiring use of a technology if and whenever its cost per ton of CO_2e mitigation reaches $25 or less. (Such costs should be a net cost, accounting for yield gains and other economic benefits.) Such promises would assure companies that they will have markets if they develop mitigation techniques that work.

Overall, our review of options to mitigate GHG emissions from agricultural production suggests some promising ways forward. Given the enormous challenge of reducing annual agricultural production emissions to 4 Gt by 2050 and the need for innovation, the key is to guarantee markets for those who develop or evolve better and more cost-effective mitigation techniques. We believe that flexible regulations—sometimes with compensation—realistically need to be a part of such approaches.

ENDNOTES

1. Hristov et al. (2014) and Gerber et al. (2013) provide good summaries of the research results to date for all these approaches.
2. Clark et al. (2011).
3. Hristov et al. (2015).
4. Hristov et al. (2015).
5. Hristov et al. (2015).
6. Hristov et al. (2015).
7. Brooke et al. (2018).
8. Hristov et al. (2015); EPA (2016).
9. AgResearch (2016).
10. Hristov et al. (2015).
11. Henderson et al. (2015). This paper reasonably assumed that these techniques would only be appropriate for the minority of ruminant production that makes heavy use of crops, and they would probably be even more expensive in other systems. This paper also analyzed the benefits of urea-treatment of straw, which is also limited and expensive. Because that technique is a means of increasing straw quality for production gains, we consider it implicitly included as one of the options in our productivity field.
12. Hristov et al. (2015); Martínez-Fernández et al. (2014); Reynolds et al. (2014); Romero-Perez et al. (2015).
13. Duin et al. (2016); Hristov et al. (2015).
14. Hristov et al. (2014). The use of 3-NOP apparently leads to increased direct emissions of hydrogen gas rather than hydrogen bound into methane.
15. Duin et al. (2016).
16. Email communication with Dr. Alexander Hristov (September 19, 2016).
17. Barns also produce a great deal of ammonia, which is not a GHG but leads to air and water pollution.
18. Data on manure management systems are rough but analysis in this paper uses estimates by FAO for the GLEAM model, provided separately but reflected in Gerber et al. (2013) and the I-GLEAM model available at http://www.fao.org/gleam/resources/en/.
19. IPCC (2006), Table 10.17, lists different conversion factors for the percentage of the potentially methane-contributing portions of manure (volatile solids) based on different manure management systems. These percentages depend on temperatures, and the ratios between liquid and dry systems vary modestly because of that, so the ratios described above are those at an average annual temperature of 20 degrees Celsius. The lagoon liquid slurry system chosen is for a liquid slurry without a natural crust cover, which tends to form in some liquid slurry systems, and which applies both to liquid slurry storage and pit storage below animal confinements.
20. Herrero et al. (2016) presents estimates from FAO (2019a; the GLEAM model); EDGAR (2011); EPA (2012); Herrero et al. (2013); Hedenus et al. (2014); and the MAgPIE model from the Potsdam Institute within this range after adjustment to the same global warming potential actors of 34 for methane and 298 for nitrous oxide. However, estimates from the GLEAM model developed by FAO were reported at these higher levels of 790 Mt. Data we received from the GLEAM modelers, however, resulted in emissions estimates of 625 Mt CO_2e, which is close to the range of other estimates.
21. These estimates for the same models or other estimation systems cited above range only from 300 to 410 Mt.
22. Owen and Silver (2015).
23. Herrero et al. (2016).
24. Data on manure management systems is rough, but analysis in this paper uses estimates by FAO for the GLEAM model, provided separately but reflected in Gerber et al. (2013) and the I-GLEAM model available at http://www.fao.org/gleam/resources/en/.
25. Owen and Silver (2015) and a companion working paper, Owen et al. (2014), do the calculations for large California dairy farms and generally. Using IPCC factors, emissions from solid manure management for California dairy farms are only 2 percent of the emissions from lagoons (calculations from Tables 7 and 8 even though the IPCC guidance estimates no nitrous oxide emissions from lagoons. Using revised emission factors based on their meta-analysis, the papers found total emissions from methane and nitrous oxide from dairies managed with dry storage to be only 5 percent of the emissions of lagoons and 10 percent of slurry pits (Owen and Silver 2015, Table 2). Interestingly, the revised figures showed total emissions from manure management and the absolute difference in emissions between the two systems to be larger (although not in percentage terms). One reason was that these actual measurements led to higher estimates of nitrous oxide emissions from lagoons than those in IPCC guidance, which would mean that lagoons generate half the nitrous oxide emissions of solid piles.

26. According to the GlobAgri-WRR model, in 2010 38 percent of manure management emissions in CO_2e were nitrous oxide and 62 percent methane. In 2050, 43 percent will be from nitrous oxide and 57 percent methane. Different studies have wide ranges in estimates of nitrous oxide, ranging from 100–120 Mt CO_2e in EDGAR and FAO (2019a) (around 25 percent) to 370 Mt (47 percent) in the GLEAM model (Herrero et al. 2016, Table S2a).

27. Zahn et al. (2001).

28. Montes et al. (2014).

29. Montes et al. (2014).

30. For example, IPCC guidance estimates emissions where average annual temperatures are above 27 degrees Celsius from liquid slurry storage systems at twice those from such systems at 19 degrees Celsius (IPCC 2006, Table 10.17).

31. For studies in the United States, see Lory et al. (2004) and Kellogg et al. (2000).

32. Wang et al. (2017); de Vries et al. (2013).

33. Kaffka et al. (2016).

34. Figures are based on personal communication with Dr. Dana Kirk, Michigan State University. These costs are $25–$50 per cow operating costs plus $25 fixed costs (assuming $150 per cow fixed costs amortized over six years). Hart (2017); Ma et al. (2013).

35. Assuming average U.S. milk production per cow of 7,500 liters per year. AHDB (2017). $17/cwt = 38.6 cents per liter. So $150 per cow would add 2 cents per liter and 5 percent to the farm gate cost of milk.

36. Ma et al. (2013).

37. Bentley (2015). This is largely attributed to the significantly lower labor costs, and increased efficiency, that come with more advanced technology.

38. Dickrell (2016); Dickrell (2014); Filtration and Separation (2014).

39. This analysis is based on estimates in the supplemental Excel file for Wang et al. (2016) (see worksheet for separation system).

40. Zhang et al. (2016); Bautista et al. (2011).

41. Vaddella et al. (2010).

42. Costs of the technologies are discussed in Box 25-1. The North Carolina State costs were calculated in a unit of dollars per 1,000 steady state live weight (SSLW)/year. SSLW represents the average number of pigs that are raised at all times of an average weight. Based on guidance from the lead economic analyst for the North Carolina State study (Kelly Zering, personal communication, November 3, 2016), we translated that figure into pounds of pork per year carcass weight based on the following conversion factors: 1,000 SSLW produces 17.5 pigs per year with a "lean carcass weight" of 210 pounds. We also assign 10 percent of the economic value of the pigs to the producing of weaner pigs because the pork operations analyzed, which the principal operations in North Carolina, purchase pig lots for finishing. The calculation (17.5 * 210 * (1-.10)) equals 3,308 pounds. Thus each $100 per SSLW/year translates into a cost of 3.3 cents per wholesale pound of pork. According to USDA/ERS (2015b), the average retail carcass price from 2010–15 was $3.59 per pound (this work adjusts the quality of carcass weight into retail price equivalents). By this calculation, every $100 SSLW translates into 0.9 percent of the retail price of pork. The same citation shows average wholesale prices over 2010–15 at 62 cents per pound (adjusted to be equivalent in quality to retail). Assuming price equals costs of production, by this calculation, each $100 SSLW/year translates into an additional 5 percent in the wholesale costs of producing pork. Based on these figures, the technology would add 5.2 cents to 9.2 cents per pound of pork, equal to 1.4–2.6 percent of the costs.

43. Washington State University Extension (2015).

44. Bruun et al. (2014).

45. Liebetrau et al. (2013) found digestate leakage rates at up to 11 percent of total methane produced in the digester.

46. The emissions for nitrous oxide depend on the quantity of nitrogen excreted but using the numbers for California dairies from Owen et al. (2014), a switch from dry storage to a 10 percent leaky digester would increase emissions of methane by 2,600 kg CO_2e per cow and reduce emissions from nitrous oxide by 360 kg CO_2e per cow.

47. A simple way to calculate how much would be to assume that each kilogram of carbon in the methane saves a kilogram of carbon from fossil use. In that event, 100 kg of carbon in methane would save 100 kg of carbon from fossil fuels but would be canceled out by a net increase in methane release from leakage of 3 percent because methane has 34 times the global warming effect over 100 years as carbon dioxide and because both methane and carbon dioxide utilize one carbon atom. If methane replaces charcoal, the savings in carbon in trees could be much larger than 1 kg of carbon.

48. Lansche and Müller (2012).

49. Liebetrau et al. (2013); de Vries et al. (2010).

50. Lansche and Müller (2012); Berglund and Börjesson (2006).

51. Vu et al. (2015).

52. Bruun et al. (2014) provide estimates that combine the GHG emissions from manure management with potential reductions in energy emissions. Counting in benefits of avoided wood harvest or reductions in coal use, this study estimated that leakage rates from digesters could be as high as 35–38 percent without actually increasing GHG emissions. For replacement of natural gas, a leakage rate of 12 percent in this calculation would eliminate GHG benefits.

53. Dhingra et al. (2011).

54. For example, for a typical large dairy farm in New York State with 500 mature cows, researchers at Cornell University estimate the costs of abating emissions in this way at roughly $5 per ton CO_2e for an anaerobic lagoon, but the costs rise to roughly $25 for a 100-cow operation. Calculations performed using CoversVX file authored by Shepard et al. (2008) downloaded from the Cornell University Extension Service website on July 14, 2018.

55. Gao et al. (2012).

56. Strokal et al. (2016).

57. North Carolina Department of Environmental Quality (2018).

58. Bai et al. (2016).

59. Wang et al. (2017).

60. Hristov (2013).

61. A good summary of the evidence for different management of manure by larger and smaller farms in Canada is presented in VanderZaag et al. (2013).

62. United States International Trade Commission (2014).

63. United States International Trade Commission (2014).

64. Herrero et al. (2016).

65. Doole and Paragahawewa (2011).

66. Doole and Paragahawewa (2011).

67. de Klein et al. (2011).

68. Doole and Paragahawewa (2011).

69. Ledgard et al. (2014).

70. Welten et al. (2013).

71. Minet et al. (2016).

72. Yasuhara et al. (1997); OECD (2003); NIOSH (2007). Dicyandiamide seems to be minimally toxic based on the few lab animal studies that have been performed. The Organisation for Economic Co-operation and Development released an SIDS Initial Assessment Report for cyanoguanidine, another name for dicyandiamide, which determined that the oral LD50 (median lethal dose) is greater than 30,000 mg/kg per body weight in female rats (OECD 2003). Additionally, the chemical was determined to be a skin irritant for guinea pigs. However, nonlethal doses had no effect on clinical signs, body weights, food consumption, reproductive parameters, or necropsy findings in SD rats. Due to its low hazard, potential further assignment of the chemical has remained low priority.

73. Smith and Schallenberg (2013).

74. Smith and Schallenberg (2013).

75. Byrnes et al. (2017).

76. Subbarao et al. (2006a, 2006b, 2007, 2009).

77. Ward et al. (2016); Galbally et al. (2010); Barneze et al. (2014); Mazzetto et al. (2015); Pelster et al. (2016); Sordi et al. (2014).

78. Kelliher et al. (2014); Saggar et al. (2015); Chadwick et al. (2018).

79. Chen et al. (2016); Turner et al. (2015); Miller et al. (2012); Crutzen et al. (2008).

80. Turner et al. (2015).

81. By our estimate, using the 2 percent nitrous oxide emission factor of the IPCC, grazing in arid areas generates slightly less than half of the nitrous oxide emissions from pasturelands, but if those emission rates are too high, and emissions result from hotspot areas on wetter grazing land, then these arid pasturelands probably generate a lower percentage of emissions from pasturelands.

82. Email from Subbarao Guntur (CIAT) to Tim Searchinger (February 25, 2018).

83. Total nitrous oxide emissions are higher, but they include nitrous oxide from urine left on pasture, which we address in the livestock section. Davidson and Kanter (2014) estimate that agriculture is responsible for around 80 percent of total human emissions of nitrous oxide, and nitrous oxide was estimated at 6.2 percent of total emissions in 2010 (IPCC 2014).

84. Lassaletta et al. (2014), Figure 5c.

85. Erisman et al. (2013).

86. WRI (2013).

87. Peñuelas (2013).

88. Zhang et al. (2015b).

89. Zhang et al. (2015b), Table 1, estimates crop nitrogen use efficiency (NUE) at 42 percent while Lassaletta et al. (2014) estimate crop nitrogen use efficiency at 47 percent. Different estimates of nitrogen available from nitrogen fixation, animal agriculture, and deposition help to explain the differences, as do different estimates of the portion of nitrogen fertilizer used on pasture. Some estimates of nitrogen use efficiency focus only on synthetic fertilizer, but because the nitrogen available to crops includes other sources, estimates based on all fertilizer applied are more informative.

90. Nitrogen use efficiency can be defined in different ways. We define it as the percentage of total nitrogen applied to farms that is removed in the edible portions of crops, which excludes the nitrogen returned to farm fields in the crop residues left on the farm.

91. These figures rely on estimates for NUE in China that the International Fertilizer Association recently altered, which would very modestly improve the global average (IFA 2017).

92. Zhang et al. (2015b).

93. Chen et al. (2011).

94. Zhang et al. (2015b) estimate the NUE in China in 2010 at 25 percent (harvest of 13 Mt and total nitrogen from all sources on cropland of 51 Mt), but revisions down of roughly 7 Mt based on new estimates by the International Fertilizer Association bring that efficiency up to 30 percent IFA (2017).

95. Zhang et al. (2015b).

96. Lasselatta et al. (2014), Figure 1. A European nitrogen directive limited nitrogen application to 170 kg/ha, although the Dutch obtained a waiver for dairy farms whose feed was supplied primarily by grazing land (more than 70 percent) to apply up to 250 kg/ha until 2017. A new Dutch manure management directive restricting phosphorus levels will impose tighter constraints on manure management.

97. Lassaletta et al. (2014), Figure 2.

98. Lassaletta et al. (2014).

99. Mueller et al. (2012); Liu (2010).

100. See Figure 4b in Zhang et al. (2015b).

101. This issue is discussed in EU Nitrogen Expert Panel (2015).

102. Kanter and Searchinger (2018).

103. EPA (2015a).

104. Turner et al. (2015).

105. EPA (2015b).

106. Lasalleta et al. (2014), Figure 5b; Zhang et al. (2015b).

107. Use of synthetic nitrogen rises from 104 to 159 Mt (GlobAgri-WRR model). For comparison, FAO estimated an increase from 166 Mt to 263 Mt from 2006 to 2050, an increase of 58 percent (Alexandratos and Bruinsma 2012, 127), but adjusting for the roughly 25 percent greater population growth between 2006 and 2050 now expected by the United Nations (an increase of 3.1 billion instead of 2.5 billion), this projection by FAO would now be on the order of 70 percent (although it starts in 2006). A separate study by Bodirsky et al. (2014) estimates a "middle of the road" reference with an increase of reactive nitrogen in all agriculture from 2010 to 2050 of 25 percent. One of the differences in the estimates lies in the assumptions about changes in the efficiency of fertilization, which FAO assumes increases only around 4 percent, but which Bodirsky et al. (2014) assume increases by 13 percent.

108. GlobAgri-WRR does not estimate total losses of nitrogen to the environment. Zhang et al. (2015b) calculated a nitrogen surplus on cropland of 100 Mt in 2010. Although GlobAgri-WRR incorporates most of the Zhang et al. (2015b) crop nitrogen model, it estimates lower emissions because it incorporates a lower estimate of nitrogen produced from manure based on formulas established in Herrero et al. (2013).

109. This figure is not directly comparable to many other estimates because it includes emissions from the energy used to produce and transport fertilizer, which can be controlled by more efficient use, but which we also discuss in Chapter 28 below on reducing energy emissions.

110. Fertilizer Institute (2016).

111. USDA (2017).

112. Kanter and Searchinger (2018)

113. Ciampitti and Vyn (2014); Debruin et al. (2017).

114. van Grinsven et al. (2012); Velthof et al. (2013); Hansen et al. (2012).

115. Mueller et al. (2012); Ju et al. (2009); Chen et al. (2011).

116. Kitchen et al. (2017).

117. Robertson (1997). Nitrogen is taken up for only 8–12 weeks following crop canopy closure in most cropping systems.

118. Trenkel (2010).

119. Various meta-analyses are summarized in Kanter and Searchinger (2018); and Trenkel (2010), p. 94.

120. Akiyama et al. (2010).

121. Fuglie et al. (2011).

122. Bindabran et al. (2015).

123. Trenkel (2010).

124. Beach et al. (2015).

125. According to USDA (2013c), the average nitrogen fertilizer rate on corn in the United States was 140 lbs/acre, which equals 157 kg/ha. At IPCC N_2O default emission rates of 1.45 percent for both direct and indirect emissions, $20 per hectare to apply a nitrification inhibitor, and an effectiveness of 35 percent, nitrification inhibitors would save 0.37 tons of emissions (CO_2e) per hectare at a cost of $54 per ton of CO_2.

126. Robertson and Vitousek (2009).

127. According to Robertson and Vitousek (2009), "Agronomic evidence that any nitrification inhibitor consistently increases NUE is lacking."

128. Abalos et al. (2014, 2016).

129. Trenkel (2010), citing Gutser (2006), estimated nitrification inhibitors would cost 8 to 20 euros per hectare but reduce fertilizer application needs with a savings of 13 to 21 euros per hectare.

130. Abalos et al. (2014).

131. Qiao et al. (2015).

132. Qiao et al. (2015) reviews a number of studies and justly finds farmers seek to apply nitrogen in the spring.

133. McKinsey & Co. (2009), 188.

134. MarketsAndMarkets (2015) estimated global sales of controlled release fertilizers at $2.2 billion in 2014, out of worldwide nitrogen sales (for 2012) of $99 billion (MarketsAndMarkets 2017).

135. For example, Trenkel (2010) gives a difference in materials costs for polymer coating of urea as five times the cost of urea alone. However, other compounds may be in the range of $15 to $25 per hectare.

136. Qiao et al. (2015); Yang et al. (2016).

137. Marino (2017).

138. Subbarao et al. (2017, 2013).

139. Subbarao et al. (2017, 2013).

140. Bindraban et al. (2015); Dimkpa and Bindraban (2016).

141. The authors in Zhang et al. (2015b) established a goal of limiting nitrogen losses to the environment from cropland to 50 Mt. Although GlobAgri-WRR uses the Zhang et al. (2015b) nitrogen model, it adjusts future food needs to meet a larger population, makes more precise calculations by crop type and location. It also uses lower estimates for nitrogen in manure applied to crops based on the underlying analysis presented in Herrero et al. (2013). Because of this, under the GlobAgri-WRR scenario that achieves the Zhang et al. (2015b) NUE target, global NUE actually rises to 71 percent in 2050.

142. Zhang et al. (2015b).

143. Turner et al. (2015).

144. Bento et al. (2015).

145. Padhee (2018).

146. Ellis (2014).

147. See papers discussed in Jayne and Rashid (2013) finding that African farmers tend to apply fertilizer at rational rates given prices. For China, see Zhou et al. (2010).

148. Zhang et al. (2015b).

149. Fan et al. (2007); Morris et al. (2007).

150. Fan et al. (2007).

151. Mueller et al. (2012); Zhang et al. (2015b).

152. Yuxuan (2014).

153. Li et al. (2014).

154. Personal communication, Jikun Huang, April 2017. These results are expressed in Huang et al. (2017).

155. Huang et al. (2017).

156. Huang et al. (2017), Figure 5.5.

157. Huang et al. (2017), Table 5.1.

158. Huang et al. (2017).

159. As one example of the differential subsidies, the prices of nitrogen rose by only 16 percent from 2000–2001 to 2013–14, while the price of phosphorus rose 250 percent from 2009–10 to 2013–14 and the price of MOP rose 355 percent in the same period (Huang et al. 2017, 152).

160. Authors' calculations from FAO (2019a). In 2011, countries with a total population of 3.75 billion reported rice consumption in excess of 500 calories per day—in each case substantially more than any other single food. The world population in 2011 was 7 billion.

161. Roughly 500 Mt are the estimates both of the Food and Agriculture Organization of the United Nations (FAO), which can be found at FAO (2019a), and of the U.S. Environmental Protection Agency (EPA), at EPA (2012). The EPA estimate uses outdated estimates of the global warming potential of methane.

162. These estimates are generated by GlobAgri-WRR using estimated nitrous oxide emission rates for rice by the IPCC.

163. GlobAgri-WRR estimates of rice emissions are based on a model of rice emissions down to the subnational level published by Yan et al. (2009) using IPCC Tier 2 methods for estimating rice. However, the originally published paper used estimates of midseason drawdowns from a report for the Asian Development Bank. We believe these estimates are accurate for China (Li et al. 2002), Japan, and Korea. Together, these three countries accounted in 2014 for 33 Mha, roughly 20 percent of global rice paddy area (authors' calculations based on FAO 2019a). However, the view among agricultural researchers is that few farmers perform midseason drainage in most other countries, which account for the remaining 80 percent of global rice paddy area. Adjusting the model in Yan et al. (2009) to reflect our rough estimate of 10 percent midseason drainage rates in other countries raises the estimate of global methane emissions to roughly 600 Mt of CO_2e. When we further adjust these figures for a global warming potential for methane of 34, as recommended by the most recent integrated assessment by the IPCC, rather than the 21 used by FAO and the EPA, emissions rise to roughly 1.1 Gt.

164. Emissions from rice in five major rice-producing countries of Southeast Asia as reported in the most recent national communication to the UNFCCC as of September, 2016. The percentage of total emissions in Indonesia is low due to very high emissions from deforestation, whereas the high percentage of the total in Myanmar is due to generally low emissions from nonagricultural sectors.

Country	Total GHG emissions from rice (Gt CO_2e)	Percentage from total	Percentage from agriculture sector
Indonesia	34,861	2.5	46.2
Myanmar	5,511	28.4	43.5
Philippines	16,437	13.0	44.4
Thailand	29,940	10.6	57.5
Vietnam	37,101	24.8	57.5

165. As yields grow, so will the production of rice straw, and methane emissions can increase with the incorporation of rice straw into the soil. If rice straw is burned in the field, that will also emit nitrous oxide and methane. However, the actual amount of GHG emissions depends on how the rice straw is managed. If it is removed and used, there is no increase in methane. Because it is difficult to predict future management of rice straw, we do not factor in this possible effect of yield increases.

166. FAO (2019a).

167. Fischer et al. (2016).

168. GlobAgri-WRR model, based on Alexandratos and Bruinsma (2012) with adjustments.

169. That estimate is based on an empirical correlation between rice yields and nighttime temperature obtained in Peng et al. (2004), a long-term field experiment in the Philippines. Zhang, Tang, et al. (2013) also showed a correlation, though the amount differs by breed.

170. Nguyen (2005).

171. Ziska et al. (2009).

172. van Groenigen et al. (2013).

173. Alexandratos and Bruinsma (2012); FAO (2019a). Global rice yields in 2010 were 4.3 t/ha.

174. Authors' calculations based on necessary rice yield growth to 5.5 t/ha by 2050 to accommodate a 28 percent increase in rice consumption between 2010 and 2050 with no land expansion. Necessary annual yield growth would be 30 kg/ha/yr between 2010 and 2050, or 62 percent of growth between 1962 and 2006 (48.4 kg/ha/yr).

175. Fischer et al. (2014), Table 4.6.

176. Gogoi et al. (2008).

177. Jiang et al. (2017).

178. Su et al. (2015).

179. Biochar is a high-quality charcoal that can be made from crop residues. It can help store carbon in soils and, in some soils, increase fertility.

180. Setyanto et al. (2000).

181. IPCC (2006).

182. Gathala et al. (2011).

183. Gathala et al. (2011).

184. Wassmann et al. (2000). The early stages of directed seeding rice require a very shallow floodwater cover, so that initial emission rates under direct seeding are typically low. However, the plants take longer to grow in the field, increasing flood duration. (Young rice plants grown in a nursery are also flooded but typically occupy only 15–20 percent of the rice area; see IRRI 2007.)

185. Pittelkow et al. (2014).

186. Itoh et al. (2011).

187. Siopongco et al. (2013).

188. Joshi et al. (2013), Table 3.

189. IPCC (2006).

190. Linquist et al. (2014).

191. Joshi et al. (2013).

192. Sander et al. (2014); Tariq et al. (2017); Oo et al. (2018).

193. Kritee et al. (2018).

194. Yan and Akiyama (2008).

195. Global Commission on the Economy and Climate (2014).

196. According to Gassert et al. (2013), 29 percent of the world's rice is grown in areas facing high to extremely high levels of water stress.

197. Li et al. (2014); Bouman et al. (2007).

198. Hafeez et al. (2008).

199. Bouman and Tuong (2001).

200. Rejesus et al. (2011).

201. Lampayan (2013).

202. Kürschner et al. (2010).

203. Water Technology Centre (2009); World Bank (2006).

204. Siopongco et al. (2013).

205. Committee for Formulation of Agriculture Policy for Punjab State (2013).

206. Rajkishore et al. (2013); Pathak et al. (2013); Rajkishore and Sunitha (2013); Bhatia et al. (2013).

207. World Bank (2006).

208. Central Water Commission (2010); Department of Agriculture, Punjab (2012).

209. Government of Tamil Nadu (2009).

210. Chauhan et al. (2012).

211. Mahajan et al. (2013).

212. Mahajan et al. (2013).

213. FAO (2019a).

214. Pinoy Rice Knowledge Bank (2014).

215. Sander et al. (2014). Studies include the following:

Study	Location	Methane	
		Emissions under continuous flooding	Relative emissions under single drawdown
		kg/ha/season [kg/ha/day]	Percent
Corton et al. (2000)	Maligaya, Nueva Ecija	89 [0.91]	57.1
		75 [0.73]	63.0
		348 [3.75]	92.5
		272 [3.23]	55.1
Wassmann et al. (2000)	Los Baños, Laguna	251 [2.51]	17.9
		10 [0.10]	80.0
		35 [0.35]	31.4
Bronson et al. (1997)	Los Baños, Laguna	17.3 [0.20]	38.5
		371 [4.36]	57.2

216. Dawe (2005); Hafeez et al. (2008). A study of one irrigation system in Central Luzon, showed that 10,000 farms (about 20 percent of the area under rice) had a pump density of at least one pump per 10 ha.

217. Mariano et al. (2012).

218. Rejesus et al. (2011).

219. Rejesus et al. (2011).

220. Belder et al. (2004); Lampayan et al. (2009); Tabbal et al. (2002).

221. Sibayan et al. (2010); Rejesus et al. (2011).

222. Rejesus et al. (2013).

223. Authors' calculations from FAO (2019a).

224. USDA (2014b).

225. Linquist et al. (2014).

226. This is based on work by Linquist et al. (2014).

227. Pittelkow et al. (2014).

228. Linquist et al. (2014).

229. Linquist et al. (2014); California Rice Research Board (2014).

230. Authors' calculations from FAO (2019a).

231. Zhang et al. (2013b, 2013c); Liu, Zhang, Ji, et al. (2013); Zhang and Li (2003).

232. Zhang et al. (2013c).

233. Fan et al. (2005); Li et al. (2007); Liu et al. (2003); Zeng (2012).

234. Li et al. (2004); Li et al. (2007).

235. Adhya et al. (2014) include an estimate of plastic film costs of 750 RMB, but savings in pesticides and fertilizer input of 657 RMB, plus labor savings of 2,700 RMB. Zeng and Liu (2012) found similar savings.

236. Wei et al. (2000); Wang et al. (2002).

237. Cai et al. (2000).

238. Wei et al. (2000); Wang et al. (2002, 2012).

239. Wang (2008).

240. See Adhya et al. (2014), which relied on earlier FAO estimates.

241. FAO (2019a).

242. On the relatively pessimistic side, one study found only around a 6 percent increase in energy efficiency of tractors in the United States from 1979 to 2009 (Grillo et al. 2014), and a European Commission analysis shows little gain in the energy efficiency of freight transport from 1995 to 2010 (European Commission 2016, 128, Figure 31). On the optimistic side, the European Union is also projecting a 44 percent increase in the efficiency of heavy-duty vehicles between 2010 and 2050 (European Commission 2016, 131).

243. IFA (2009).

244. See, e.g., IEA (2015a); Deep Decarbonization Pathways Project (2015); and New Climate Economy (2016).

245. Saini (2013).

246. CCAFS (2016).

247. IEA (2015a); IEA (2016a); UNIDO (2010).

248. FAO (2011f). FAO's breakdown for direct energy use in agriculture in 2010 is as follows. We use this information while adding information on energy use in aquaculture from WorldFish and Kasetsart University (Mungkung et al. 2014).

FAO Breakdown of Direct Farm Energy Use in Agriculture in 2010	
Gas-diesel oil	357,532
Motor gasoline	18,172
Natural gas (including LNG)	22,924
Liquefied petroleum gas (LPG)	8,007
Fuel oil	5,723
Coal	97,982
Electricity	325,517
Total energy	835,857

249. See previous endnote.

250. IEA (2015a); U.S. DoE (n.d.).

251. Patil et al. (2016).

252. Patil et al. (2016).

253. FAO (2019a).

254. Zhang et al. (2013c).

255. Zhang et al. (2013c).

256. Michalsky et al. (2012).

257. Pfromm (2017).

258. U.S. Drive Partnership (2017); Pfromm (2017).

259. Chowdhury et al. (2018); Nakamura et al. (2015).

260. Service (2018).

261. University of Toronto (n.d.).

262. Rolex Awards for Enterprise (2005).

263. Upadhyay (2014); Enciso and Mecke (2004).

264. EPA (2017).

265. Seeberg-Elverfeldt and Tapio-Biström (2010); Smith et al. (2007).

266. Smith et al. (2007). Carbon storage represents 89 percent of the total mitigation estimated economically feasible; a few percent, however, was focused not on new sequestration but on reducing the loss of carbon in wetland soils by restoring the wetlands.

267. In Figure 11.13 of the most recent IPCC assessment, Smith et al. (2014) essentially reproduce the mitigation estimates from the 2007 assessment. In Figure 11.14, the chapter then adds bar charts showing more recent assessments—grouped into agriculture and forestry—and including mitigation through demand reductions. But this chart identifies mitigation potential only in broad categories, such as forestry or agriculture, and does not identify the types of agricultural mitigation. It therefore does not modify the impression from Figure 11.13.

268. Paustian et al. (2016) cited Smith et al. (2008), which was the peer-review paper that presented the modeling analysis that went into the 2007 IPCC report.

269. Van Groenigen et al. (2017).

270. Lal (2004).

271. Although there are great variations in soil carbon losses, this figure seems a reasonable estimate based on meta-analyses as summarized in the supplement of Searchinger et al. (2018a).

272. See examples provided in Chambers et al. (2016).

273. See Minasny et al. (2017) for articulation of this goal.

274. See Chambers et al. (2016); Minasny et al. (2017); de Moraes et al. (2017); Lal et al. (2018), and many other papers summarized in Stockman et al. (2013).

275. See, e.g., Powlson et al. (2016); Powlson et al. (2014); van Groenigen et al. (2017).

276. Poulton et al. (2018).

277. Transferring carbon from trees to soils by itself is inefficient. Most of the carbon will decompose and be released back into the atmosphere as carbon dioxide, and while the precise levels will vary, only on the order of 10–20 percent of the carbon is likely to remain in a more stable form in the soil (Liska et al. 2014). The initial result is likely to be a substantial carbon debt. If the tree regrows, it will eventually pay off the carbon debt after many years, but if a middle-age tree were used, there is actually a further net loss of carbon sequestration for probably 10 years or more because the newly planted tree would grow more slowly and therefore sequester less carbon per year than the original tree if left in place.

278. Powlson et al. (2011a); McCarthy et al. (2011).

279. Strokal et al. (2016).

280. Cassou (2018).

281. Pinheiro et al. (2010); Cerri et al. (2010).

282. IPCC (2006) (Chapter 4, Section 4A.2.1.1) estimates 10 percent of residues as burned as the best estimate for developing countries. The FAO also assumes that burning of crop residues is 10 percent of crop residue; http://fenixservices.fao.org/faostat/static/documents/GB/GB_e.pdf.

283. Liska et al. (2014).

284. Powlson et al. (2011b).

285. See papers cited in Paustian et al. (2017) and Chambers et al. (2016).

286. Baker et al. (2007). This paper was quickly followed by another important paper, Blanco-Canqui and Lal (2008).

287. Powlson et al. (2014) provides an excellent summary of the literature. Other good papers include Powlson et al. 2012) and Luo et al. (2010).

288. Kravchenko and Robertson (2011).

289. Kravchenko and Robertson (2011) argued that if we analyze each layer of the soil profile separately, we can find statistically meaningful estimates of soil carbon gain in the upper profile and no statistically meaningful signal below. If there were strong biochemical reasons to believe changes would only occur in the upper profile, this argument would be persuasive. But if you think there are biochemical reasons that changes would occur within the entire top meter, then the higher carbon content in the top layer is not meaningful by itself.

290. Powlson et al. (2014).

291. De Freitas and Landers (2014).

292. Selenobaldo et al. (2016); Zotarelli et al. (2012); Boddey et al. (2010).

293. Powlson et al. (2014), summarizing studies.

294. Kurkalova and Tran (2017). Another study with similar findings is Hill (2001).

295. Wade et al. (2015).

296. Powlson et al. (2014) cite a variety of studies showing losses of the carbon gain. One study from 2007, however, found the data to be variable (Conant et al. 2007).

297. Six et al. (2004) performed a meta-analysis and found that nitrous oxide increased enough to more than cancel out soil carbon gains unless no-till was practiced for more than six years—even using large estimates of soil carbon gains. Van Kessel et al. (2013) found the same to be true for no-till in drier climates for 10 years but found no increase in nitrous oxide in wetter climates and reductions after 10 years of continuous no-till.

298. Pittelkow et al. (2015).

299. Conant et al. (2001).

300. McCarthy et al. (2011); Derner and Schuman (2007). For example, Badini et al. (2007)—a study of grazing intensities in the western Sahel on drier, low-carbon lands—found no response in carbon content to grazing intensity.

301. Asner and Archer (2010); Giller et al. (2009).

302. Whitehead et al. (2018).

303. Franzluebbers and Stuedemann (2009) tracked 12 years of carbon sequestration on a pasture under different test management in the southeastern United States. They found that light grazing had a higher rate of carbon sequestration than no grazing, which had a higher rate than heavy grazing. Their paper was cited in Chambers et al. (2016) as a study that helped find the potential for carbon sequestration "for improved management on grazing lands." Yet, as their paper states, the study covered the period 1994–2005, and the site had been restored to grassland from cropland only in 1991. This paper is therefore truly exploring how management affects rates of soil carbon sequestration during the restoration process; it is not proof of soil carbon sequestration potential of mature grassland. Smith (2014) warns of the same potential miscommunication in a paper of which Smith was himself a coauthor. That paper, by Senapati et al. (2014), concluded, "The results clearly indicate temperate sown grasslands to be a carbon sink under grazing management," without communicating in this sentence that the carbon gains measured were of a site resown with grass seed only four years earlier.

304. Smith (2014).

305. Soussana et al. (2014); Schulze et al. (2009).

306. These "eddy covariance" studies are summarized in Soussana et al. (2014, 78).

307. Soussana et al. (2014).

308. IPCC (2014).

309. Smith (2014).

310. Chang et al. (2016).

311. To confirm this understanding, WRI underlaid maps of European grazing land with estimated natural vegetation using the LPJmL vegetation model and found that more than 80 percent of grazing land would naturally be left forest if undisturbed.

312. Stanley et al. (2018).

313. Kirkby et al. (2011).

314. Van Groenigen et al. (2017).

315. This initiative is the 4 per 1000 Initiative (https://www.4p1000.org/—last accessed December 30, 2018), which aims to increase global soil carbon by 4 percent per year.

316. Soussana et al. (2017).

317. Kirkby et al. (2016).

318. For example, in the meta-analysis finding small carbon gains from residue retention discussed above, Powlson et al. (2011b)), many of the benefits credited were from reduced losses (email from David Powlson to Tim Searchinger, July 26, 2018).

319. Zhao et al. (2018), based on national soil surveys in top 20 centimeters, calculated a net gain of 140 kgC/ha/yr.

320. West et al. (2010) estimate small soil carbon gains while Liska estimates soil carbon losses in the Upper Midwest. The Liska analysis for Upper Midwest Soil Carbon is given in the presentation "Biofuels from Crop Residue: Soil Organic Carbon and Climate Impacts in the US and India" at Indo-US Workshop on Addressing the Nexus of Food, Energy, and Water, April 19–21, 2017, Indian Institute of Science, Bangalore, India, but it is based on the same modeling presented in Liska et al. (2014).

321. Smith and Falloon (2005).

322. Ladha et al. (2016)—a recent global nitrogen budget for cereals—estimated losses of nitrogen from soils globally from cereals at 61 Mt per year. Liu et al. (2010) also found global losses of nitrogen of 11.5 Mt per year. The Ladha paper estimates higher losses in large part because it estimated higher rates of biological nitrogen uptake by plants and therefore higher global loadings of nitrogen.

323. According to Kirkby et al. (2014), global average ratios of carbon to nitrogen in humified soils is roughly 11:1. Multiplying 61 Mt of nitrogen loss estimated by Ladha et al. (2016) by 11 to obtain carbon and then by 3.67 to convert carbon to carbon dioxide equals 2,462 million tons of carbon dioxide.

324. We use the word "essentially" because to the extent these carbon losses are occurring on recently converted cropland (e.g., last 20 years), their losses of carbon could be implicitly counted as emissions from land-use change, but this is a very small percentage of total global cropland.

325. See, e.g., Powlson et al. (2016).

326. See, e.g., Zhao et al. (2018).

327. Kirkby et al. (2011).

328. Abraha et al. (2016).

329. Stockman et al. (2013).

330. Lal (2004).

331. For a more recent study, see Zomer et al. (2017).

332. Braz et al. (2013).

333. Kemp and Michalk (2011); Wang et al. (2011).

334. Poeplau et al. (2018).

335. Conant et. al. (2017) found carbon sequestration rates for improved, on-going grazing of 0.28 tC/ha/yr.

336. Gerber et al. (2013).

337. IPCC (2007).

338. Zomer et al. (2016).

339. One reason for some skepticism is that global cropland maps generated in different ways vary greatly and all are known to have many errors (Fritz et al. 2010). Zomer et al. (2016) used GLC, one of the global maps, which identifies cropland on around 2.2 billion hectares, which is roughly 600 million more than identified by FAO and nearly all other studies. This map therefore captures substantial land that is not truly in cropping use but is part of the farming landscape. A breakdown in the paper also showed that the carbon gains occurred overwhelmingly on land estimated to have more than 50 tC/ha, which means a high level of tree cover. Satellite maps are particularly prone to erroneously estimating cropland in such mixed environments. More specifically, by examining changes on the same land between 2000 and 2010, and focusing on such areas of high forest, the paper could quite possibly be identifying not growth of trees on cropland but reversion of agricultural land to forest, which occurs at high rates globally even as other lands are cleared. They may also just be capturing a thickening of tree cover on nonagricultural land.

340. Henry et al. (2009).

341. Schmidt et al. (2011).

342. Treseder and Holden (2013).

343. Salk Institute (n.d.).

344. For example, Bryan et al. (2011) found that many farmers would achieve net economic gains by leaving 50 percent to 75 percent of their residues on soils to boost yields, even if that required them to buy napier grass to replace their crop residue as feed for their cows, assuming they also had access to fertilizer. Tui et al. (2015) found a chance for profitability in shifting crop residues to soils in Zimbabwe if farmers could produce mucuna, a forage legume, to replace the residues.

REFERENCES

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

PHOTO CREDITS

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The Complete Menu: Creating a Sustainable Food Future

The analysis of individual menu items in Courses 1–5 estimates how much each item could help the world close our three gaps to meet targets for increasing food production, minimizing expansion of agricultural land area, and reducing greenhouse gas (GHG) emissions. In this section, we use the GlobAgri-WRR model to examine several plausible (or at least possible) combinations of menu items for closing these gaps and achieving a sustainable food future.

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CHAPTER 32

COMBINING MENU ITEMS: THREE INCREASING LEVELS OF GLOBAL AMBITION

In this chapter, we describe and, where possible, quantify the level of effort required in each menu item to realize each of our three combined scenarios: the Coordinated Effort, Highly Ambitious, and Breakthrough Technologies scenarios.

Modeling efforts often categorize each component action (what we call "menu items" in this report), into three levels of ambition: "low, medium, and high" or "conservative, moderate, and aggressive." Each level is determined by expert judgment, degree of change relative to current or projected status, cost,[1] or other criteria. Modelers then aggregate the "low ambition" components into a combined "conservative" scenario, the "medium ambition" components into a combined "moderate" scenario, and the "high ambition" components into a combined "aggressive" scenario.

The "Coordinated Effort," "Highly Ambitious," and "Breakthrough Technologies" Scenarios

We also aggregate our menu items into three levels of ambition, but we follow a different approach in combining them. We do not automatically aggregate all the low-ambition menu item scenarios into one "low" scenario and so on. The lower, medium, and higher scenarios of each individual menu item require different kinds of changes in behavior, different scales of government effort, and different levels of technological innovation. The changes required, for example, to obtain different levels of land use or GHG savings by shifting diets differ from the changes required to achieve different levels of reduction in emissions from fertilizer. To establish three scenarios with changes in each menu item that are conceptually consistent, we therefore apply the following principles as scenarios advance in ambition:

- **Coordinated Effort scenario.** For each component menu item, this aggregate scenario involves levels of progress that we are confident the world could achieve with a strong, coordinated, global commitment to action. Changes would come at limited economic cost (or even economic gains) and without the need for any fundamental breakthroughs in technology. Success would depend primarily on political will. The level of commitment required in the Coordinated Effort scenario would mean that the world's governments would need to muster financial resources and, in many situations, overcome political and logistical obstacles. Coordination is necessary in part to share technological knowledge and scientific understanding—such as reasonable progress in manure management—and also to implement globally consistent policies to ensure that progress in one country does not simply shift unsustainable practices to another. For example, effective forest and savanna protection in one set of countries could result in land- clearing for agriculture in other countries if the latter do not impose similar forest and savanna protection. Reductions in demand for meat in one country could lower meat prices and increase meat consumption in another if the latter does not have similar initiatives to reduce demand for meat. We do assume continued progress in and support for some technologies that are already developing, such as commercialization of some promising drugs or feed additives that lower enteric methane emissions and further improvements in plant-based meat substitutes, but we do not assume any fundamental technological breakthroughs.

- **Highly Ambitious scenario.** This scenario includes the menu items from the Coordinated Effort scenario and extends them by choosing a level of achievement that is based on technical achievability but is less concerned with cost or practicability. In some situations, this level of achievement will require existing technology to advance beyond current performance, but it will not require true technological breakthroughs. Some of these measures might be costly in economic terms and would require government support or regulatory action, but they should be technically feasible.

- **Breakthrough Technologies scenario.** This scenario includes all menu items in the Coordinated Effort and Highly Ambitious scenarios plus additional levels of achievement that could be realized only with technological breakthroughs that improve both performance and cost effectiveness. We consider technological breakthroughs only in fields where science has shown significant progress.

To illustrate the thinking behind our categorization, consider the menu item regarding fertility rates.

Our Coordinated Effort scenario includes population growth in sub-Saharan Africa that follows the "low fertility" projection of the United Nations. That projection assumes reductions in total fertility rates that are 0.5 children per woman lower in each country in each year than in the baseline "medium fertility" scenario. Achieving this reduction in fertility rates would require major new political and social efforts to improve access to education for girls, improve children's health care, and provide access to family planning. Although ambitious politically, these measures involve social investments that would be valuable for many political, social, and moral reasons independent of food security and sustainability concerns. In that sense, such measures would pay for themselves regardless of their effects on food security and the environment. We conclude they would be achieved if the world directed appropriate attention and ambition to these efforts.

For our Highly Ambitious scenario, we choose a reduction in fertility rates to replacement levels by 2050 because we consider such efforts to be socially and technologically achievable with even higher investments in health and education and in light of the speed of change that has occurred in some other countries. However, our Breakthrough Technologies scenario includes no more ambitious target because we are aware of no breakthrough technologies that would further reduce fertility rates—and in any case, replacement level fertility would have already been achieved and no further reductions would be necessary.

As another illustration, consider reducing methane emissions from ruminants. Our Coordinated Effort scenario assumes that a feed additive becomes commercially available at low cost that can reduce enteric methane by 30 percent from cattle, and that this additive is provided to most cattle that are fed from a central location at least every day. That level of application equates to roughly half of all dairy cattle and roughly one-quarter of beef cattle.[2] This effort would require modest improvements to a feed additive that is already invented and an ambitious—but entirely feasible—strategy to induce farmers worldwide to give that additive to their animals where practicable. Our Highly Ambitious scenario extends this 30 percent emissions reduction to two-thirds of all beef cattle that are at times fed concentrated feed or cut-and-carry grass, and to all dairy cattle and one-sixth of all sheep and goats. Such an achievement would require either some additional technological innovation for long-lasting, slow-release additives—which we do not consider rises to the level of a major breakthrough technology—or some more active, and likely expensive, practice involving feeding grazing animals. In the Breakthrough Technologies scenario, we extend the 30 percent methane emissions reduction to all ruminants, including goats and sheep, which we consider impractical without greater technological innovation.

Our food loss and waste and fertilizer management menu items illustrate our judgment about breakthrough technologies. We regard a 50 percent reduction in global food loss and waste as appropriate only for our Breakthrough Technologies scenario because such a high level of reduction would probably require innovative, simple, and inexpensive technologies that enable foods to be stored for far longer without spoilage. Similarly, in our "reduce nitrogen emissions from fertilizer" menu item, the shift to producing ammonia fertilizer using solar energy sources occurs only in the Breakthrough Technologies scenario. We believe that technological breakthroughs are necessary before these levels of reductions become practical and economical, but we also believe that promising technological options exist that make this scenario feasible.

For most of the menu items in Courses 1–5, one could hypothesize innovations that achieve far greater closure of gaps than those we incorporate even in the Breakthrough Technologies scenario; for example, food additives for ruminants that eliminate nearly all methane emissions, crop yield gains that easily produce three times as much food on the same land, or plant-based steak that is indistinguishable from the best Argentinian filet. A few of these technologies might become realities, and we consider research to realize these innovations important, but for now we consider them too speculative to meet our criteria. Including them in our scenarios could lead to unrealistic expectations or misplaced "bets" on necessary actions over the coming 5–10 years to get the world on a path to a sustainable food future.

As these examples illustrate, the level of ambition selected for each menu item in each of the three combined scenarios ultimately reflects our educated guess as to how hard it will be to achieve. Other researchers may reasonably disagree with our choices. The purpose of this exercise is to illustrate the kinds of combinations of menu items that could close the three gaps.

Table 32-1 shows the level of ambition we adopted for each menu item in each of the three combined scenarios. More detailed discussion of the rationale behind each level of ambition is provided in each of the relevant menu item chapters of this report.

Summary of the Baseline and Combined Scenarios

Table 32-1 | Summary of the GlobAgri-WRR 2050 baseline projection and three combined scenarios

MENU ITEM	2050 BASELINE	COORDINATED EFFORT	HIGHLY AMBITIOUS	BREAKTHROUGH TECHNOLOGIES	COMMENT
DEMAND-SIDE SOLUTIONS					
Course 1. Reduce growth in food demand					
Reduce food loss and waste	Rate of food loss and waste (24% of calories globally) maintained in each country and food type	10% reduction in rate of food loss and waste	25% reduction in rate of food loss and waste	50% reduction in rate of food loss and waste	The Coordinated Effort seems plausible because the United Kingdom reduced its food loss and waste by 14% between 2007 and 2012. A 25% reduction seems possible as an outer limit, but a 50% reduction seems unlikely without breakthroughs in technology (e.g., improved storage systems or technology that prevents spoilage for longer).
Shift to healthier and more sustainable diets	88% increase in demand for ruminant meat between 2010 and 2050 as incomes grow across the developing world	Ruminant meat demand increases only 69% above 2010 levels, and calories shift to pulses and soy. This represents a 10% reduction in ruminant meat demand relative to baseline.	Ruminant meat demand increases only 32% above 2010 levels, and calories shift to pulses and soy. This represents a 30% reduction in ruminant meat demand relative to baseline.	Same as Highly Ambitious	We do not include reductions in total consumption of animal-based foods in the combination scenarios because our baseline scenario (based on FAO projections) is arguably conservative in projecting "business-as-usual" demand for these foods. But U.S. and European experience shows that large reductions in beef demand are possible. A global 30% reduction in ruminant meat demand (relative to 2050 baseline) would require reductions of more than 20% in Europe, 40% in North America and Russia, and 60% in Brazil relative to 2010 levels, which we consider highly ambitious.

Table 32-1 | Summary of the GlobAgri-WRR 2050 baseline projection and three combined scenarios (continued)

MENU ITEM	2050 BASELINE	COORDINATED EFFORT	HIGHLY AMBITIOUS	BREAKTHROUGH TECHNOLOGIES	COMMENT
Avoid competition from bioenergy for food crops and land	Crop-based biofuels maintained at 2010 share of global transportation fuel (2.5%)	Both food and energy crop-based biofuels phased out	Same as Coordinated Effort	Same as Coordinated Effort	Our analysis shows no environmental or food security benefits from these biofuels, so phasing them out is solely a political question rather than an economic or technical question.
Achieve replacement-level fertility rates	UN medium fertility estimate; global population 9.8 billion in 2050	UN low fertility estimate in sub-Saharan Africa; global population 9.5 billion in 2050	Sub-Saharan Africa fertility drops to replacement level by 2050; global population 9.3 billion in 2050	Same as Highly Ambitious	Although the UN "low fertility" estimate is plausible, each new UN population projection since 2012 has revised sub-Saharan Africa's population in 2050 upward since the region's fertility rates have not dropped as rapidly as previously projected. Evidence from other countries of rapid drops in fertility rates nevertheless suggests that the Highly Ambitious scenario is possible.
SUPPLY-SIDE SOLUTIONS					
Course 2. Increase food production on existing agricultural land					
Increase livestock and pasture productivity	62% growth in beef output per hectare of pastureland, 53% growth in dairy output per hectare, and 71% growth in sheep and goat meat output per hectare	Same as baseline	Productivity growth is 25% faster, resulting in 67% growth in beef output per hectare, 58% growth in dairy output per hectare, and 76% growth in sheep and goat meat output per hectare	Same as Highly Ambitious	Because the baseline projection already includes faster efficiency gains than in the past 50 years, we maintain the baseline in the Coordinated Effort scenario. However, because pure technical potential is probably higher, we increase this level in Highly Ambitious scenario. Although improved breeding is critical to all progress, we foresee no breakthrough technologies.
Plant existing cropland more frequently	5% increase in cropping intensity between 2010 and 2050 (to 89%)	10% increase in cropping intensity between 2010 and 2050 (to 93%)	Same as Coordinated Effort	Same as Coordinated Effort	Extremely limited information on potential to increase double-cropping or reduce fallow periods— particularly without irrigation expansion—bars any confident predictions. But modest FAO prediction in the baseline leads us to estimate some higher potential in Coordinated Effort scenario.

Table 32-1 | Summary of the GlobAgri-WRR 2050 baseline projection and three combined scenarios (continued)

MENU ITEM	2050 BASELINE	COORDINATED EFFORT	HIGHLY AMBITIOUS	BREAKTHROUGH TECHNOLOGIES	COMMENT
Improve crop breeding to boost yields **Improve soil and water management** **Adapt to climate change**	48% increase in crop yields above 2010 levels (similar to average linear rates of yield growth from 1962 to 2006)	Same as baseline	Crop yields rise to 56% above 2010 levels (20% improvement over baseline growth rate)	Crop yields rise to 69% above 2010 levels (50% improvement over baseline growth rate)	Because baseline yields assume faster growth rates than recent decades, we believe they already require a large-scale, global coordinated effort. But technical potential to boost yields could allow a faster growth rate in the Highly Ambitious scenario, and new molecular biology methods suggest capacity for breakthrough technologies with adequate research effort.
Course 3. Protect and restore natural ecosystems and limit agricultural land-shifting					
Link productivity gains with protection of natural ecosystems	Linkage prevents most shifting of locations of agricultural land encouraged by yield gains	Same as baseline	Same as baseline	Same as baseline	Viewed globally, helping farmers to boost yields (Course 2) while at the same time avoiding gross agricultural land expansion is a necessary and cost-effective strategy to stabilize the climate. Since yield gains are realized in Course 2, this linkage to ecosystem protection is a political rather than a technical or economic challenge and belongs in all scenarios.
Limit inevitable cropland expansion to lands with lower environmental opportunity costs	Inevitable land expansion is limited such that carbon effects are offset by the next menu item (reforestation)	Same as baseline	Same as baseline	Same as baseline	Avoided conversion of forests and other natural ecosystems is embedded in the actions to reduce demand (Course 1) and increase crop and livestock production on existing agricultural land (Course 2).
Reforest abandoned, unproductive, and liberated agricultural lands	Reforestation of lands with little agricultural potential offsets carbon effects of inevitable shifting of locations of agricultural land	Same as baseline	Same as baseline	80 Mha of liberated land fully reforested (to achieve 4 Gt CO_2e/year target) 585 Mha of liberated land fully reforested to offset all remaining agricultural production emissions	Because of the ambitious nature of our strategies to liberate agricultural lands, we are reluctant to place too much emphasis on potential for large-scale reforestation. We therefore show two scopes of potential carbon sequestration gains from reestablishment of natural vegetation on liberated land in our Breakthrough Technologies scenario, which are shown as annual emissions offsets over a 40-year period.

Table 32-1 | Summary of the GlobAgri-WRR 2050 baseline projection and three combined scenarios (continued)

MENU ITEM	2050 BASELINE	COORDINATED EFFORT	HIGHLY AMBITIOUS	BREAKTHROUGH TECHNOLOGIES	COMMENT
Conserve and restore peatlands	Annual peatland emissions stay constant at 1.1 Gt CO_2e between 2010 and 2050	50% reduction in annual peatland emissions	75% reduction in annual peatland emissions	Same as Highly Ambitious	Although politically challenging, high levels of peatland restoration are probably an economically rational mitigation option. Technical potential suggests the possibility of increased hectares in the Highly Ambitious scenario, but some drained peatlands are in such intensive agricultural use or disrupted by changes in water flows that restoration of these peatlands is unfeasible.
Course 4. Increase fish supply					
Improve wild fisheries management	10% decline in wild fish catch between 2010 and 2050	Wild fish catch stabilized at 2010 level by 2050	Same as Coordinated Effort	Same as Coordinated Effort	Strategies to curb overfishing are well documented, and literature suggests that optimal fisheries management could even lead to increases in annual wild fish catch above 2010 levels, but overfishing remains near historical highs. Coordinated effort would be necessary just to maintain 2010 catch levels, and since optimal management in all major fishing countries seems overly optimistic, we decline to include scenarios of increases.
Improve productivity and environmental performance of aquaculture	10% increase in aquaculture production efficiencies between 2010 and 2050 across the board	50% of extensive pond production switches to semi-intensive production, and 50% of semi-intensive switches to intensive	Same as Coordinated Effort, plus 20% increase in aquaculture production efficiencies between 2010 and 2050 across the board	Same as Highly Ambitious	Shifts to more intensive production are technically possible although costs and feasibility will vary by location. Aquaculture is a young industry and additional efficiency gains (relative to terrestrial animals) seem possible.

Table 32-1 | Summary of the GlobAgri-WRR 2050 baseline projection and three combined scenarios (continued)

MENU ITEM	2050 BASELINE	COORDINATED EFFORT	HIGHLY AMBITIOUS	BREAKTHROUGH TECHNOLOGIES	COMMENT
Course 5. Reduce GHG emissions from agricultural production					
Reduce enteric fermentation through new technologies	Enteric methane emissions of 3.4 Gt CO_2e in 2050 (51% above 2010 level)	30% emissions reduction from half of dairy cows, and one-quarter of beef cattle—leading to a 9% reduction in methane emissions from ruminants (38% growth above 2010 level)	30% emissions reduction from all dairy cows, half of beef cattle, and one-sixth of sheep—leading to an 18% methane emissions reduction from ruminants (24% growth above 2010 level)	30% methane emissions reduction from all ruminants, including those permanently grazed (6% growth above 2010 level)	Recent progress in feed additives suggests the potential for 30% reductions but only in cattle that can be easily fed additives daily, and possibly, many times. However, the technical potential exists to extend to all cattle through daily feeding. No credible science, however, suggests higher potential with additives free of other major environmental or health limitations.
Reduce emissions through improved manure management	Manure management emissions of 770 Mt CO_2e in 2050 (31% above 2010 level)	40% reduction of methane emissions from wet manure (14% growth above 2010 level)	80% reduction of methane emissions from wet manure plus 20% reduction of all other manure management emissions (17% reduction below 2010 level)	Same as Highly Ambitious	Digesters can greatly reduce emissions from wet manure compared to baseline if carefully implemented, and solid separation can probably reduce nitrous oxide emissions generally, although efforts must reach vast numbers of farms. Although other technologies may emerge, they are too speculative to include here.
Reduce emissions from manure left on pasture	Emissions from manure left on pasture of 653 Mt CO_2e in 2050 (46% above 2010 level)	Same as baseline	20% reduction of nitrogen left on pastures for nonarid systems (31% growth above 2010 level)	40% reduction of nitrogen left on pastures for nonarid systems (15% growth above 2010 level)	Most promising technologies involve nitrification inhibitors either spread on intensively grazed farms or consumed by animals. Because the technology is not so advanced, we include them only in the two more aggressive scenarios yet at modest levels of progress.
Reduce emissions from fertilizers by increasing nitrogen use efficiency	Nitrogen use efficiency grows from 46% in 2010 to 48% in 2050	57% nitrogen use efficiency due to a range of management measures	61% nitrogen use efficiency due to a range of management measures	67% nitrogen use efficiency due to a range of management measures plus new technologies	Coordinated Effort assumes better general management while Highly Ambitious and Breakthrough Technologies assume different levels of progress on changing nitrogen compounds (including inhibitors), and possibly in crop breeding to enhance efficiency.

Table 32-1 | Summary of the GlobAgri-WRR 2050 baseline projection and three combined scenarios (continued)

MENU ITEM	2050 BASELINE	COORDINATED EFFORT	HIGHLY AMBITIOUS	BREAKTHROUGH TECHNOLOGIES	COMMENT
Adopt emissions-reducing rice management and breeds	Rice methane of 1.3 Gt CO_2e in 2050 (13% above 2010 level)	10% reduction in rice methane (17% below 2010 level) thanks to new water management practices and new rice breeds	Same as Coordinated Effort	Same as Highly Ambitious, plus 20% faster rate of rice yield gain (31% reduction of rice methane below 2010 level)	Alternate wetting and drying (AWD) and straw management are proven technologies but require major efforts for implementation, probably including improvements in many irrigation systems. Science shows some rice varieties have lower methane emissions and new breeds have potentially lower emissions. High crop yields in some locations also suggest potential for higher yields if full breeding potential is utilized.
Increase agricultural energy efficiency and shift to non-fossil energy sources	25% decrease in energy emissions per unit of agricultural output between 2010 and 2050	Same as baseline	50% decrease in energy emissions per unit of agricultural output between 2010 and 2050	75% decrease in energy emissions per unit of agricultural output between 2010 and 2050	Because baseline incorporates increases in energy efficiency, we consider that it already requires coordinated effort. Highly Ambitious effort could further reduce emissions through incorporation of renewable energy. The Breakthrough Technologies scenario requires new technologies for nitrogen synthesis in fertilizer manufacturing.
Focus on realistic options to sequester carbon in agricultural soils	Soil carbon gains sufficient to assure no net loss of soil carbon globally and contribute to yield gains	Same as baseline	Same as baseline	Same as baseline	The most promising opportunity for soil carbon gains are those that would result from increased productivity, and thus are already built into our baseline and Course 2. Because of the scientific uncertainty, we do not rely on additional soil carbon gains for offsetting ongoing agricultural production emissions.



CHAPTER 33

A TALE OF THREE GAPS, REVISITED

In this chapter, we quantify the contribution of each of the combined scenarios to reducing the food gap, the land gap, and the GHG mitigation gap.

Table 32-1 summarizes the components of each combined scenario. The "waterfall charts" in this chapter show the role played by the various menu items (and courses) in each combined scenario. Because the quantitative effects of menu items to some extent depend on or affect others, simply adding the effects of each individual menu item would not correctly calculate the effect of any combination of menu items. We therefore employ a form of mathematical averaging to estimate the distinct role of each item in a combined menu.[3]

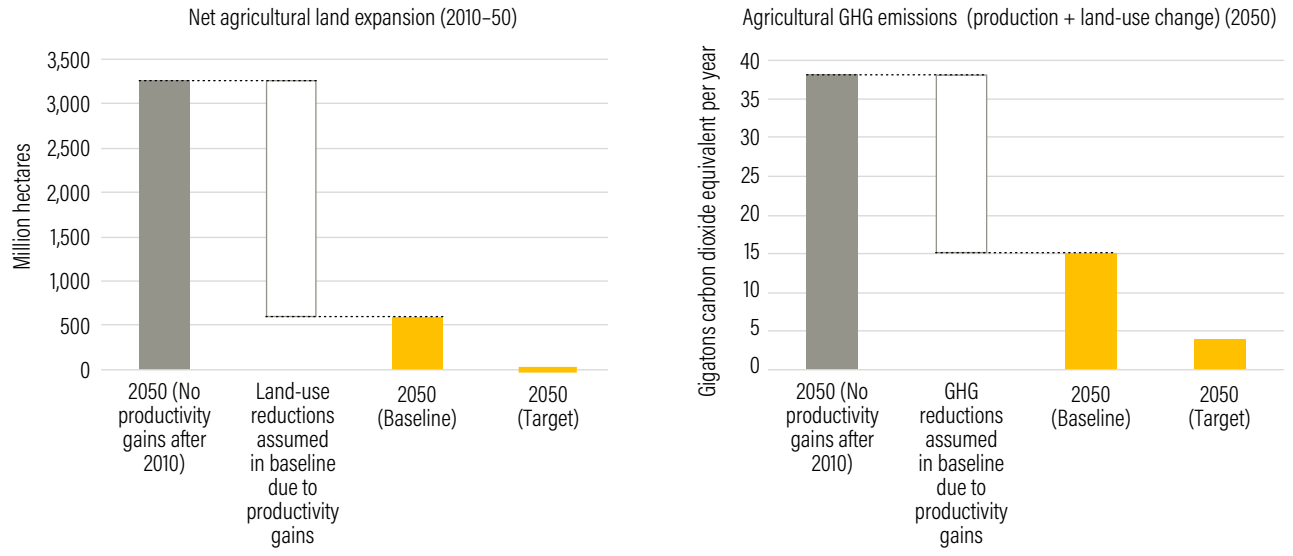
As discussed in Chapter 2, we define the food gap as the entire gap between crop calories produced in 2010 and those required to feed everyone in 2050 under the baseline scenario. This definition of the gap allows us to focus on demand-side measures that can reduce the size of the gap and thereby assist in closing the land and GHG mitigation gaps. Narrowing the food gap also provides greater assurance that the world will produce enough food to feed everyone nutritiously and at a price they can afford.

In the case of land use and GHG mitigation, the gaps represent the difference between our expected area of agricultural land and level of agriculture-related emissions in 2050 under a "business-as-usual" scenario (our 2050 baseline) and the targets for a sustainable food future; that is, net zero agricultural land expansion and agricultural emissions at or below 4 gigatons carbon dioxide equivalent (Gt CO_2e) per year. See Chapter 2 in "Scope of the Challenge and Menu of Possible Solutions" for a full explanation of the food, land, and GHG mitigation gaps.

Understanding Our Baseline Scenario

It is important to repeat that our business-as-usual baseline scenario already assumes significant progress in agricultural productivity, based on projections by the Food and Agriculture Organization of the United Nations (FAO) and our own effort to project gains in livestock and pasture productivity. Agricultural productivity gains built in to the 2050 baseline close more than 80 percent of the land gap and roughly two-thirds of the GHG mitigation gap that would occur if no productivity gains occurred after 2010 (Figure 33-1). All the combined scenarios therefore focus on *additional* productivity gains beyond our baseline, as well as other menu items that reduce demand for agricultural products or that further reduce GHG emissions.

Figure 33-1 | Improvements in crop and livestock productivity already built in to the 2050 baseline close most of the land and GHG mitigation gaps that would otherwise exist without any productivity gains after 2010



Source: GlobAgri-WRR model.

Table 33-1 summarizes the results of the three combined scenarios in terms of their contribution to closing the food, land, and GHG mitigation gaps and their effects on absolute changes in agricultural land area and GHG emissions by 2050. For reference, the table also summarizes the results of our baseline scenario (business-as-usual with built-in productivity gains) and the "no productivity gains after 2010" scenario, in which we assume no change in crop yields or pasture and livestock productivity beyond 2010 levels.

A caveat on the contribution of individual menu items

Within the combined scenarios, the contribution to closing gaps made by individual menu items does not illustrate the potential gains *relative to effort* (e.g., cost of menu item implementation) because the size of the contribution of each menu item inherently reflects the scale at which that menu item is defined. For example, we define our menu item "reduce food loss and waste" as a single global-scale percentage reduction in all sources of loss or waste of all plant- and animal-based foods. That definition results in enormous land savings globally but requires changes by millions of farms, food processors, and retailers, as well as by billions of consumers all over the world. The contribution would appear much smaller if we had instead defined 100 or 1,000 separate menu items for reducing food loss and waste differentiated by region, food type, and stage in the food supply chain. Such an analysis was not possible due to lack of reliable information about potential reductions at these more granular scales.

By contrast, our menu item "achieve replacement-level fertility rates" is defined at the regional level. We focus on the benefit of reducing fertility rates in sub-Saharan Africa alone, since all other regions are projected to have fertility rates at or below replacement level by 2050. The population of sub-Saharan Africa will account for less than one-quarter of the world's projected 2050 population, but we present

Table 33-1 | Global effects of combined 2050 scenarios on the three gaps

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[a]	Peatlands	Total	
No productivity gains after 2010	62	2,199	1,066	3,265	11.3	25.8	1.1	38.2	34.2
2050 Baseline	**56**	**401**	**192**	**593**	**9.0**	**4.9**	**1.1**	**15.1**	**11.1**
Coordinated Effort	43	128	4	132	7.4	1.1	0.6	9.1	5.1
Highly Ambitious	35	-390	-180	-570	5.5	0.0[b]	0.3	5.8	1.8
Breakthrough Technologies	29	-446	-355	-801	4.4	0.0[b]	0.3	4.6	0.6

Notes: Numbers may not sum correctly due to rounding.

a. Does not include peatland emissions.

b. Under the Highly Ambitious and Breakthrough Technologies combined scenarios, total agricultural area declines between 2010 and 2050. In order to keep estimates of associated emissions reductions conservative, here we do not credit any negative land-use change emissions as offsets against agricultural production emissions. We discuss the need to reforest "liberated" agricultural lands to offset agricultural production emissions in Chapter 20.

Source: GlobAgri-WRR model.

Figure 33-2a | The combined scenarios reduce the size of the food gap by reducing growth in demand (Coordinated Effort scenario)



Note: Includes all crops intended for direct human consumption, animal feed, industrial uses, seeds, and biofuels.
Source: GlobAgri-WRR model.

in these tables the contribution of changes in sub-Saharan Africa's fertility rates to reducing the three gaps at the global level. The effects therefore appear comparatively small. Similarly, improvements in aquaculture appear to make modest contributions to closing the global gaps, but this is because farmed fish are likely to occupy "only" 40 million hectares (Mha) of ponds and make up roughly 1 percent of all calories consumed in 2050. Because we do not believe that sufficient reliable information exists to make quantitative economic estimates of future menu item costs, there is no obvious data-backed way to evaluate savings relative to scope of effort.

Effects of the Combined Scenarios on the Food Gap

All of our three combined scenarios make a meaningful contribution to closing the food gap because each one has significant effects on demand for agricultural products (Figures 33-2a–c).

The demand-side menu items reduce the challenge of producing more food (as measured by crop calories) from the 56 percent increase needed between 2010 and 2050 in our baseline scenario to increases of 43 percent, 35 percent, and 29 percent,

Figure 33-2b | The combined scenarios reduce the size of the food gap by reducing growth in demand (Highly Ambitious scenario)



Note: Includes all crops intended for direct human consumption, animal feed, industrial uses, seeds, and biofuels.
Source: GlobAgri-WRR model.

respectively. Viewed another way, the Breakthrough Technologies scenario reduces the size of the food gap by nearly half.

The biggest potential reductions in the food gap result from reductions in food loss and waste. Reductions in ruminant meat consumption do not significantly reduce the food gap (technically, a crop calorie gap) in this analysis because ruminants consume relatively few crops; however, this menu item is of far greater importance in closing the land and GHG mitigation gaps.

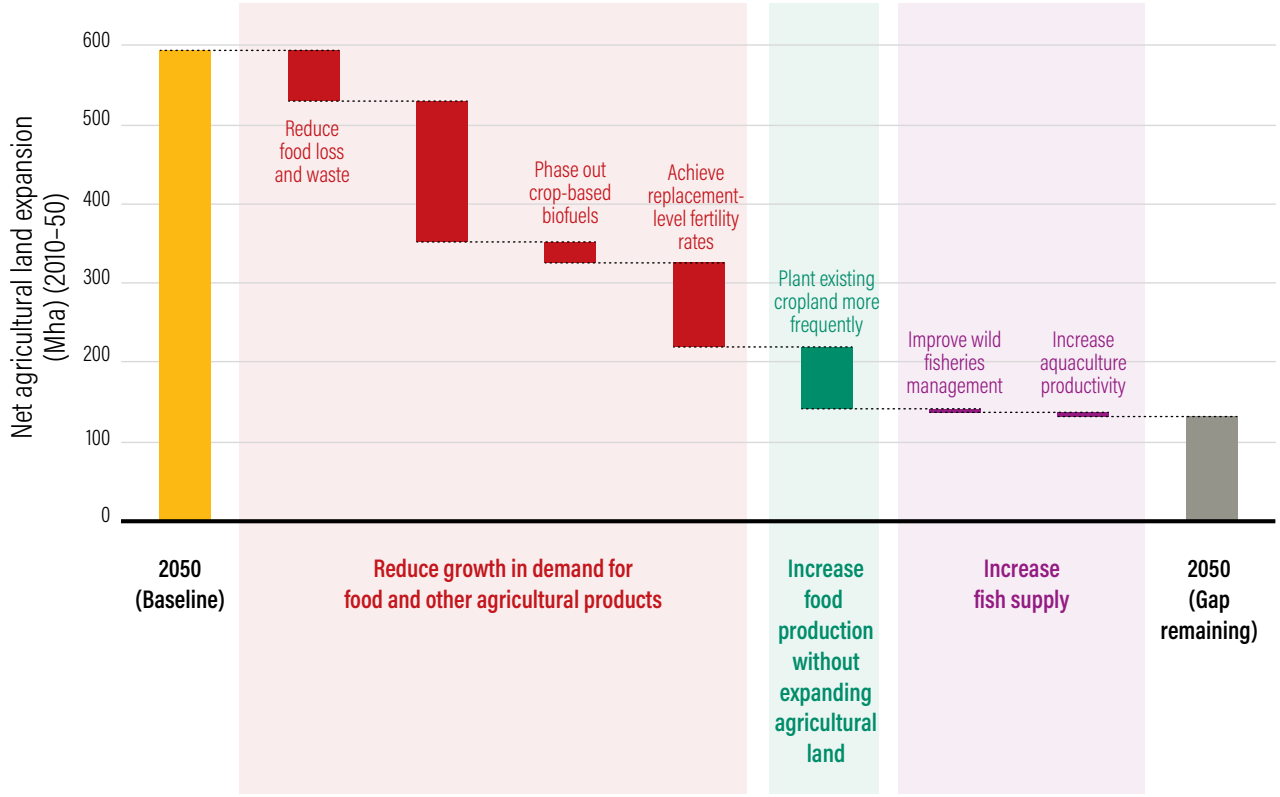
In the Coordinated Effort scenario, the phasing out of crop-based biofuels makes a significant contribution to closing the food gap. However, this estimate is contingent on the assumption in our baseline scenario that there will be no further growth in the share of crop-based biofuels in the transportation fuel mix, despite current public policy goals that seek to greatly expand this share. The assumption is likely optimistic. Changing public policies to phase out crop-based bioenergy production and avoid future expansion of land-based bioenergy production should be recognized as critical to closing the food gap.

Figure 33-2c | The combined scenarios reduce the size of the food gap by reducing growth in demand (Breakthrough Technologies scenario)



Note: Includes all crops intended for direct human consumption, animal feed, industrial uses, seeds, and biofuels.
Source: GlobAgri-WRR model.

Figure 33-3a | Two of the three combined scenarios could more than close the land gap and liberate land for reforestation (Coordinated Effort scenario)



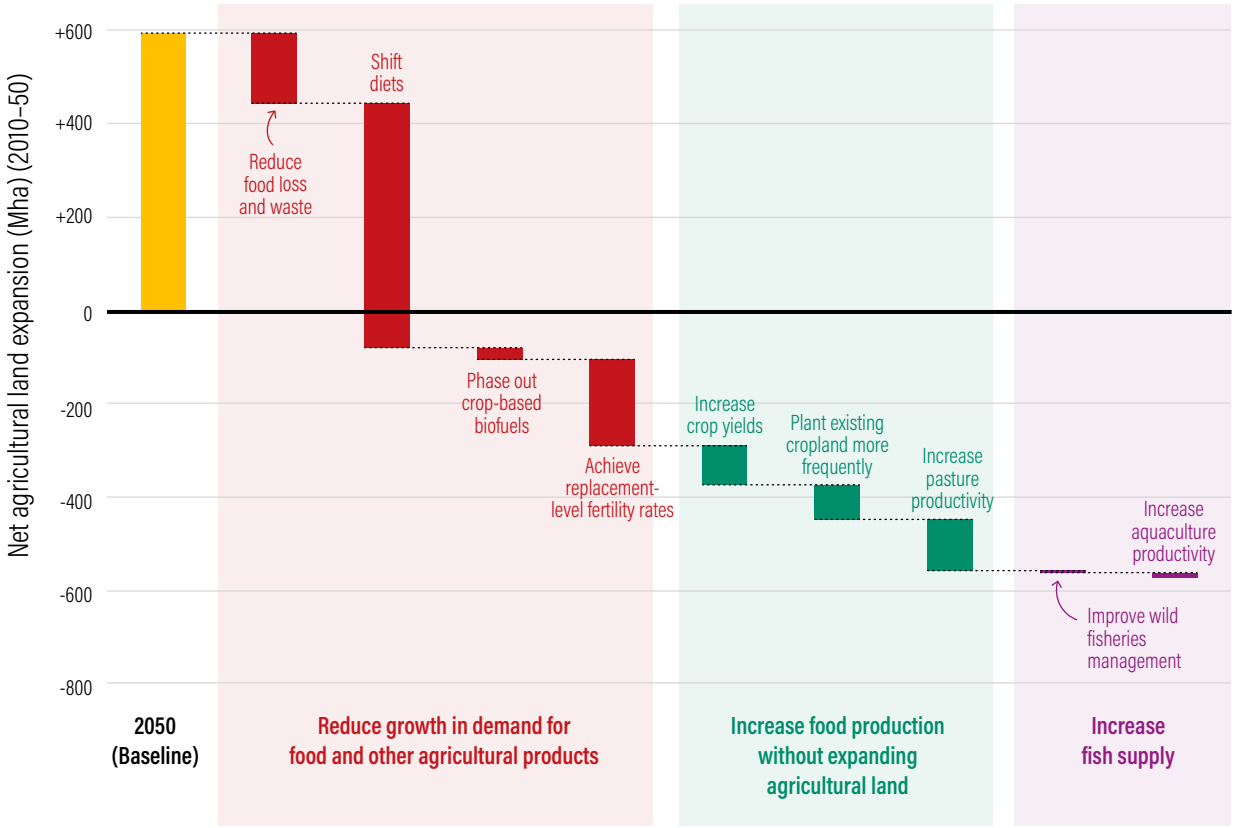
Source: GlobAgri-WRR model.

Effects of the Combined Scenarios on the Land Gap

All three scenarios have large consequences for closing the land gap (Figures 33-3a–c). In the Coordinated Effort scenario, cropland area remains relatively constant between 2010 and 2050, but pasture area still expands by 128 Mha. The Highly Ambitious and Breakthrough Technologies scenarios completely close the 593 Mha land gap and potentially make hundreds of millions of hectares available for other uses or for reforestation, which we discuss further below.

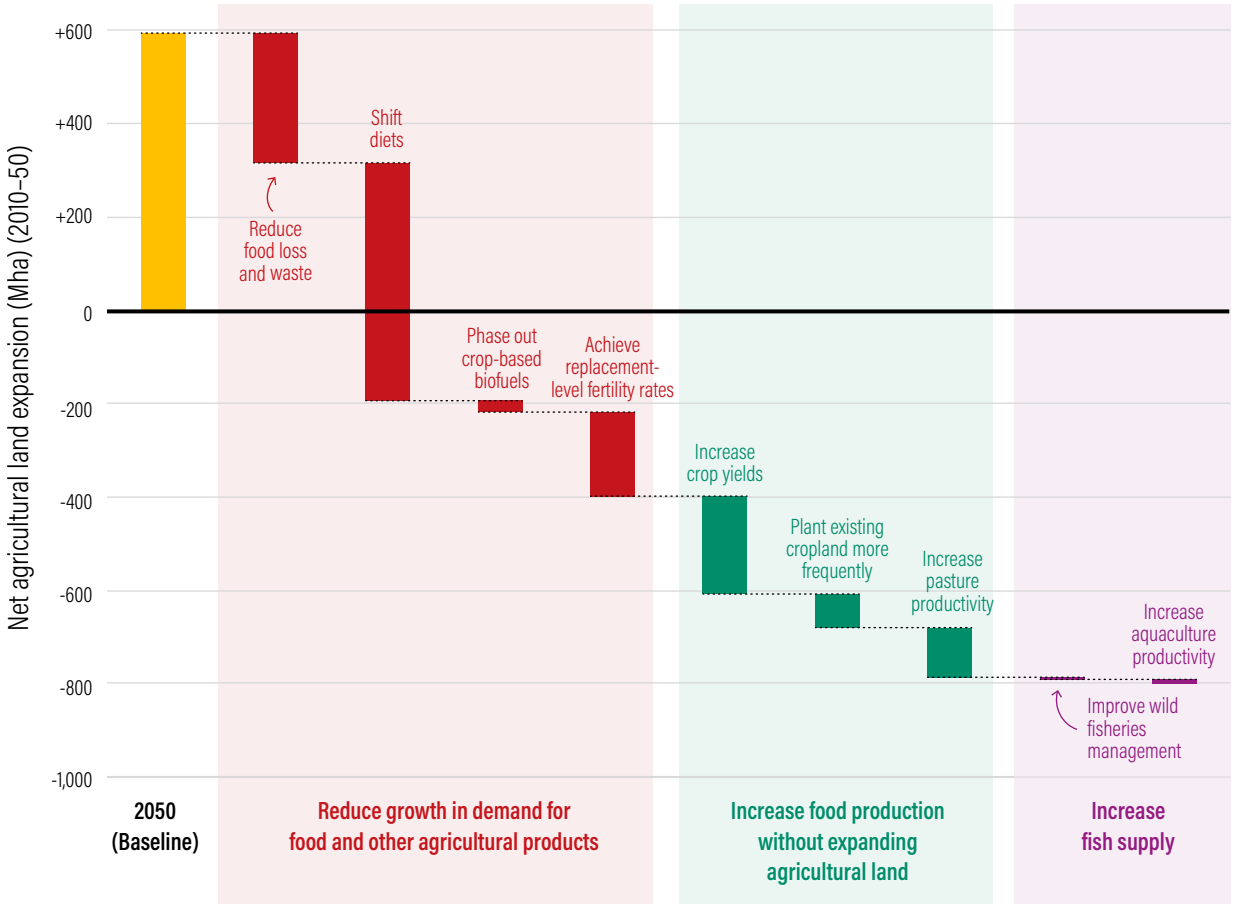
As discussed in Course 3 (Protect and Restore Natural Ecosystems and Limit Agricultural Land-Shifting), slower demand growth and increased productivity do not guarantee the full potential benefits of avoided agricultural land expansion for protecting biodiversity and storing carbon. These changes, by themselves, do not prevent shifts in locations of agricultural land between and within regions and countries. Yield growth can even trigger further agricultural land expansion as farming becomes more profitable in some regions. To achieve reductions in agricultural land area and the associated environmental benefits, additional policies are necessary to reduce shifts in locations of agricultural land, avoid conversion of the most valuable and carbon-rich lands, and actively restore lands that will be abandoned as a result of some inevitable shifts in location of agriculture.

Figure 33-3b | Two of the three combined scenarios could more than close the land gap and liberate land for reforestation (Highly Ambitious scenario)



Source: GlobAgri-WRR model.

Figure 33-3c | Two of the three combined scenarios could more than close the land gap and liberate land for reforestation (Breakthrough Technologies scenario)



Source: GlobAgri-WRR model.

Effects of the Combined Scenarios on the Greenhouse Gas Mitigation Gap

Under all three combined scenarios, the most difficult gap to close completely is the gap in GHG mitigation (Figures 33-4a–c), because it is difficult to reduce annual agricultural production emissions to the 4 Gt CO_2e target while providing enough food for everyone in 2050. Measures taken in the Coordinated Effort scenario would still leave total emissions from agriculture and land-use change at 9.1 Gt of CO_2e per year by 2050, more than 5 Gt above our 4 Gt target. The Highly Ambitious scenario reduces emissions to 5.8 Gt per year. Only the Breakthrough Technologies scenario, resulting in annual emissions of 4.6 Gt, gets close to the target. The implication is that it is easier to hypothesize scenarios that eliminate net land-use change than scenarios that eliminate production emissions. Reaching the 4 Gt goal would require major technological advances as well as full reforestation on at least 80 Mha of liberated agricultural land.

The Potential of Reforestation and Savanna Restoration to Further Reduce Greenhouse Gas Emissions

Two of our three combined scenarios result in a net reduction in agricultural land area between 2010 and 2050—a total of 570 Mha in the Highly Ambitious scenario and roughly 800 Mha in the Breakthrough Technologies scenario. These reductions could be used to sequester carbon by reforesting land and restoring savannas by midcentury. The resulting carbon sequestration could count as negative emissions.

Although GlobAgri-WRR can estimate the potential GHG emissions reductions from reforestation and savanna restoration, we are concerned about fully crediting these potential gains for two reasons.

First, we believe that some shifting in the location of agricultural land (between and within regions and countries) is inevitable, and that such shifts will result in net positive amounts of GHG emissions, so some active reforestation of net abandoned land will be necessary just to offset the emissions from this agricultural land-shifting. Second, some amount of the "liberated" agricultural land under these three scenarios will likely be needed to accommodate projected expansion of urban areas and forest plantations.

Because of these caveats, in Figure 33-4c (Breakthrough Technologies scenario), we show first the potential for ecosystem restoration to achieve our 4 Gt CO_2e target, which would require restoring at least 80 Mha to natural vegetation and would generate an annual average of 0.6 Gt of negative emissions for 40 years.[4]

A variety of analyses have also suggested that to meet the more ambitious 1.5 degree warming target enshrined in the Paris Agreement, the world will need to use the land sector to achieve negative emissions.[5] Typically, these scenarios do not require the elimination of nitrous oxide and methane emissions from agriculture, but they do require uses of land either for reforestation or some other mechanism for negative emissions—either to offset remaining emissions from other sectors (e.g., energy) or to reduce carbon dioxide levels after "overshooting" temperature targets. To reach a target of net-zero emissions in the land sector, restoration of natural vegetation on at least 585 Mha would be necessary, which would be 73 percent of the 801 Mha potentially liberated by our Breakthrough Technologies scenario.[6] Thus we also show the potential to achieve net-zero emissions in Figure 33-4c (Breakthrough Technologies scenario) through restoring at least 585 Mha.

Figure 33-4a | Only the Breakthrough Technologies scenario comes close to closing the greenhouse gas mitigation gap; reforestation and peatland restoration would be necessary to meet the target of 4 gigatons per year (Coordinated Effort scenario)

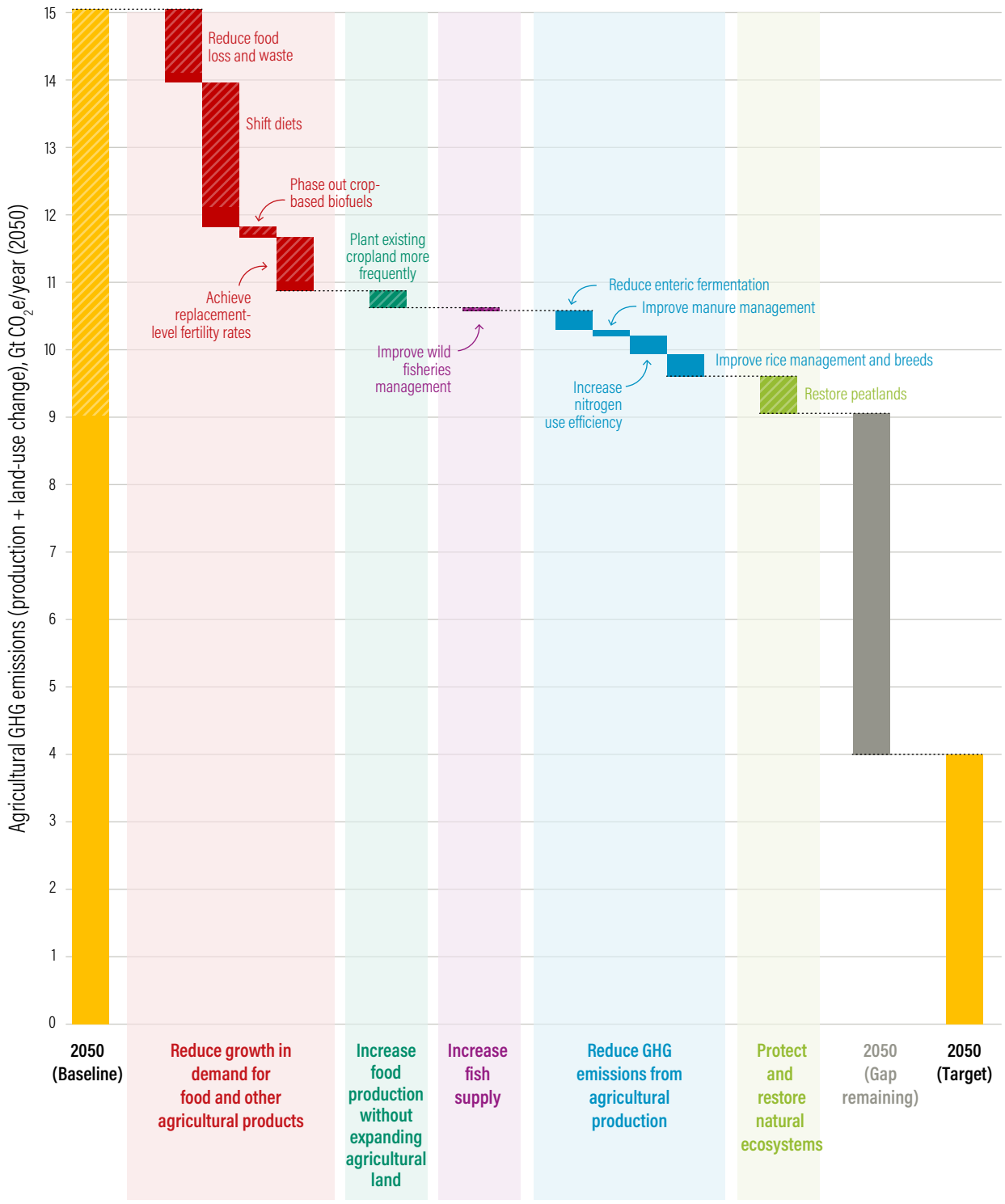


Figure 33-4b | Only the Breakthrough Technologies scenario comes close to closing the greenhouse gas mitigation gap; reforestation and peatland restoration would be necessary to meet the target of 4 gigatons per year (Highly Ambitious scenario)

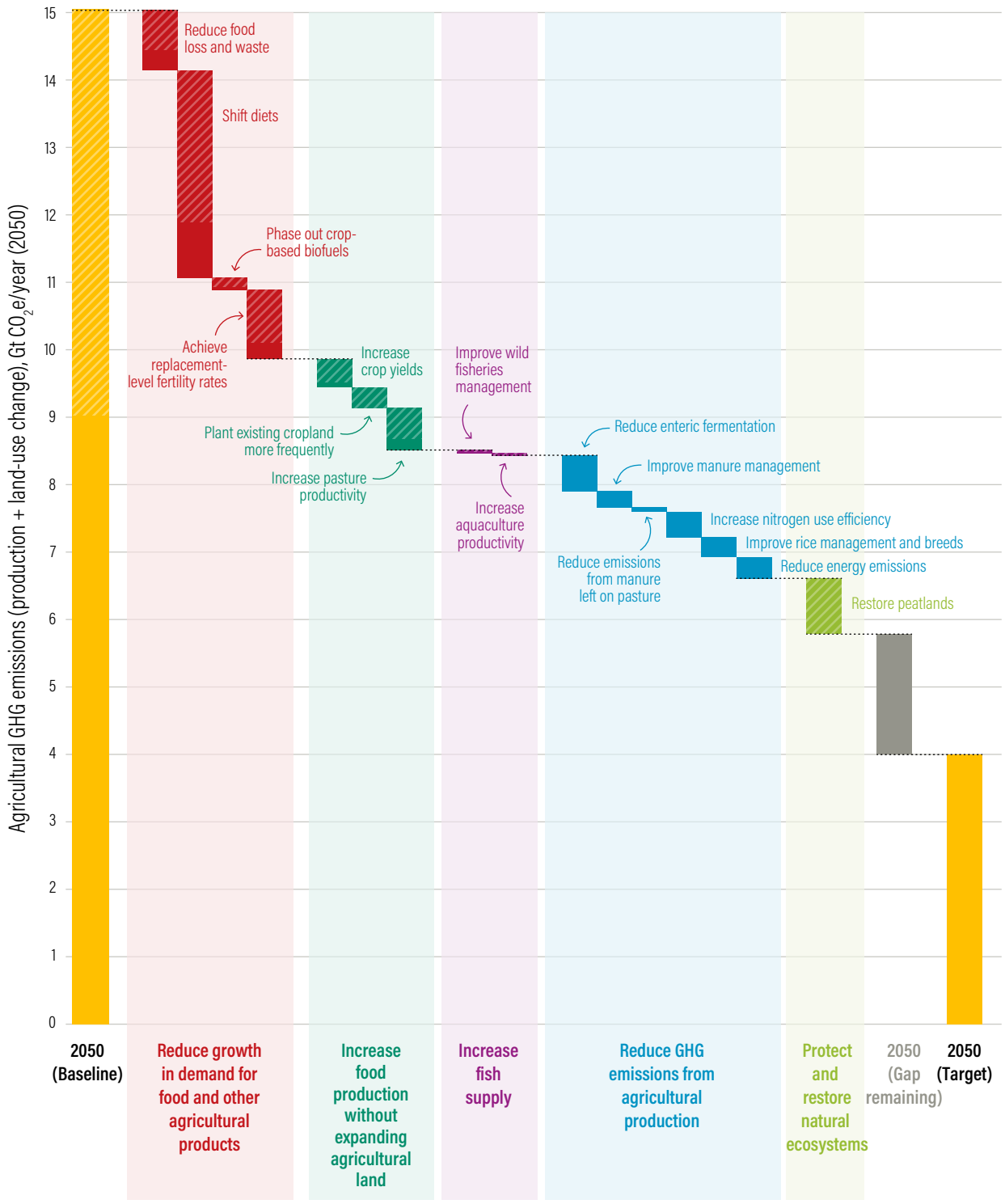
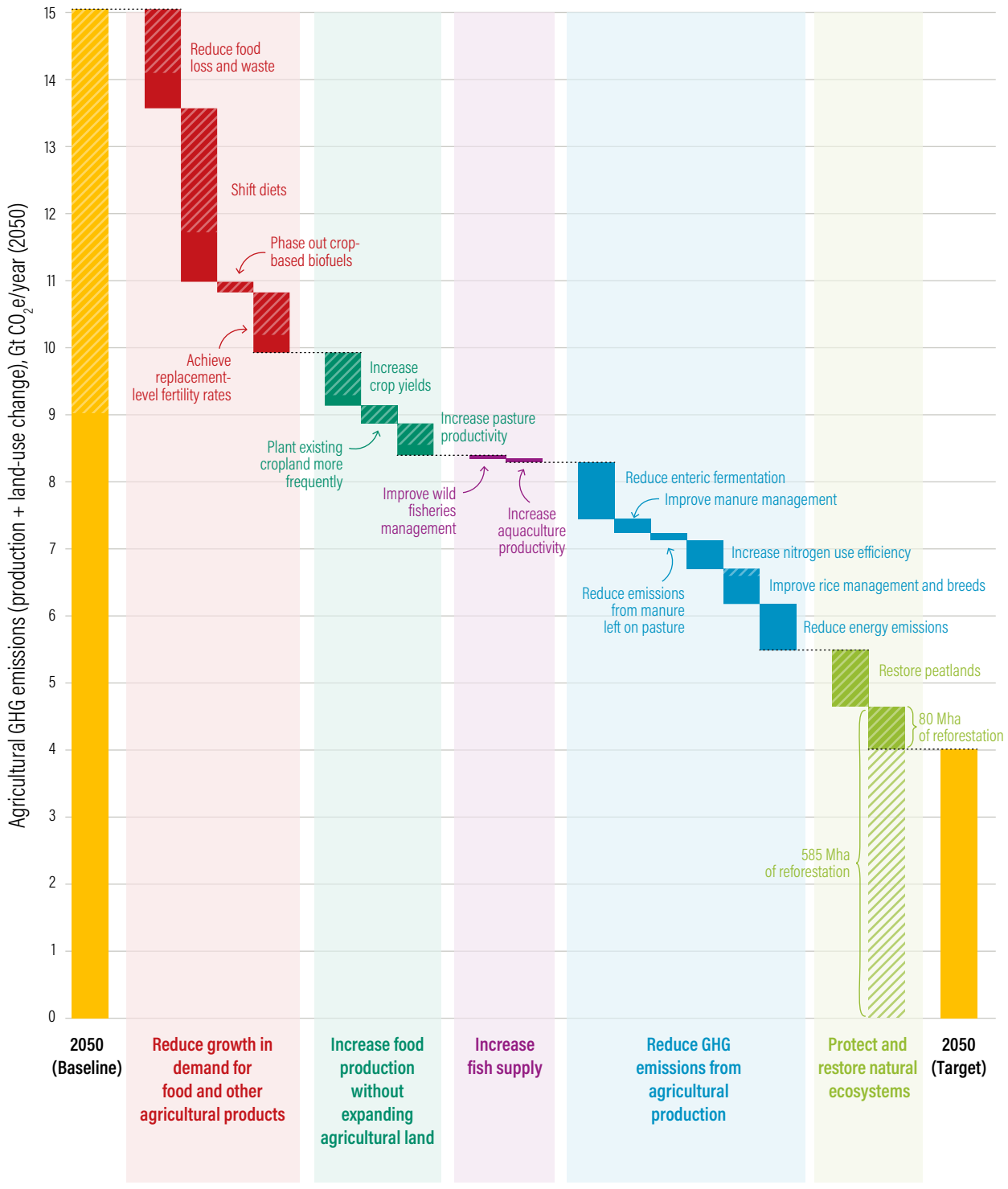


Figure 33-4c | Only the Breakthrough Technologies scenario comes close to closing the greenhouse gas mitigation gap; reforestation and peatland restoration would be necessary to meet the target of 4 gigatons per year (Breakthrough Technologies scenario)



Note: Solid areas represent agricultural production emissions. Hatched areas represent emissions from land-use change.
Source: GlobAgri-WRR model.


TRADING

CHAPTER 34

INSIGHTS FROM THE MENU COMBINATIONS

We believe that plausible paths exist toward closing the food, land, and GHG mitigation gaps and reaching our targets for world food production, agricultural land use, and emissions. This chapter presents several insights that flow from our analysis of the three scenarios. Realizing the potential of these scenarios will require strong political and social commitments.

Truly closing the GHG mitigation and land gaps would require taking all reasonable actions globally that we know of today, which will entail changes on billions of hectares of land, implemented by tens of millions of farmers. Fortunately, even though we do not know enough to generate true economic estimates, all of the actions contemplated can plausibly be expected to impose only modest costs or even lead to economic benefits, as discussed throughout Courses 1–5.

Achieving Even Our Coordinated Effort Scenario Requires Reversing a Wide Range of Current Trends

On the demand side, we rely on large reductions in ruminant meat consumption, relative to the 2050 baseline. However, as discussed in Chapter 6, many modelers project even larger global increases in consumption of animal-based foods than we do in our baseline. To take another example, our 2050 baseline assumes no increase in the share of biofuels in transportation—even though global policy is encouraging a fourfold increase. Current bioenergy strategies, if fully realized, could require harvesting levels of biomass equal to all the world's presently harvested crops, crop residues, wood, and forages consumed by livestock. And although we rely on large reductions in food loss and waste to close the three gaps, most food loss and waste reduction efforts are still in their infancy.

On the production side, the Coordinated Effort scenario requires faster rates of crop yield growth than historical rates (going back to the 1960s), but we have shown that recent yield trend lines (starting from the 1980s) are slower than those in our baseline, and far from the additional yield gains required. Ruminant meat and milk yield gains for the Coordinated Effort scenario require massive increases in output per hectare of grazing land—far greater than the output gains projected by extending a linear trend line from the 1960s.

Four Categories of Menu Items Are Particularly Important at the Global Level

All menu items are needed to have any hope of achieving the 4 Gt per year emissions target. In focusing on the relative role of different actions, however, we emphasize four particularly important types of menu items:

- **Boost agricultural productivity.** Without the productivity gains already built into our baseline, agricultural land would expand by more than 3 billion hectares and emissions would rise to 38 Gt CO_2e/year, including emissions from land-use change. Productivity gains already in our baseline are responsible for closing two-thirds of the GHG mitigation gap and more than 80 percent of the land gap that would exist if there were no productivity gains at all between 2010 and 2050. Additional productivity gains play a relatively smaller role than built-in productivity gains in reducing the gaps defined by our baseline. But, when we add in the additional productivity gains required to meet our 4 Gt target, the role of productivity gains grows to 72 percent.[7]

- **Shift diets away from ruminant meat.** Reducing ruminant meat consumption by 30 percent globally, relative to the 2050 baseline, reduces emissions by more than 5 Gt and reduces agricultural land demand by more than 500 Mha. Assuming the yield gains in our baseline, this change alone nearly eliminates net land-use change on a global basis. We believe this menu item is particularly promising because relatively few people eat large quantities of ruminant meat, there are highly attractive alternatives to ruminant meat, and people in the United States and Europe have already reduced per capita beef consumption by one-third from peak levels in the 1970s.

- **Reduce food loss and waste.** Globally reducing the rate of food loss and waste by 10, 25, or 50 percent would contribute significantly to closing all three gaps. However, we caution that while there are abundant options, there is little precedent for achieving such large-scale reductions. In particular, as countries' economies develop, waste near the consumption side of the food supply chain tends to grow even as food loss near the production side decreases. The overall share of food produced that is lost or wasted tends to stay at similar levels although the sources of the loss and waste shift downstream.

- **Restore peatlands and reforest liberated agricultural lands.** These menu items are essential to reach GHG mitigation targets. Because peatland emissions of more than 1 Gt CO_2e per year result from only 26 Mha, half of which has limited agricultural use, peatland restoration provides a highly promising mitigation opportunity. In addition, to achieve the 4 Gt target for 40 years, reforestation of at least 80 Mha of liberated agricultural land will be necessary, and additional reforestation will likely be necessary to compensate for emissions that result from shifting of locations of agricultural land between and within regions and countries.

Achieving Technological Innovations

Even our Coordinated Effort scenario requires measures such as further refinement of additives to reduce enteric methane emissions from livestock, new forms of manure management, and accelerated energy conservation steps. However, none of our scenarios require innovations for which scientists have not already shown a promising path.

Agricultural production emissions are the hardest to reduce, but technological innovations could make significant reductions possible. One reason why production emissions may appear harder to reduce than emissions from land-use change is that there is less of a track record of production emissions reductions. The measures in our more ambitious scenarios can actually reduce agricultural land area, and we have some confidence in these results because the world has a long track record of increasing crop and pasture yields. Past yield gains reflect vast and expensive commitments by farmers, governments, and agriculture-related industries. By contrast, conscious efforts to reduce production emissions—except as a by-product of yield gains—have been miniscule. There is no track record of mitigation of production emissions that we can build into our baseline or our mitigation scenarios. Yet the reality is that we do not know what the world could achieve. For example, even in our Breakthrough Techologies scenario, we assume no more than a 30 percent reduction in enteric methane emissions through use of feed additives, and only a 10 percent reduction in methane emissions achieved by new rice varieties. With strong research efforts, larger reductions might become possible.

ENDNOTES

1. Some analyses regarding agriculture, land use, and climate change attempt to rank greenhouse gas mitigation potential into categories of low, medium, and high based on US$ per ton of emissions reduction and then develop combined scenarios based on cost. Economic estimates of agricultural mitigation potential tend to be low, in part because they focus on a small set of mitigation targets and in part because the ability to provide cost estimates for mitigation is highly limited. The data on costs of agricultural production today are rough, the distribution of these costs across different farms in different regions is even rougher, the knowledge of mitigation costs is limited, and for most practices that are not common today or that depend on new technology, quantitative cost estimates can become quite speculative. Therefore, we do not use cost to distinguish our low, medium, and high scenarios.

2. In 2050, we estimate that 77 percent of beef cattle (including buffalo) will be raised in mixed or urban production systems. Unlike dairy cow herds, which require milking every day, many farm animals in mixed systems lack direct human management every day. We estimate that roughly one-third of these bovines will have daily human feeding and could therefore be given a daily feed supplement. For milk production, we estimate that 86 percent of production will be in mixed or urban systems, and we perhaps conservatively estimate that 50 percent of all dairy cattle will be fed such an additive.

3. Simply summing each individual menu item in combined scenarios does not correctly estimate the effect of implementing all menu items together because the interactions among menu items reduce the effect of each menu item modeled separately. To scale the effect of each menu item, we used the following four-step process: (1) add up individual menu items' contributions as analyzed in Courses 1–5 to generate a "sum of the individual modeled results"; (2) use GlobAgri-WRR to estimate the reductions for each scenario; (3) estimate a ratio by dividing the result in step 2 by the result in step 3, which always produces a fraction less than 1; and (4) multiply the result in step 1 by the ratio in step 3. In effect, we downscale each individual menu item so that the sum of menu items equals the combined effect of implementing multiple menu items at the same time.

   Because the GlobAgri-WRR model does not model emissions from existing peatland loss, we treated peatland emissions separately. GlobAgri-WRR, however, does account for new peatland conversions, so the effect of menu items in reducing new peatland conversions is counted as the effect of those menu items. For example, if reductions in waste lead to less growth in palm oil production, GlobAgri-WRR will project fewer emissions from additional peatland conversions to produce palm oil.

4. The GlobAgri-WRR model estimates that fully restoring 801 Mha would sequester 6.3 Gt CO_2e per year over 40 years. Therefore, to offset at least 0.6 Gt CO_2e per year and achieve the 4 Gt target would require restoring at least roughly 10 percent of that land, or 80 Mha. This calculation assumes that these carbon levels (approximating that of natural vegetation) could be achieved in 40 years. Many forests will continue growing and sequestering carbon over 40 years, but our estimates of carbon stocks for areas in natural vegetation do not assume restoration to pristine carbon stocks. Instead they are based on estimates of natural vegetation in turn based on measured carbon stocks of types of vegetation for these types and locations of ecosystems, and the great majority of the world's forests are already highly disturbed (Erb et al. 2017).

5. Rogelj et al. (2018), 60, Figure 2.26.

6. The GlobAgri-WRR model estimates that fully restoring 801 Mha would sequester 6.3 Gt CO_2e per year over 40 years. Therefore, to offset at least 4.6 Gt CO_2e per year and achieve a target of 0 Gt would require restoring at least roughly 73 percent of that land, or 585 Mha. See note 4 above for additional details on assumptions of carbon stocks in natural vegetation.

7. GlobAgri-WRR model.

REFERENCES

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

PHOTO CREDITS

Pg. 402 Anguskirk, pg. 404 shankar s./Flickr, pg. 414 Elina Sazonova/Pexels, pg. 428 istockphoto.



Cross-Cutting Policies for a Sustainable Food Future

The menu items for a sustainable food future described earlier in this report focus heavily on technical opportunities and solutions to help drive implementation. But menu items cannot be implemented in isolation, and they are all subject to (or need) a variety of cross-cutting public and private policies. Chapters 35–37 discuss policies relating to farm structure, productivity, and poverty reduction; agricultural emissions mitigation and climate funding; and agricultural research and development.

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CHAPTER 35

FARM STRUCTURES, LARGE LAND ACQUISITIONS, PROPERTY RIGHTS, AND CONTRACTUAL ARRANGEMENTS

Is there a conflict between the goals of increasing global food production and providing livelihood opportunities for the world's hundreds of millions of poor farmers and workers? Do large land acquisitions help or hinder these goals? Can the world sufficiently boost yields on smallholder farms or should large farms replace small farms? And if the world continues to support small farmers, what farm structures and property rights rules should policymakers support?

One of the challenges to answering these questions is the lack of a sound, quantitative definition for "small farms." Farm sizes and productivity per hectare (ha) vary greatly from one part of the world to another. Building on a 2008 landmark World Bank report,[1] this chapter addresses these often-contentious questions.

Large versus Small Farms

Public justification for consolidation of smallholder farmland is rooted in a perception among many analysts that large farms are more successful than small farms.[2] For example, although small farmers remain more numerous in Brazil, medium-sized and large farms dominate agricultural production, and their numbers and share of production and production value in the country have increased in recent years.[3] Brazil's large farms can be regarded as a model to replicate elsewhere. Small farms face many obstacles to improving their productivity:[4]

- Financial institutions face higher transaction costs when dealing with many small farms rather than one large farm, making access to capital more expensive for small farmers.
- Poverty traps arise when subsistence farmers must sell critical assets to survive periods of hardship, which undermines their future production or productivity gains.
- Smallholders face challenges in meeting quality, sanitary, and/or environmental standards or other demands made by large purchasers such as supermarket chains.

In 1998, the economist Paul Collier attracted great attention when he argued that small farmers in Africa were unsuited to cope with "investment, marketing chains, and regulation [of food quality]," and called for the gradual replacement of "peasant farms" with larger commercial farms.[5] In addition to pointing to the agricultural achievements of countries like Brazil, Collier pointed out that subsistence peasant farming is arduous and that farmers readily abandon subsistence farms when alternative job opportunities present themselves. To African governments faced with a history of poor agricultural production and limited resources, contracting with large-scale investors who will come in and upgrade agriculture therefore seems attractive.

In some countries, analysis supports the pure production advantages of larger farms. Yields of Brazilian maize and Chilean wheat, for example, have been significantly higher on large farms.[6] In Indonesia and Malaysia, large oil palm plantations have far higher yields than oil palms grown on most smallholder farms.[7]

However, Collier's argument touched off several counterarguments by agricultural economists:

- In China and India, comparatively small farmers have led agricultural improvements. According to data from the Food and Agriculture Organization of the United Nations (FAO), in India, farms smaller than 5 ha account for 70 percent of all farm area, and farms smaller than 10 ha account for 87 percent.[8] One 2011 study estimated the average farm size in China at 0.6 ha, and in India at 1.2 ha.[9] Yet, in both countries, small farms achieve yields at least as high as those of large farms.[10] In both countries, fertilizer use is high.[11] Based on Indian agricultural census data, the 2011 study found that small farmers actually used twice as much fertilizer as large farms per hectare, as well as more irrigation and high-yielding seeds. These findings reflect an intense effort on the part of small farmers to produce high yields, although there are environmental implications. Strong efforts by governments to support small farmers through credit programs, extension, and input subsidies played a major role in these developments.[12]
- In Africa, several studies have found that farms become less productive per hectare as they get bigger.[13] The typical explanation is that small farmers put in greater effort per unit of land. Because of the consistency of this finding, the main academic debate around this phenomenon has focused on whether it is explained by poor data, by failure to include very large farms in the analysis, or by some uncontrolled factor, such as soil quality. But a recent review of studies on this issue confirms that larger farm size generally does lead to lower yields per hectare.[14]
- Improvements on small farms contribute more to poverty reduction than improvements on larger farms—at least absent concerted government efforts to transfer income from overall

economic improvement. As one analysis notes, "Smallholdings are typically operated by poor people who use a great deal of labor, both from their own households and from their equally poor or poorer neighbors. Moreover, when small-farm households spend their incomes, they tend to spend them on locally produced goods and services, thereby stimulating the rural nonfarm economy and creating additional jobs."[15]

Yet the evidence in support of smaller farms in Africa has tended to exclude the largest farms. Studies showing higher productivity on small farms have typically focused on farms up to 10 ha.[16] There is some evidence of a "U-shaped curve" with productivities rising again on the largest farms.[17]

In addition, even if small farms are often more productive per hectare, studies around the world tend to find that larger farms are often more productive per day of work.[18] As a result, larger farms tend to have equal or lower costs of production per ton of crop.[19]

Good data are necessary to determine public policy but analyzing data on agricultural productivity is complicated. Some of the data on which researchers must rely are more than a decade old because national studies are expensive. The World Bank and FAO, both important sources of data, tend to analyze farm sizes and their characteristics on a rotating basis among different countries over many years. Although studies tend to group farms by area, area is a highly imperfect way of determining large and small farms. The size of farms as measured in hectares may not properly convey size from the standpoint of output or true scale of operation because agricultural lands have widely varying productivity. For example, "small farms" in grazing areas will often be larger than "medium-sized farms" in quality croplands.

Using the most recent available data—even though some national data may be more than a decade old—the best estimate placed the total number of farms around the world at 570 million.[20] Of these, farms smaller than 2 ha account for 80 percent of the total number, while they occupy only 12 percent of global agricultural land.[21] In surveys of 14 African countries in 2000, 85 percent of farms were smaller than 2 ha.[22]

Choosing any single size threshold to measure small and medium-sized farms is an imperfect approach, but the data suggest a few general developments:



- In most developed countries, farms are becoming larger.[23] This trend reflects the increasing role of mechanization, reduced labor requirements, and increasing opportunities for workers off-farm.
- In Africa and Asia, average farm sizes (measured by both mean and median) tend to become smaller over time because the number of farm households is increasing, meaning that small farms are divided into smaller and smaller units.[24]
- Although small farms are increasing in number, their average size is shrinking, and they do not appear to be increasing their share of farm area. In some countries small farms appear to be losing land to medium-sized or large farms. For example, one paper analyzing farms in Ghana between 1992 and 2012 found that even though the number of farms smaller than 5 ha grew by 37 percent, the percentage of farmland they occupied declined by 12 percent.[25] Meanwhile farms from 20 to 100 ha grew to occupy an additional 11 percent of the country's farmland. In Zambia, just between 2008 and 2014, the number of farms smaller than 5 ha grew significantly, but the percentage of farmland they occupied declined by 15 percent. By contrast, farms with 10 to 100 ha occupied an additional 10 percent of the country's land. A 2016 study in China also found that, while small farms continue to dominate, there is a growing class of medium-sized and larger farms.[26]

The growing share of agricultural land held by medium-sized and larger farms may reflect a number of increasing economic opportunities that are not available to small farms.[27] As new technology requires more expensive seeds, fertilizers, machinery, and pesticides, challenges in raising capital become more important. Some small farms cannot take advantage of large machinery, even if it is affordable.[28] As supermarkets become a larger part of the retail process and wish to deal with larger suppliers, and as quality and sanitary standards rise for high-value crops, small farms face more obstacles in accessing these markets.[29]

Beyond national food production goals, there is also a question of which strategies are best for helping small farmers, particularly because small farms are often too small to support their owners with adequate income. One recent study found that even if African and Asian small farms took advantage of opportunities for technological innovation, they could not escape poverty, although they could somewhat boost incomes and food security.[30] Another study found that in Kenya it was very difficult for mixed crop/livestock farms smaller than 0.4 ha to satisfy farmers' income and food needs.[31] The implication is that to escape poverty, small farms will generally need better market access and opportunities for off-farm incomes. One study across seven countries in Africa found that those two factors were strongly correlated with the food security of small farmers.[32]

Overall, the evidence suggests that small farms can be productive if governments support their development, and that strongly pushing their purchase by or consolidation into large farms has not been an effective strategy. At the same time, powerful forces do encourage eventual economies of scale in agriculture, particularly at higher levels of development. In addition, small farms in many countries are on a trajectory to becoming too small to provide more than supplemental income for their owners. Even strong advocates of smallholder farming therefore view appropriate public investments in small farms as part of a strategy to help people to transition out of small farming. "This is a paradox of early development: the need for agricultural development to allow people to move out of agriculture."[33]

Recommended Policies Regarding Farm Sizes

The literature overall has a number of policy implications, the essence of which is to let the market play out—neither favoring large or small farms, nor blocking farms from reaching their appropriate size:

- In general, governments should not force small farms to consolidate or encourage large farms to take over small farms, as neither approach is likely to accelerate agricultural production or benefit the poor. Not only is the evidence of higher yields from even very large farms limited, there is even less evidence that pushing or forcing consolidation raises productivity. Oil palm plantations may be an exception, where large farms outperform small farms, but, at this time, clearing land for oil palm plantations contributes to large-scale deforestation and often has adverse consequences for indigenous people. The place of palm oil production in a sustainable food future will involve more protection of the rights of indigenous populations and targeting new production in the least environmentally harmful areas (as discussed in the next section).
- Even so, agricultural policy should support farms as they become more commercially oriented and increase their labor productivity. The aim of policy should be both to support productivity gains and allow farms to become more viable and not fight these developments as they occur. Policy should support these trends even though they might eventually result in less demand for agricultural labor. However, a fair and stable economic and social transition will depend on growth in other parts of the economy, particularly in the urban sector.
- Allowing farms to acquire smaller farms or to rent land—so long as transactions take place through market forces and are not pushed by governments—is a useful part of the economic growth process. As summarized by the World Bank study, the evidence generally supports the view that such transactions support rural incomes and often make it easier for small farmers to acquire land.[34] By contrast, restrictions on land sales "tend to drive transactions underground and undermine access to formal credit without addressing the underlying asymmetries of power, information, and access to insurance."[35] This World Bank study appropriately recommends safety nets and even land taxes to achieve equity goals rather than restrictions on sales.



Large Land Acquisitions ("Land Grabbing")

In Madagascar in 2008, the government entered into a deal with the Daewoo Corporation to lease more than 1 million hectares (Mha) of land for 99 years at a minimal price. Although the deal was sufficiently unpopular that it led to the collapse of the government and eventual cancellation of the deal,[36] deals such as this one attracted world attention and led researchers to study what was going on. "Land grabbing" is complex, with important regional differences, and some concerns turned out to be unfounded. However, a picture does emerge that many governments have not been following neutral policies regarding farm size. Instead, they have been favoring large acquisitions that often do not compensate local people for what they are losing and do not lead to significant productivity gains. This process has also tended to involve clearing of at least quasi-natural habitats.

Comprehensive analysis of recent, large-scale land acquisitions is difficult. Governments do not disclose the details of most deals, and many countries lack clear land registries that could reveal what is going on.[37] Despite these limitations, researchers have begun to tabulate large-scale land acquisitions and several themes have emerged from recent studies.

Concluded acquisitions are large but smaller than the original proposals

A World Bank study in 2011 found evidence of large-scale farmland deals, in various stages of development, amounting to 56.6 Mha—roughly the size of Kenya—just between October 1, 2008, and August 31, 2009.

More than two-thirds of these deals were located in Africa.[38] A 2013 study based primarily on analysis by GRAIN, a nonprofit organization, reported between 33 Mha and 82 Mha of large-scale land acquisitions between 2002 and 2013 conducted by foreign entities only. The wide range in the estimates of area of acquisitions reflects the level of deal completion, and roughly one-third of the verified deals were in Africa.[39]

Table 35-1 | Concluded and intended transnational agricultural deals, 2000–2016

REGION	FOOD CROPS (MHA)	NONFOOD CROPS (MHA)	MULTIPLE USE CROPS (MHA)[a]	TOTAL (MHA)	TOTAL (PERCENT OF WORLD)
Africa	1.5 / 4.0	7.7 / 0.9	8.2 / 5.7	17.3 / 10.6	47 / 70
Asia	0.2 / 1.8	1.8 / 0.6	3.5 / 1.9	5.5 / 4.3	15 / 28
Latin America & Caribbean	1.1 / 0.0	1.2 / 0.0	3.0 / 0.2	5.3 / 0.2	15 / 1
Europe (Eastern & Northern)	0.4 / 0.0	1.0 / 0.0	4.6 / 0.1	6.0 / 0.1	17 / 0
Oceania	0.1 / 0.0	0.2 / 0.0	2.1 / 0.0	2.3 / 0.0	6 / 0
Subtotal (all regions with information)	**3.3 / 5.8**	**11.8 / 1.6**	**21.5 / 7.8**	**36.5 / 15.2**	**100 / 100**
No information				7.4 / 3.1	
Total (all transnational agriculture deals)				**44.0 / 18.3**	

Notes: Concluded deals are shown in red, intended deals in black. Numbers may not sum correctly due to rounding.
a. "Multiple use crops" includes crops designated as "flex-crops" or "multiple use" in the Land Matrix database.
Source: Land Matrix n.d. Data shown as of 2016.

More recent updates show that many of these large proposed or announced deals have been scuttled and new dealmaking has slowed since 2012, but the total area of completed deals remains large. GRAIN's 2016 update of international land deals identifies 491 large agricultural land deals completed since 2006, extending over 30 Mha in 78 countries.[40] Similar results can be drawn from Land Matrix data, an ongoing collaborative project of two major research institutions and two international aid agencies.[41] By mid-2016, Land Matrix estimated that international investors completed deals to acquire or lease for the long-term 44 Mha of land between 2000 and 2016. As of 2016, these investors were at some stage of agreement to acquire another 18 Mha (Table 35-1).[42]

Land Matrix and other researchers have had to rely heavily on reports from others, and the area estimates are a combination of intended size, contract size, and final operations size. Some more detailed analysis suggests that these data may overstate what has actually occurred to date, at least in Africa.[43] For example, one research team put together a list of deals reported by Land Matrix and others and then conducted field research to try to verify those deals and assess their experience.[44] Of 6 Mha of potential Chinese deals reported by others from 1987 to 2014, the team ultimately found only 240,000 ha that were actually acquired.[45] Discrepancies emerged regarding financial sizes of transactions, too. A Chinese deal for rice fields in Nigeria reported as involving 2 billion U.S. dollars turned out to involve 2 billion Nigerian naira, equivalent to only about $17 million.

Although it is possible that the total area of land acquisitions has been overestimated, the reality remains that very large land acquisitions have been occurring, generally in the form of long-term leases. One more detailed study found that 2.4 Mha of land had been allocated to foreign acquisitions through some kind of legal agreement between 2004 and 2014 in Ethiopia, Ghana, and Tanzania alone, of which 1.4 Mha had resulted in actual leases.[46] Although some land had not been leased, the authors found that for those transactions they could track, the leases mostly reflected the original memoranda of agreement, and that additional leases might continue to occur where lands subject to the agreement had not yet been leased. In 2012, a government-commissioned report of the Lao People's Democratic Republic (Lao PDR) estimates that roughly 2,642 land deals totaling 1.1 Mha had been granted as foreign land-based investments, comprising roughly 5 percent of the national territory.[47]

The main reason many proposed deals fall through appears to be the difficulty of actually implementing them. Many of the original announcements were for much larger deals, and while public opposition has scuttled some—such as the large Daewoo proposal in Madagascar—many others collapse not because of governmental concerns but because they did not prove cost-effective, or because the investor ultimately lacked the capital required.[48] Because countries continue to try to enter into large land acquisitions, even if many are unsuccessful, the relative merits of these schemes remain an important area of policy inquiry.

Large-scale land acquisitions are made by a wide range of international purchasers and locally connected wealthy buyers

Although much press attention has focused on acquisitions by quasi-state entities, including sovereign wealth funds, private companies and investors also appear to be major players.[49] The latter include both domestic and international actors, though their roles vary by country. For example, a 2014 study found that companies from the United States and Europe have played the lead role in Ghana and Tanzania, while companies from India have played the lead role in Ethiopia.[50] In-country investors are playing a major role, too.[51] For example, national individuals and companies are acquiring land or associating themselves with major international land deals in Africa.[52] The Land Matrix database has inventoried about 602 large-scale domestic transactions covering 17.3 Mha[53]—but such domestic deals are greatly undercounted because information on domestic contracts is difficult to track. These land acquisitions spanned low- and middle-income countries (for which data were compiled) on all continents. While it is difficult to determine the exact location of completed deals, about half of them were likely in Africa.

National and local governments are playing a facilitating role, and international institutions may be playing an indirect supportive role

Even when investors are private, "the active role of governments in consumer and host countries . . . has also been instrumental in facilitating large-scale land acquisitions by providing financial, technical, and administrative support to investors; providing regulatory frameworks conducive to investment; and, in the case of host-country governments, assisting in land acquisition."[54] In Indonesia, oil palm development has occurred on lands originally zoned as part of the national forest estate, which are in effect reclassified by the national government on application, and all plantations require a series of permits from the regional land-use authorities.[55]

In Africa, land is typically state-owned, even if ownership includes some recognition of "customary rights," and large-scale acquisitions nearly always involve a government player. Many governments have adopted policies to encourage these acquisitions. Under Tanzania's Kilimo Kwanza (Agriculture First) policy, the government aims to increase land available for large-scale land acquisitions to 20 percent of present village lands.[56] Ethiopia's Growth and Transformation plan also calls for devoting millions of hectares to large-scale commercial agriculture, and the national government has played an active role in directly contracting with foreign investors in the Gambella region.[57]

By contrast with this supportive role, in a separate report, WRI reviewed government processes for recognizing rights to community lands in 15 countries and found them to be lengthy, filled with obstacles, and leading almost always to only a partial grant of rights at best.[58] For example, "In Chile, indigenous communities are not eligible for the procedure unless they possess a specified historic document. And in Uganda, communities must incorporate themselves into an association, elect officers, and write a constitution." The study found that procedures were unclear and that any disputes about lands or boundaries could easily halt the process. In all but one example, governments imposed "arbitrary caps" on the areas transferred, and, governments "retain the right to allocate overlapping concessions to high-value natural resources such as timber, and communities only had rights to exercise full free, prior, and informed consent to these transactions in 2 out of the 19 surveyed procedures." Although the study recognized that estimates are rough, it estimated that half of all land globally is community land but that only 10 percent is recognized as belonging to communities and 8 percent is designated for community use.

International institutions have played little role in directly supporting these large land acquisitions, but they may be doing so indirectly and sometimes unintentionally. For example, international institutions have been supporting specific agricultural improvement corridors in Tanzania and Mozambique. Even if their goals are to support small-scale farmers, large-scale acquisitions have also been occurring along these corridors.[59]

Although acquisitions are occurring on many continents, they mainly affect rural populations in Africa and Southeast Asia

Large-scale land acquisitions are occurring across the world. For example, of proposed international agricultural deals as of mid-2016, Land Matrix shows almost 50 percent in Africa, 17 percent in Eastern and Northern Europe, 15 percent in Asia, 15 percent in Latin America and the Caribbean, and 6 percent in Oceania (Table 35-1).[60] Yet these acquisitions appear to have quite different characteristics. For example, many of the well-publicized purchases in Australia have been of large preexisting ranches.[61] In the former Soviet Union, acquisitions have occurred at a large scale but appear primarily to have been takeovers of large areas of farmland abandoned after the collapse of the Soviet Union in areas with low populations. By contrast, acquisitions of land in Indonesia and Cambodia to produce palm oil or rubber, and acquisitions in Africa for agricultural uses, often occur in areas with substantial customary use by rural populations.[62]

Acquisitions have responded to effects of increased food demand, increased biofuel demand, farm price changes, and expectations for exports

Large-scale acquisitions accelerated after 2005 when crop prices started to rise; in 2008 and 2011, prices reached levels four times higher than they had been in 2005. As crop prices stopped rising, acquisition activity appears to have slowed as well.[63] Even though land acquisitions have occurred on extremely favorable terms—and sometimes with



no purchase price at all—these projects still require substantial investment and risk. Expectations of future high crop prices therefore play a major role. Although investments are sometimes blamed on "speculation," this term adds little to understanding the land-acquisition phenomenon. All land acquisitions are speculative in that they bet on future economic returns.

Although some entities have defended land leases as ways of boosting local food supplies, the evidence overall suggests that acquisitions which have gone through are focused on exports of nonfood crops, such as rubber or cotton, or of cash food crops, such as palm oil.[64] Even those few projects focused on staple food crops appear to be focused on exports.[65]

Much of the land rush in 2006–10, especially in Africa, focused on the production of sugarcane or jatropha intended to supply the European biofuels market.[66] Technical problems with growing jatropha reduced the prospects of those projects, and substantial political doubt about the future of European biofuel policies also appears to have reduced acquisition interest. However, as Table 35-1 indicates, at least 44 percent of foreign African acquisitions tracked by Land Matrix involved nonfood crops as of 2016, and the vast majority of the rest could serve multiple purposes.

In much of the world, acquisitions involve natural and seminatural landscapes that are valuable for biodiversity and ecosystem services

The primary focus of research into "land grabs" has been the social effects on rural populations, but effects on natural habitats are also significant. Most large land acquisitions do not appear to be occurring on farmland that is being intensively cropped by small-scale farmers. Although information on this point is mostly piecemeal, it appears that, in countries dominated by small-scale farming, land acquisitions target more natural habitats—including forests, savannas, and wetlands—and long-term fallow land. These are the types of land that are mostly managed on a community basis. The large acquisitions of existing farmland occur primarily in locations where farms are already large, as in the former Soviet Union.

In the Lao PDR, for example, a government-commissioned report found that 37 percent of large-scale land acquisitions involved forest land, and that 45 percent involved what the report categorizes as "unstocked forest and ray," which are areas of bush and forests created by shifting cultivation practices.[67] Three-quarters of the acquired forest land also fell under legal categories intended for protection.[68] In Paraguay, large land acquisitions

are associated with the clearing of the biologically diverse Chaco forest.[69] In the Yala Swamp of Kenya, where the Yala River drains into Africa's largest lake, foreign investment led to large-scale clearing and drainage of a swamp rich with hippos, crocodiles, and leopards, and where local people used to fish, hunt game, harvest papyrus, grow vegetables, and graze cattle.[70] The Tana Delta, another wildlife-rich area of wetlands near the Kenyan coast similarly used by local people, is the subject of a large-scale, although highly contested, plan to grow sugarcane for ethanol.[71] In the Gambella region of Ethiopia, farming operations instigated by both Saudi and Indian investors have converted thousands of hectares of wetlands, used by local people to gather honey, hunt, and fish. Biofuel plantations in Zambia were established mainly on native Miombo woodland.[72] In Ghana, scholars found that biofuel developments were converting "large areas of secondary forest and rehabilitating fallow lands."[73]

Not all of these lands are pristine.[74] Much of the Miombo woodland in Zambia is land that has been cropped and has regrown woodland over time. One study concluded "that for every 1,000 ha of jatropha grown on smallholders' fields in the study site, an estimated 310 ha of mature forest and 196 ha of fallow land were cleared."[75] Similarly, in Indonesia, oil palm plantations were displacing not only primary forests but secondary forests, and often mixed landscapes of fallow, shrubs and grass, and cropland used by smallholders for rubber, pineapple, and maize.[76] Even in these disturbed landscapes, one can reasonably infer that lands cleared previously stored substantial quantities of carbon—or were rebuilding carbon—and provided other ecosystem services.

Analysis has shown that social and equity effects of land acquisitions differ among regions

Large acquisitions of preexisting large farms have occurred in the former Soviet Union and Australia. Although there has been some controversy about these acquisitions—including concerns about corruption and foreign ownership,[77] respectively—little scholarship has focused on local social consequences. The farms were generally large, supporting few farmers, and in the former Soviet Union many had fallen into disuse. There was little reason to believe that these acquisitions would displace farmers; rather, they had a large potential to boost overall production and the farm economy.

In contrast, both scholarship and press reports of impacts in Africa tend to find displacement, inequity, broken promises, and strong hints of corruption or self-dealing.[78] A summary of biofuel developments in Ghana by the Centre de recherche forestière internationale (Center for International Forestry Research, CIFOR) is illustrative of the conclusions:

> Large contiguous areas of suitable land were easily obtained by foreign companies through direct negotiations with Traditional Authorities, often through opaque, nonparticipatory and partially documented negotiations purportedly locking up large tracts of land for periods of up to 50 years. In this context, many affected households were forced to relinquish their land without any form of compensation or guarantees of future returns. Many land-losing households consequently experienced a marked decline in livelihood quality as a result of reduced incomes, increased food insecurity, and loss of access to vital forest products.[79]

In what may be the most socially advantageous case of biofuel investments identified by CIFOR, researchers found that a Tanzanian project followed "negotiations [which] were considered acceptable by affected communities" and produced "a number of early benefits," including "waged employment, full-time employees receiving considerably more than the minimum wage, water supply points, support for funeral costs." By 2009, however, an economic downturn had left wages "unpaid for long

periods and promises to improve the school and hospital left unfulfilled." The authors concluded, "With approximately half of household landholdings converted in the process, this case represents an unacceptably high risk for communities."[80]

There are also clearly examples in which direct employees of new plantations reported improved or more consistent incomes, as one group of employees reported in Ghana.[81] However, even in that situation, CIFOR found greater returns both to land and labor from alternative, local uses, and concluded that "employment [on plantations] would compare far less favorably if the value of other displaced crops and forest products were considered."[82]

In Indonesia and Malaysia, researchers have found at least somewhat more mixed results:

> Some communities did enjoy economic and social benefits from oil palm plantations such as more stable and reliable income, road access, [and] better healthcare services. In Kubu Raya, some communities benefited both from employment opportunities and from sales of smallholder oil palm harvests. In Kubu Raya and Boven Digoel sites, some indigenous communities and migrants developed good inter-ethnic relations, although this was not the case in Manokwari. Other communities experienced increasing restrictions on traditional land-use rights and outright land losses. . . . Conflicts over land between indigenous communities and oil palm companies were observed in all three sites.[83]

Similarly, in a series of case studies about oil palm in Thailand, Indonesia, the Philippines, and Malaysia, researchers at the Stockholm Environmental Institute found the consequences for local communities "were mixed, and that the espoused benefits for communities were not materializing as hoped."[84] It also found that "delivery of benefits at the local level was often highly skewed, with already marginalized groups being further disadvantaged, thus increasing inequity, societal fragmentation and social tensions."[85] Many communities have also found that oil palm developments led to serious problems with local water pollution and flooding.[86]

Indonesian law illustrates why transactions are likely to be unfair despite the fact that those seeking to build oil palm plantations must generally agree to a deal with local communities. To build a plantation, owners must first obtain permits, often first from the national government, to release land from status as national forest, and later from regional land authorities. These permits in effect give companies at least a temporary monopoly to buy rights to agricultural development. Only after obtaining a series of permits do companies negotiate with local communities, which therefore are not able to seek the best deal available from a choice of companies but must either agree or not agree to oil palm development with a single potential purchaser. Not surprisingly, although land for oil palm probably has a value of $4,000–$10,000 per hectare,[87] compensation for local communities rarely if ever approaches this level.[88]

By contrast, Tanzanian law applies a number of restrictions to acquisitions that would appear to mandate far more local potential for the interests of existing land users. But CIFOR found that

> the checks and balances in the law worked contrary to their intended purpose due to several factors. Both central and district governments are faced with strong incentives not only to generate revenues, but also to create conditions for enhanced economic growth and poverty reduction. Investment in the agricultural sector, which employs the majority of rural Tanzanians, is viewed as a promising pathway towards achieving these goals. Three factors exemplify the bias towards investors: land leases in excess of legal limits for the biofuel sector; the approval of flawed environmental assessments; and, ultimately, the overstatement of benefits of investments by politicians (including the President), which bolsters support from government officials and extinguishes critical debate on costs and benefits among villagers and local representatives.[89]

Recommended Policies for Land Acquisitions

Despite generally negative social and environmental assessments of the surge in large-scale land acquisitions, many critics have focused on procedural reforms.[90] One recommended reform is stronger recognition of customary rights, which we discuss below. These suggested procedural reforms for approving large-scale acquisitions typically highlight the following elements:

- Substantial consultations with affected communities
- Assurance of "informed consent" or true approval by a majority of local land users before deals go through
- More detailed contracts that specify the obligations of the investors
- Measures and procedures to oversee and assure enforcement of investor commitments
- Assurance of compensation for a wider array of customary uses and rights that recognize the real economic returns different people are now obtaining from them

We endorse these reforms. We also note that informed consent does not mean that every single user must consent. Assembling large-scale operations could involve high transaction costs even where benefits to all could be large, particularly if single holdouts can block the deal and demand a premium before others can benefit. This consideration explains why developed countries typically have procedures for government to seize land for eminent domain, but that ensure proper compensation. Informed consent instead requires rules that allow democratic decision-making by the community, with fair and transparent rules of thumb for compensation for the many different preexisting uses. Unfortunately, the evidence as marshaled by the reports we cite in this chapter is strong that these procedures are not widely or strictly followed.

Although these procedural reforms are worthy, the more fundamental questions are where, when, and under what conditions large land acquisitions should be encouraged or allowed because they benefit a country and its people and contribute to a sustainable food future.

When acquisitions involve large preexisting farms already converted to cropland, those acquisitions are less likely to displace and harm workers and natural habitats, and more likely to lead to valuable improvements in agricultural production. Some acquisitions in the former Soviet Union, Brazil, and Australia are more likely to fit these criteria, but, if benefits are to be realized, land purchasers must have the investment capital they claim to have and procedures must be in place to avoid corruption and political favoritism. In many land purchases, these conditions have not been met.

In general, other types of acquisitions rarely pass our criteria for a sustainable food future, such as ecosystem protection or climate change mitigation.[91] Large-scale land acquisitions tend to occur in forests, wetlands, or other natural or seminatural habitats. Although some governments and private companies have claimed they are merely acquiring "underutilized land" or "abandoned agricultural land," the evidence suggests that these lands typically hold more carbon and are more environmentally valuable than claimed, and that the labeling of land as "underutilized" or "abandoned" is an unjustified disparagement of secondary forests and savannas. Even when some of these areas are "degraded" from their purely natural state, they are typically being used by the poor and marginalized groups that rely on wetlands, grasslands, and trees (which in some locations may be common-pool resources) to diversify their livelihoods and increase their resilience to droughts and other shocks.

To truly support a sustainable food future, such acquisitions would have to meet one of two additional criteria: they occur on lands with relatively low environmental opportunity costs, including land for which the carbon costs per likely ton of crop are significantly lower than the global average; and they occur in countries where crop expansion is inevitable and are based on land-use plans consistent with the country's climate change mitigation obligations.

Cooperative, Contract, and Magnet Farming

What tools and contracting procedures can policymakers provide to help millions of smallholder farmers cope with the disadvantages presented by their size? What is necessary to help these farmers gain access to credit, buy inputs at low costs, acquire necessary technical understanding, and market their products at advantageous prices? Traditional tools involve three kinds of contractual mechanisms:

- Farmer cooperatives, through which farmers collectively own and run distribution facilities and input suppliers
- Contract farming, in which farmers agree to produce specific crops for future delivery at a set price and often receive assistance to do so
- Magnet farms, which typically involve contract farming around a central, large farm

Although these three mechanisms differ in detail, each involves an operational entity that works with smallholder farmers to increase access to inputs, expertise, and credit, and/or to process and distribute the final product.[92]

As countries' economies develop, and markets become increasingly long-distance and anonymous, these mechanisms are likely to become more important. Farmers working in these systems enjoy the benefits of branding,[93] gain expertise, spread risk, share costs of inputs and machinery, and access more remunerative and specialized markets.

Yet cooperatives, contract farming, and outsource farming by magnet farms also have costs. In the case of contract and outsource farming, larger farming enterprises may develop local monopoly power over purchases, and farmers can become particularly vulnerable to them once they have invested in the production systems needed to grow specialized crops.[94] In the case of cooperatives, there are administrative costs and risks that cooperatives will be managed unfairly. There is also the risk that a single cooperative may not prove to be as efficient at supplying farm inputs or marketing crops and livestock products as a competitive, private market of multiple businesses.

Contract farming is also vulnerable to cheating, either by the contractor or by the farmer. The core of contract farming is an agreement for farmers to provide and companies to purchase a quantity of a commodity at a predetermined price (or price range), at a specified time. For certain kinds of agricultural products, such as a highly processed tree crop, the contract may need to apply over several years to justify the upfront costs for either farmers or purchasers. By the time of the promised sale, changes in growing conditions worldwide or consumer preferences may have led to dramatically higher or lower crop prices, providing strong incentives either for a farmer to try to sell to someone else at a higher price or a company to try to avoid purchasing—perhaps by falsely claiming quality limitations—if market prices are lower. Overall, policing contracts is costly, and some products are harder to police than others.

The benefits of contract farming are hard to prove conclusively because there are many reasons why farmers who already have other advantages—whether these be better lands, better locations, or better training—are also more likely to be contract farmers.[95] There is evidence—gleaned from subtle statistical analysis—that studies of contract farming are subject to a publication bias in which studies that show benefits are more likely to be published.[96] Even so, and while the evidence can be conflicting, meta-analyses of studies generally find that contract farmers in developing countries tend to make more money than noncontract farmers and that contract farms tend to have higher productivity.[97]

The combined weight of the evidence and many studies indicate that contract farming should be able to provide valuable benefits, but there are several important caveats.

First, because of the mix of benefits and costs, these systems tend to evolve primarily for foods of higher market value.[98] For example, companies may pay a premium for vegetables or other high-value crops (e.g., cocoa, vanilla) of the right quality, or milk or poultry that meets the right sanitary standards and is reliably delivered year-round. If the quality cannot be assured through relatively quick and easy inspection, as with sanitary standards, for example, contract farming can provide a solution. Companies may also have special technical advantages—such as particular vegetable varieties, breeds of chicken,

or feed formulations—which they can exploit only by maintaining some production control, particularly if goods are hard to store. Cooperatives may also evolve in similar circumstances, for example, to market milk because of the need for an assured buyer shortly after milk is produced. There are examples of contract farming for staple crops, such as rice, that seem to have economic benefits, but contract farming is less common for such crops, and there are also findings that efforts by aid agencies to promote contract farming for staple crops can make the costs of farming too high.[99]

Second, studies consistently find variability in results from different contract farming arrangements even where they tend to find benefits on average. The details therefore matter.

Third, the challenges of meeting the demands of contractors tend to favor somewhat larger farms (at least, the larger of small farms), and relatively few farmers tend to benefit from these arrangements. Today, fewer than 5 percent of smallholder farmers typically participate in some form of contract farming.[100]

Recommendations for Contract Farms

In general, the literature implies that governments can support smallholder productivity and livelihoods by supporting strategies that allow farmers to take advantage of these different contractual arrangements. We offer a few suggestions for policies to increase the benefits and reduce the costs.

Focus more development efforts on high-value crops

Agricultural development assistance to smaller farmers should be directed more toward high-value crops that carry a premium for quality because the benefits of collective action are more likely to apply to such crops. Many of these kinds of crops also tend to improve with heavier investments of labor. In general, our modeling analysis also projects larger growth in demand for these crops than for staple crops. Even farmers engaged in subsistence agriculture can raise cash crops to boost income, diversify production, and increase assets that may also be used to build staple crop production.

Provide basic social security

Because hunger is such a core risk, subsistence farmers are highly risk-averse and will often produce staples even if production of an alternative crop would on average provide more income and thus greater food security. For the same reason, farmers will typically avoid specializing in the most promising agricultural option unless the expected rate of return is extremely high relative to the increased risk. Government programs that provide an alternative form of income or food guarantee could therefore help farmers take more risks and make more profitable investments, such as growing crops likely to earn a higher return. Brazil's *Bolsa Família* program and Mexico's *Oportunidades* program, for example, provide small guaranteed incomes to the poor if they send their children to school, and both have had considerable success in alleviating hunger and poverty.[101] Research on the agricultural effects of these types of social security programs is limited, but it suggests that they allow farmers to focus more of their production on higher-value crops.[102] Both Brazil and Mexico are middle-income countries, and many countries in Africa probably cannot afford such extensive programs, but moving in this direction as soon as possible may also be a way to stimulate agricultural growth.

Ensure fair contracts and try to enforce them

A first step is to help ensure fair contracts up front, and small farmers would benefit from legal and marketing advice. The risk of cheating by either party poses a major barrier to mutually beneficial contract farming so efforts to make cheating harder are important. Such efforts can take advantage of improved remote and ground sensors and spatial tools to confirm production, which would increase the confidence level of companies. They should also enable faster and fairer arbitration and enforcement procedures, increasing farmers' confidence. Civil society organizations might provide these services. Governments should consider laws to facilitate such arrangements, including basic codes of conduct to help protect against abuses.

Build on sustainability commitments

Many major private food companies have committed to reducing deforestation and GHG emissions and improving the income of farmers in their supply chains. Deeper involvement with farmers through contract farming provides one opportunity for embedding these commitments further up supply chains and building longer-term relationships between companies and their producers.

Land Rights for Sustainable Intensification

Large-scale land acquisitions can occur in much of the world because traditional users of land generally lack full and protected property rights. In some parts of the world, neither smallholder farmers' rights nor common rights to community land are officially recorded in written form. In addition to increasing vulnerability to seizure of land by others, this lack of clear, full title—according to standard economic theory—undermines both the ability of farmers to borrow money and their desire to invest in long-term improvements because farmers may not be able to reap future benefits of their investments. Weak property rights therefore encourage short-term exploitation of land rather than longer-term stewardship. The resulting sustainability concerns have led international institutions and nongovernmental organizations to advocate secure land rights.

Property rights

Determining the best and most appropriate kinds of rights regime has proved challenging. The standard treatment of land rights in Western countries recognizes something similar to total rights of dominion over a parcel of land, subject to regulation but including the right to buy and sell and typically to exclude all, or nearly all, other uses. These rights are typically recognized in written documents recorded in government registries. International institutions have sought to mimic these types of property rights in countries without such systems, and many governments have made efforts in this direction.

These efforts have had some success but also many problematic results. From an equity standpoint, efforts to recognize rights in this way have sometimes led to failures to recognize a range of



traditional rights on common lands, ranging from hunting, wood gathering, and grazing to gleaning. By definition, if a piece of land has long been subject to overlapping rights but the new property rights system is oriented toward recognizing single ownership, then some people who have previously used the land will lose their rights (with or without compensation).

The process of recognizing rights has also provided an opportunity for political favoritism and unfairness. As the World Bank wrote in 2008, "Land policies were often adopted less to increase efficiency than to further interests of dominant groups."[103] In many contexts, granting recognition of individual property rights to people without experience of private land ownership and without establishing communal regulation has allowed elites to buy up rights and assemble vast complexes of land.[104]

The effect of individual property rights on agricultural productivity is complex. In theory, title should give farmers greater incentive to improve farms and greater means to borrow funds to do so. The

ability to sell or rent land should make it easier for land to be transferred to more productive farmers. In studies of land reform effects in Latin America, Eastern Europe, and Asia, researchers have found productivity gains to be significant.[105]

But in studies of land reforms in Africa, researchers have generally found no particular gain, a result for which they have offered two possible explanations.[106] One is that customary land rights have been sufficiently secure that providing land titles has not provided much additional security—although there is evidence that customary land rights are generally not sufficient to use as collateral to obtain a loan.[107] The other explanation, in effect, is that while secure land rights are very helpful in promoting productivity investments, they are not by themselves sufficient, and the myriad other obstacles facing farmers in Africa have blocked improvement. Among these obstacles are poor soil quality; inadequate transportation, electricity, and financial infrastructure; weak marketing infrastructure and networks; and poverty traps.

As one critic has written about Africa, "In practice, many of the land policy reforms and titling programs of the 1970s and early 1980s failed to achieve the expected increase in agricultural investment and productivity, did not facilitate the use of land as collateral for small farmers, and often encouraged speculation in land by outsiders, thus displacing the very people—the local users of the land—who were supposed to acquire increased security through titling. The programs frequently exacerbated conflicts by ignoring overlapping and multiple rights and uses of land and led to or reinforced patterns of unequal access to land based on gender, age, ethnicity, and class."[108]

Customary rights

During the past decade, researchers, international agencies, and governments have learned from these lessons and begun to emphasize the recognition of customary rights. These are the complex rights recognized by many communities in much of the world (including Africa) to land uses that may accommodate both overlapping rights to the same piece of property and the process within a community of allocating rights. A number of African countries have taken steps to recognize customary rights, but the strength of measures varies. For example, Mozambique has recognized customary rights in general but still retains national ownership rights that may supersede the communal rights. As one study concluded, "A greater challenge to customary rights in Africa is not tenure conversion per se, but the fact that customary arrangements lack adequate constitutional and legal recognition in many countries."[109]

Customary rights, however, are not always completely fair. They may recognize the authority of local chiefs in the allocation of land, but decisions by the chief may be inequitable or may fail to prevent unbalanced deals with large investors seeking land. A study by CIFOR found that many of the large and inequitable land deals in Mozambique and Tanzania were the work of local chiefs, who directly received money as an incentive.[110]

Translating customary tenure rules into formal property rules also can institutionalize the inequality of women. For example, in southwest Ghana, women's ownership of land is customarily discouraged, and women often obtain land only by the license of their husbands.[111] One study by the World Bank concluded that in sub-Saharan Africa, "the vast majority of women, who are the primary subsistence producers, are locked out of landownership by customary laws."[112] Sometimes customary laws do recognize substantial rights for women, but they are hard to translate into property rights based on Western principles. For example, women in northern and eastern Uganda have many traditional land-use rights, but when sales transactions occur through the legal system, those rights are often lost.[113] Moves to recognize customary rights need, at a minimum, to recognize these rights. More broadly, recognition of customary rights should be seen as an opportunity to change those rights to increase fairness and broaden access to resources in ways that will simultaneously benefit productivity.

The development economics literature generally agrees that "(1) property rights need not always confer full ownership and be individual—they can, and should be, individual, common, or public, depending on the circumstances and (2) most important for sustainable development is that property rights are deemed secure."[114]

Beyond the challenge of determining the best system of rights, the sheer process of recording

property rights has often proved to be expensive because it requires drawing precise property lines and settling potential disputes. That process has led some studies to question whether such efforts are always or even usually worth the cost. Modern information technology, however, seems capable of reducing this challenge. For example, Rwanda completed a national registration program of 10.3 million parcels in less than five years at a cost of $10 per parcel using aerial photographs and rectified satellite imagery.[115] Ethiopia implemented a similar program. Both countries used this process to improve women's rights by legally recognizing women's inheritance rights, elevating secondary rights so that they are equal to those of men, and allowing the joint registration of spousal land rights. Studies have found that Ethiopia's reform led to improvements in agricultural productivity.[116]

In addition to influencing equity and productivity, tenure arrangements have implications for forests and agricultural conservation. In some contexts, traditional property systems may discourage agricultural conservation practices. For example, the long-established principle of acquisitive prescription, common in Latin America, allows landowners who clear forests to obtain ownership and thereby encourages deforestation. In Africa, rights to use trees may be divided among those with the right to collect fruit and those with the right to cut the tree for timber, which in some cases may be the government.[117] This split in rights can reduce incentives for farmers to plant and care for trees. In many parts of Africa, members of the community may have the right to graze cattle on residues after the harvest, reducing incentives to return the carbon in residues to the soil.

Better recognition of the rights of indigenous users can help protect forests, however. Researchers have found that indigenous reserves in Brazil have been far more effective at preserving forests than other land ownership arrangements—although this may result in part from restrictions on deforestation built into the establishment of those reserves.[118] Overall, in Brazil, Bolivia, and Colombia, deforestation rates inside indigenous forest lands with secure tenure have been one-half to one-third those outside indigenous lands.[119] But many local people will also be attracted to the potential revenue from agricultural conversion, as long as the price is fair and other measures to boost their incomes are lacking. Recognizing land rights may help but will not always be an adequate measure to protect natural ecosystems from conversion to agriculture.

Recommendations for Land Rights

Despite the complexity of tenure issues, we offer a few general recommendations based on literature and our own conclusions:

- Governments should recognize and secure the rights of those who have used land (and water) under both formal and customary arrangements to protect against large-scale seizures by governments themselves and to provide sufficient security for farmers to obtain credit.
- Governments should use modern information technology to expedite the identification and recording of land boundaries and issuance of associated documentation. They can move the process along quickly by segregating parcels that are subjects of dispute (for subsequent resolution) from those that are not.
- Governments should eliminate rules that allow individuals to secure property by clearing forests and other natural landscapes.
- Where land ownership in the form of individual plots has a strong tradition, as in much of Asia and long-settled parts of Latin America, moving toward property rights systems similar to those of Western countries can work.
- Processes to formalize customary rights, because of their high potential to disadvantage those who are less powerful or whose rights are more transient, should specify rules and employ oversight systems to assure fair treatment.
- Where customary rights systems exist that recognize physical overlapping land uses, the systematizing process is also an opportunity to address fundamental unfairness, as in the treatment of women's rights, and to develop alternatives to traditional rules that impede productivity gains.



CHAPTER 36

CARBON-PRICING STRATEGIES AND FINANCING OF CLIMATE-SMART AGRICULTURE

Voluntary actions alone will likely not achieve climate goals. Economists generally favor pricing strategies that attempt to internalize climate costs, such as carbon taxes and cap-and-trade systems. Some policies would use carbon "offsets" to fund agricultural mitigation. We find that broad pricing strategies are likely impractical but that opportunities exist to apply them selectively as part of flexible regulations. Finding a limited role for offsets, we discuss reforming agricultural subsidies and increasing access to climate finance.

Carbon-Pricing Strategies

No one knows the precise changes in management or land uses that each farm should undertake to most cost-effectively boost production while reducing GHG emissions immediately today, let alone over time. In the same way, no one knows the precise mix of technologies most cost-effective for reducing emissions from factories and power plants. For these reasons, economists and most environmental organizations favor policies that target outcomes—by imposing costs or caps on emissions or possibly rewarding sequestration—rather than laws that mandate particular technologies or practices. Outcome-oriented approaches offer more certainty about the level of emissions that will ultimately be achieved and should be more cost-efficient because farmers and other emitters are given the flexibility to choose the most cost-effective ways of reducing emissions at any given time. But are such approaches politically or practically feasible for agriculture?

Carbon taxes and cap-and-trade systems

Governments can impose costs flexibly on emitters by imposing a tax on each ton of emissions, typically called a "carbon tax." They can also create a "cap-and-trade" system. In a cap-and-trade system, the government imposes a cap, or limit, on the total amount of allowable carbon dioxide equivalent emissions and allocates emissions "allowances," representing shares of the cap, to emissions sources that have been designated as entities under the cap. Cap-and-trade systems can allocate allowances at different parts of the supply chain, and participating entities can trade emissions with each other as long as total emissions from all entities remain under the cap. If applied in agriculture, for example, farms (or whatever entity is allocated allowances) that emitted more than their allowance would have to purchase more allowances from others, while farms that reduced their emissions below their allowance could sell credits for extra emissions reductions to others.[120]

Carbon taxes and cap-and-trade systems can create incentives that work their way through agricultural and food supply chains. For example, science and technology companies that develop more efficient fertilizers or feed additives to reduce ruminant methane would find a market for these innovations because farmers would pay for inputs that help them avoid taxes or the need to purchase allowances. Consumers would also have incentives to switch to lower-carbon foods, because the costs of high-carbon foods, such as beef, would rise to reflect their carbon costs. In such systems, markets can identify the most cost-effective sources of emissions reductions on their own.

These mechanisms can be implemented without imposing additional net costs on farmers or food consumers. For example, governments could refund farmers using taxes raised downstream from the food sector or by using funds from selling allowances. Such systems would work if those who reduced emissions ultimately received more of the economic benefits than those who did not, and if those advantages were proportionate to the reductions. Governments could also design either a tax or a cap-and-trade system to protect the interests of small farmers, including those who today generate high emissions relative to their production. The key need is to structure such a system to focus on improvements from a baseline, for example, by allocating carbon allowances to farmers who match their existing emissions levels. As small farms probably have some of the best opportunities to reduce emissions per ton of crop, meat, or milk, such pricing mechanisms could even favor them.

Despite their theoretical advantages, these pricing approaches face significant technical challenges in the agriculture and land-use sectors. In the energy sector, emissions generally track the amount of carbon in coal, oil, or natural gas. As a result, emissions are relatively easy to estimate per fuel type and form, so pricing the carbon in these fuels is a reliable proxy for emissions. In the agriculture sector, however, the quantity of emissions resulting from different farm practices can vary greatly. It is not practical to measure most agricultural emissions directly (such as the nitrous oxide released when using fertilizers or ruminant methane). Even if it were, monitoring millions of farmers globally would present enormous challenges in practice. Many mitigation options are relatively subtle—such as improving the efficiency of feed use for cattle—and it would be difficult to monitor how emissions change because of changes in management.

Land use also presents measurement and verification challenges, long acknowledged by the Intergovernmental Panel on Climate Change (IPCC).[121] Many natural factors, such as variations in rainfall and temperature, greatly influence how much carbon a forest or savanna adds or loses. As a result, holding landowners directly accountable for increases in land-use related carbon emissions that they cannot control may be unfair. Imposing penalties on owners for losing forests, for example, would raise questions about what to do and how to know when forest clearing results from natural fires or fires set by others. Monitoring carbon through remote sensing is not yet practical at the individual landowner level.[122]

Introducing carbon taxes or cap-and-trade systems likely faces even more significant political challenges than applying such approaches to other sectors of the economy. Neither agriculture nor forestry is part of Europe's emissions trading system, which applies only to large manufacturing sites and power plants. When the U.S. House of Representatives passed a bill to create an emissions trading system in 2009 (that ultimately was not introduced in the Senate and did not become law), the bill did not impose obligations to reduce emissions from agriculture or land use. In 2008, New Zealand established an emissions trading system[123] that was originally intended to apply both to agriculture and conversion of forests into agricultural use, beginning in 2015.[124] But the government suspended the law's application to agricultural production as the start date approached and replaced it with reporting obligations only—although the government did retain limitations on conversion of forests.

More selective pricing strategies

Given the technical and political challenges of these carbon-pricing strategies, agriculture may not be subjected to the same carbon-pricing mechanisms used in the energy and manufacturing sectors. However, the advantages in efficiency and flexibility afforded by pricing strategies should motivate governments to explore alternative, more limited variations. For example, although New Zealand's emissions trading system is not focusing on agricultural production emissions, it still requires those who cut down forests established before 1990 to have offsets for those emissions.[125] It might also be possible to tax the production of forest products, and to do so differentially based on the type of forest those products come from to influence the location, method, and quantity of wood products that are produced.

Creative pricing approaches could also apply to features of agricultural production that are measurable. For example, governments in countries where farmers have opportunities to apply fertilizer more efficiently could impose a tax on fertilizer that does not incorporate a nitrification inhibitor or time-release mechanism. The tax level would be based on the likely additional releases of emissions expected from use of conventional versus improved fertilizer. Different forms of manure management could also be taxed separately. Whether used to help set the level of a carbon tax or simply to monitor emissions more carefully, scientists need to develop useful proxy indicators to estimate emission levels and how emissions change with various mitigation practices. Taxes on high-emissions foods, discussed in Chapter 6 on shifting diets, represent another option.

In an ideal world, governments should impose taxes that reflect the costs of pollution, but political feasibility will depend in part on confidence in the technical feasibility and cost of mitigation options. Just as enhanced forest protection in Brazil was accompanied by increased confidence in the potential to intensify production on existing agricultural land, some method of taxing beef production that generates high levels of methane emissions becomes more plausible if scientists can demonstrate to farmers that safe, effective, and reasonably priced additives are available to limit methane generation from cow digestion.

Overall, given the complexities of the world's agriculture and land-use system and the scope of the climate challenge, it appears that taxing emissions would be the most efficient and effective approach to reducing them. Governments should explore selective application of this approach wherever practicable.



Carbon Offsets

Much of the interest in applying emissions trading systems to agriculture has focused on agriculture as a supplier of offsets to capped sectors. Energy users, for example, would pay farmers to reduce their emissions, creating credits that they could use to offset or cancel out their own emissions at less cost than any actions they could take in their own operations.[126] Similarly, some nongovernmental organizations and foundations have hoped that offsets could fund agricultural improvements by small farmers in developing countries, particularly through incentivizing measures that add soil carbon and improve soil fertility.[127]

To date, European companies capped under an emissions trading system have been able to pay farmers in developing countries for a limited number of mitigation measures under the Clean Development Mechanism (CDM).[128] The Canadian province of Alberta also established a system that allowed extensive use of offsets.[129] Interest in this approach in richer countries has been political as well as technical: trading systems could provide financial reasons for agricultural interests to support climate change efforts and reduce compliance costs for factories and power plants. In Alberta, for example, offsets have generated more reductions than those achieved by factories and power plants reducing their own emissions.

Despite these hopes, there are serious limitations and challenges to the use of offsets. The most obvious is that offset systems by themselves do not generate net greenhouse gas (GHG) emissions reductions from agriculture. The emissions reductions in agriculture are credited to the energy sector, which then reduces its emissions less than it would have done without the purchase of an offset. For years, climate mitigation policies have paid little attention to the need to reduce agricultural emissions. Given delays in taking action on climate change, it is now clear that by 2050, in addition to massive reductions in energy-generated emissions, agricultural emissions must also be significantly reduced to help stabilize the climate. This means that selling agricultural offsets to the energy sector can play at most a transitional role, perhaps stimulating progress in the agricultural sector. Large-scale agricultural mitigation is needed just as it is for other carbon-intensive sectors.

Beyond this need to limit both agricultural and energy sector emissions, other practical challenges limit the use of offsets:

Additionality

A critical requirement for offsets is "additionality," which is proof that a mitigation measure would not have occurred anyway but rather results from the payment of the mitigation credit. To establish additionality, the CDM requires an analysis that the measure would not otherwise be economical and

customary. But there is debate as to whether most CDM projects truly meet the additionality test.[130] One problem is that the more economical a mitigation measure—and therefore the more desirable and likely to be successful—the less likely it is to be additional. The additionality problem is so challenging to apply robustly in practice that many researchers and some policymakers have called for abolishing offsets altogether, thereby avoiding the additionality problem, and replacing offsets with an alternative mechanism that rewards countries for holding emissions below a projected baseline.[131]

Baseline

Related to additionality is the question of what baseline to use to assess mitigation. Should an offset require reductions from recent historical emissions, or recognize that emissions are likely to grow without additional effort (e.g., to improve livestock feeding efficiency or nitrogen use efficiency from fertilizers)? Although such improvements offer the best short-term options for reducing emissions while meeting growing food needs, it can seem odd to award offsets to farms for absolute increases in emissions (even though they are smaller increases than would occur under "business as usual" growth) and to use those activities to justify reduced mitigation by factories and power plants.

Administration

Developing offset agreements with millions of farmers is a major administrative challenge, as is monitoring the results. Solutions probably require a large "aggregator," which pays farmers for practices and then assesses progress over large areas using indirect means. But monitoring and payment require some entity to manage the process and probably assume much of the risk.

Leakage and permanence

When any activities claim mitigation, an important question is whether the activity truly reduces total emissions or just transfers emissions to other sources. For example, if some farmers plant forests on some of their land or reduce fertilizer use in ways that reduce yield, other farms may then clear more forest to meet demand for food. Efforts to estimate these effects are challenging and present large conceptual problems. For example, should carbon offsets reward producers if an economic model estimates that the amount of land-use change elsewhere to replace the food is less because higher prices cause people to consume less food?[132] Leakage is an issue for all emissions mitigation activities, but the likelihood of leakage is even greater when mitigation actions are counted at an individual farm level rather than at the national level. In addition, when the estimated reductions are sold as an offset to a purchaser, which can then increase emissions or avoid reductions itself, the consequences are even worse. Permanence is also an issue. Forms of mitigation that involve carbon sequestration might not store carbon over the long term.

Certainty and discounting

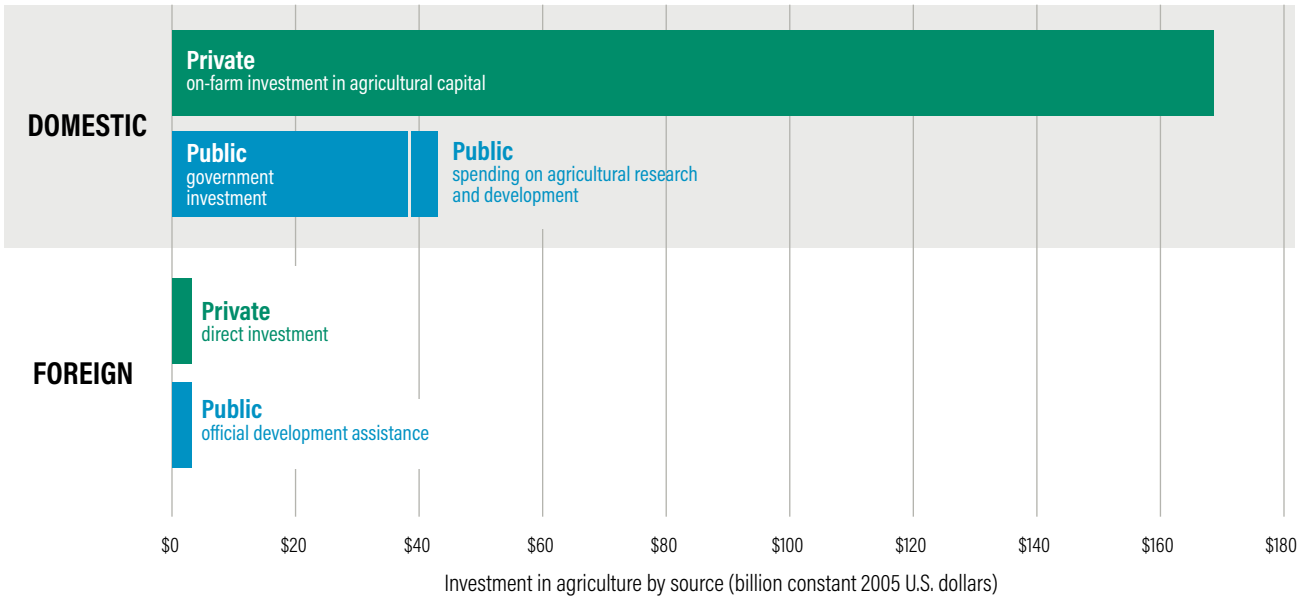
Accurately estimating emissions reductions in the agriculture sector is more challenging than in the energy sector. As a consequence, agriculture-based offsets are sometimes discounted relative to energy-based ones (e.g., of two tons of estimated reduction, only one ton can be traded). Such discounts reduce the financial incentives for agriculture-related offsets.

Small farmers

Participating in offset programs presents particular challenges for small farmers. Precisely because they are small, the amount of mitigation potentially available from any one farm is modest, although many of the transaction costs will remain. Small farmers also face timing and flexibility issues. For example, many offset projects only pay based on success, or after several years of operation. But many small farmers lack access to the capital necessary for up-front investments and cannot absorb the risk of failure. They also reasonably fear the multiyear commitments required by project designers, as those commitments reduce opportunities to adjust to changing personal, weather, or market realities.[133]

Because of these obstacles—and above all because the agricultural sector itself must achieve significant emissions reductions in addition to other sectors—agriculture-generated GHG emissions offsets have only a limited and short-term role to play in achieving a sustainable food future.

Figure 36-1 | Farmers' investments in agriculture are much higher than public investments



Note: Data on country-level sources of investment in agriculture vary among low- and middle-income countries. The number of countries covered by these data varies from 36 for foreign direct investment to 76 for on-farm investment in agricultural capital and government investment. See Appendix 1 in Lowder et al. (2012) for more detail on the country-level data included in this chart. Although the data are not comprehensive, they are sufficient to indicate that private on-farm investment far outweighs any other source of investment.
Source: Lowder et al. (2012), Figure 2.

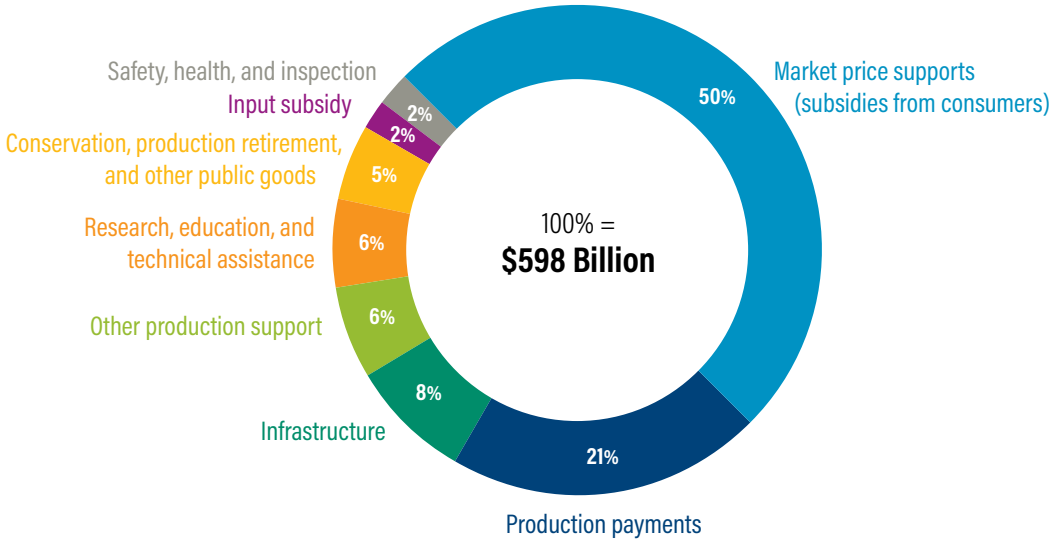
Funding Climate-Smart Agriculture

Agriculture is a major sector of the global economy, so is not surprising that estimates of the investment needed to maintain and improve it, as well as to address climate challenges, involve enormous sums of money. The private sector will likely provide the bulk of these funds. The great majority of those private investors will be farmers, who are primarily investing to replace and improve their own farm equipment, animals, farm roads, and irrigation and drainage systems. FAO estimates the total accumulated investment by farmers around the world at more than $5 trillion.[134] Despite assessing only 76 countries because of limited data, the FAO estimates that private investment per year of nearly $170 billion dwarfs public investments (Figure 36-1).[135]

The dominance of farmers in agricultural investment makes clear that a core role of government is to facilitate and guide their investments by internalizing environmental costs and establishing sound policies regarding tenure, land acquisitions, and cooperation or contracting. For example, in sub-Saharan Africa, much of the agricultural stagnation between 1980 and 2005 is attributed to an annual decline of roughly 0.6 percent of agriculture's capital stock compared to increases in all other regions of 0.7 percent more.[136] This decline was probably due to poor government policies, including policies that sought to tax agriculture to pay for industrialization.[137]

Nonetheless, there is still a need for government financial resources to support necessary infrastructure, research, and assistance to small farmers if they are to escape or avoid poverty traps. Classic poverty traps force farmers to sell off necessary assets in times of hardship or to avoid reasonable investments in productivity improvements because of an inability to cope with almost any level of risk. In the case of mitigating GHG emissions, such assistance to farmers is both advisable and fair. So where should these funds come from?

Figure 36-2 | The world's leading agricultural producers provided nearly $600 billion in public funding to support farms in 2015



Note: OECD assessment of 51 countries excluding India.
Source: Searchinger et al. (2018b), based on analysis of OECD (2016) data.

Redirecting subsidies

Government policies today already provide major financial support to agriculture. According to estimates by the Organisation for Economic Co-operation and Development (OECD), the 51 top countries in total agricultural production (excluding countries in South Asia, which the OECD data do not address) provided nearly $600 billion in farm support in 2015 (Figure 36-2).[138] This figure was equivalent to roughly 19 percent of total global agricultural production.[139] This level of support suggests that it would be difficult to obtain substantially higher levels of support from governments. Yet these funds, as a whole, are doing little to support the kinds of improvements outlined in this report.

Half of this total support takes the form of "market price supports," which are any kind of market barriers that raise prices to consumers. Examples include import limits, tariffs, or systems that limit production by farmers to increase prices. If these barriers benefit some group of farmers in a country, they do so at the expense not only of consumers but also of farmers in other countries. In fact, because these supports are more prevalent in higher-income countries, they offer little market protection for the world's poor overall. From a global perspective, reducing or redirecting the costs of these market interventions would reduce prices and benefit consumers.

The other half of farm support, about $300 billion, flows directly from governments, mostly through direct expenditures or tax credits. About $167 billion takes the form of direct payment to farmers for current or past production. This funding will only spur productivity to the extent that farmers decide to use these funds to boost investment rather than income, so it is an inherently diffuse way of boosting productivity. Another $14 billion is for input subsidies, which have modest benefits and often lead to environmentally damaging results (as discussed in the next section, on fertilizer subsidies). Approximately $46 billion supports infrastructure, including irrigation. These funds have probably boosted production in various ways. Finally, $74 billion is spent on research or technical assistance, conservation payments, or health and safety inspection.

This analysis indicates a real opportunity to redirect farm support toward the needs identified in this report. Redirecting market price supports would be most difficult administratively because these market barriers raise costs to consumers—and so are real costs—but generally do not create a pot of money that governments could transfer to other purposes. Both Europe and the United States, however, have experience in reducing these kinds of market barriers in return for increases in direct government subsidies. Subsidies could then be targeted more at the strategies and approaches necessary to close the food, land, and GHG mitigation gaps and achieve a sustainable food future.

Redirecting the $181 billion per year in direct payments to farmers—$167 billion for production and $14 billion for input subsidies—toward the priorities identified in this report provides the easiest administrative opportunity to achieve these objectives.

In recent decades, governments have been steadily reducing the extent to which their subsidies distort trade, in part because of trade negotiations. The most offensive subsidies from the perspective of trade are subsidies that pay farmers more as they produce more of a particular crop, known as "coupled payments." Researchers have estimated that coupled payments are often environmentally damaging because they encourage overuse of farm chemicals. However, their true impacts on land use and GHG emissions have rarely been estimated and are probably variable and complicated because of their effects on where crops are produced.

In the United States, there has been a major shift from direct price guarantees to "crop insurance." But crop insurance is highly subsidized and insures not merely against losses from bad weather but also against low prices. In effect, it serves as a revenue guarantee that is tied to the amount a farmer produces, and therefore has more similarities to than differences with traditional price guarantee programs.[140]

The United States has also seen modest movement toward imposing some kind of environmental criteria on farming as a condition of payments. Since 1985, farmers have been required to implement plans to reduce soil erosion and avoid draining wetlands, although enforcement has never been strong.[141] There is evidence that these requirements have had some effect although probably a modest one.[142]

Europe has done a little more to shift its agricultural funding toward conservation goals. The bulk of the Common Agricultural Policy's direct payments are now tied to conservation compliance, which involves two types of mandates. The first requires that farmers comply with applicable environmental and food safety laws that are already mandatory, such as an EU-wide directive on nitrogen use. This mandate also requires that farms comply with authorization requirements on irrigation use where they exist. The second mandate requires farmers to comply with Standards of Good Agricultural and Environmental Condition, which are set forth in general language at the European level and which member states are supposed to make more specific. For example, the standards protect against soil erosion, protect soil organic matter, and recommend the protection of important "landscape features" to provide some buffering of streams and hedgerows.

Unfortunately, the requirements are vague at the European level, and often minimally applied by national governments. For example, the United Kingdom protects streams, but it requires maintenance of only a one-meter buffer from the top bank of a stream. Ecologists recommend much larger buffers to effectively filter out pollutants or provide shade. In 15 of the 28 EU countries, the only soil carbon requirement is not to burn crop stubble. Europe also requires that 30 percent of total agricultural funding, or almost 13 billion euros per year, go only to farmers who meet three additional environmental requirements, but these criteria also are very modest.[143]

Probably the most important reform has been to direct roughly one-quarter of total agricultural support to rural development, which includes roughly 19 billion euros per year for conservation.[144] Approximately half was directed toward projects viewed as enhancing ecosystems or climate, and a small number of projects have truly focused on climate mitigation.[145]

China has also substantially changed its agricultural policies in the past few years. It has phased out its direct subsidies for fertilizer, which were as high

as $21 billion in 2011.[146] It has also made hundreds of millions of dollars per year available for pilot projects to subsidize more efficient use of fertilizer and for agricultural research focused on environmental objectives.[147] China also devotes roughly $7 billion per year in funding to rehabilitate grasslands and restore forests on poor-quality agricultural land. These funds have done much to reduce soil erosion and have stored some carbon, although the focus on plantation forests, typically of a single species, has meant few gains and possibly even losses in biodiversity.[148] China also boosted agricultural research and development (R&D) spending heavily to roughly $12 billion per year between 2013 and 2016, more than doubling spending from 2006 to 2009. Even so, these funds represent only a modest share of China's total support for agriculture, which averaged $255 billion from 2014 to 2016 and was skewed heavily toward import barriers.

Agricultural subsidies are much lower in Africa and most of Latin America. One reason for Africa's poor agricultural development from 1960 to 2005 was low government investment combined with taxation or export restrictions designed to keep crop prices artificially low.[149] In 2003, the heads of state of most countries in the African Union pledged to increase the share of agriculture in government spending to 10 percent. An analysis by the International Food Policy Research Institute (IFPRI) in 2013 found that eight countries had met the target, and others had increased their spending, but that the overall goal had not yet been met.[150]

Overall, redirecting agricultural support provides a major opportunity for financing some of the needs identified in this report. Of course, all reforms of this kind are politically challenging. Even if agriculture would benefit overall, individual farmers who lose direct financial subsidies or market protections are likely to oppose such reforms. One prerequisite for these reforms will be increasing attention paid to farm programs by individuals and public officials who care most about climate change, biodiversity, and global poverty. These parties have an important stake in structuring farm support programs, though the connection is often not sufficiently recognized. Another opportunity may exist, however, by focusing on the linkages between agricultural productivity gains and climate protection. Even if some individuals would benefit by being allowed to clear more land, most farmers can benefit from programs that increase their productivity. So long as such programs are tied to protection of natural areas, they will contribute to a sustainable food future.

Reforming and redirecting fertilizer subsidies

The benefits and costs of fertilizer subsidies are particularly important questions for decision-makers allocating government spending because they can account for a large percentage of government support to agriculture. Fertilizer subsidies have been particularly large in Asia and in many parts of Africa, where fertilizer subsidies have consumed much of the government funding devoted to agriculture in recent years.[151] What is their proper role in a sustainable food future?

In Asia, the nonpolitical answer seems clear: fertilizer subsidies should be phased out. As Chapter 27 on reducing emissions from fertilizer use showed, farmers in both China and India overuse nitrogenous fertilizer (excess applications have little to no yield effects). Excess applications not only result in farmers spending more money than necessary but also cause high GHG emissions, particularly because much of the fertilizer in China is manufactured using power generated from emissions-intensive coal.[152] Studies have found that fertilizer subsidies contributed to agricultural growth and poverty reduction in the early years of introducing fertilizer but had little impact thereafter.[153] After the early years, fertilizer subsidies have contributed far less to raising agricultural productivity than other types of funding such as agricultural R&D, roadbuilding, irrigation, and education. Reforms in tenure and agricultural market liberalization have also had large effects.[154]

Subsidies encourage overuse of fertilizer. In China, one study estimated that fertilizer subsidies of all kinds—including many provided to manufacturers—reached $18 billion in 2010[155] although, as mentioned in the previous section, China has recently phased out fertilizer subsidies. A wide range of economic research supports the view, predicted by economic theory, that farmers' application rates of fertilizer reflect the ratio of fertilizer prices to crop prices.[156] If subsidies artificially lower the prices farmers pay for fertilizer, then farmers will use more fertilizer. This principle appears to hold true across countries, at least for cereals.[157]

In India, fertilizer subsidies have been especially distorting because they have been applied more heavily to nitrogen than to other nutrients, resulting in an inefficient balance of fertilizer application.[158] Reforms have tried to reduce support for some but not all nitrogen fertilizers, but the initial efforts may have had the opposite effect and led to more imbalanced nutrient application and higher costs.[159] By 2015, subsidy costs had reached $11.6 billion per year, roughly five times higher than 15 years earlier.[160] Although policymakers intend fertilizer subsidies to spur food production and to help small farmers, the evidence is strong that fertilizer subsidies are an economically and environmentally costly way of achieving these goals. There is also widespread evidence in China that average applications of synthetic fertilizers per hectare exceed efficient levels and could be reduced substantially with negligible impact on yields.[161]

In Africa, by contrast, fertilizer use is extremely low—around 9–10 kilograms per hectare on average in 2013, compared with an average of 150 kg/ha in Asia.[162] A World Bank publication in 2007[163] summarized the reasons for such low application rates, which still apply:

- Fertilizer prices are high in Africa compared to the rest of the world, which results in high prices of fertilizer relative to crop prices, a key determinant of how much fertilizer farmers use.[164]
- Exceptionally high year-to-year variation in fertilizer production and prices makes annual investments in fertilizer by African farmers risky compared to investments by farmers in other regions.
- The physical responses of crops to fertilizer are relatively poor, due in part to rainfall variability and in part to poor soil quality.[165]
- A variety of market imperfections, including poor access to credit for small farmers, make all agricultural investments challenging.

In efforts to overcome the market challenges, fertilizer subsidies in Africa were widely implemented from the 1960s through the 1980s. After that time, most countries phased them out or greatly reduced them in response to large balance of payments deficits and absence of foreign exchange reserves. Strong concerns expressed by the International Monetary Fund, the World Bank, and other international donors also played a significant role. These financial institutions worried about the cost of subsidies to governments, the challenges of targeting subsidies only to those who most needed them, and adverse effects on the development of private-sector fertilizer systems.[166]

However, the experience of Malawi helped change perceptions of what could be achieved by fertilizer subsidies.[167] Between the 1970s and the 1990s, Malawi went from producing a large food surplus to a large deficit. Three-quarters of the country's rural households experienced food shortages four to five months of the year and, in 2001–2 and 2004–5, Malawi faced severe hunger, exacerbated by an influx of refugees from civil war in Mozambique. In 2005, the country announced a subsidy program to provide 26 kg of fertilizer and 5 kg of improved seed to 2.5 million farmers. The program that year contributed to a 15–22 percent increase in maize production, restoring the national production surplus. Maize yields continued to grow in the next several years, and the program received considerable public attention.[168]

This apparent success in Malawi encouraged other African countries to reinstitute extensive subsidy programs.[169] As of 2013, subsidies supported roughly 40 percent of fertilizer use in sub-Saharan Africa.[170]

Faced with the Malawi example, international institutions and aid agencies to some extent modified their views, but they recommended that governments direct their efforts toward "smart" subsidies:[171]

- Subsidies should be structured to avoid displacing existing commercial sales, which means they should be tailored to support farmers who would not otherwise use fertilizer.
- Subsidies should encourage development of private markets, for example, by the use of coupons that can be used to purchase fertilizer from any supplier, rather than through government distribution channels.
- Subsidies should be temporary.

Nonetheless, economists have done much analysis of fertilizer subsidy programs and have expressed a high level of skepticism about their merits based on several considerations:

- Due to the difficulty of targeting fertilizer subsidies only to farmers who would not otherwise use fertilizers, several studies have found that farmers use much of the money not to increase fertilizer use but to purchase fertilizer they would have bought anyway. One reason is that even programs based on vouchers distributed to the poor may result in poor farmers selling the vouchers to better-off farmers.[172]
- One study showed that the quantities of fertilizer imported by the government to be sold in subsidized form was much larger than the quantity ultimately purchased by farmers in subsidized form, indicating that one-quarter to one-half of subsidized fertilizer was actually diverted to intermediaries before being sold to farmers.[173]
- Due to political favoritism, corruption, or simply the difficulty of truly targeting programs, many of the funds have supported wealthier farmers and have not been targeted at those who are most vulnerable.[174] In Zambia, one study found that the 73 percent of farms cultivating less than 2 ha, with 78 percent of those smallholders in poverty, received only 45 percent of the subsidies. Farms of 10–20 ha were significantly more likely to receive fertilizer subsidies.[175]

At least some of the fertilizer subsidy programs have not worked to encourage the emergence of private fertilizer distributors and retailers and therefore have had negative impacts on the development of the private sector and competition.[176]

Moreover, more recent studies of Malawi's experience have started to shed some doubt on initial claims that the subsidy program boosted production. Some researchers have pointed out that official estimated growth in maize yields in Malawi appeared inconsistent with farm-level studies and other data, and there was little evidence of declines either in rural poverty or in maize prices after the new subsidy program, both of which should have declined if production had increased.[177] Weather also played a large role. Maize yields that reached roughly 2 tons per hectare per year from 2007 to 2009 fell back to roughly 1.5 tons in 2010–12 even with continuation of the subsidy program. At least one study, however, has found small positive effects on agricultural wages.[178]



Ultimately, the biggest issue remains cost. In 2011, 10 African countries spent $1.05 billion on input subsidies, mostly fertilizer, which represented 29 percent of their collective public expenditures on agriculture.[179] In 2004–5, Zambia devoted one-third of its entire public budget to fertilizer subsidies.[180] In Malawi, the cost reached 60 percent of the entire national budget in a peak year. As FAO noted, fertilizer subsidies "are too costly and, as such, unsustainable in the long-term."[181]

Recommendations

A key question is what alternative policies exist for judiciously boosting fertilizer use. One set of options involves efforts to make fertilizer less expensive because evidence shows that farmers in Africa, as elsewhere, respond to lower fertilizer prices.[182] Reasons for high fertilizer costs identified by the World Bank include the small market (which inhibits economies of scale), lack of access to credit by importers, high transportation and handling costs, excessive differentiation of fertilizer products, and poor dealer networks.[183] Policies to boost fertilizer use could address these challenges through several measures:

Encourage private fertilizer markets

Public policies have often contributed to the high cost of fertilizer through measures that restrict or tax fertilizer imports, limit credit, or use government agencies to control fertilizer sales, all of which tend to lead to high prices.[184] A first set of advisable measures is therefore to eliminate these barriers and encourage private fertilizer markets. Kenya successfully boosted fertilizer use largely by avoiding government competition and eliminating import and price controls. Between 1993 and 2007 fertilizer use doubled, despite the elimination of subsidies.[185] Between 2002 and 2009, fertilizer use in Kenya averaged almost 30 kg per hectare,[186] fertilizer applied to maize rose from 84 kg/ha to 111 kg/ha, and maize yields increased by 18 percent. In the more productive areas of western Kenya, fertilizer use now rivals that of Asia and Latin America.[187]

Reduce transportation costs

High transport costs appear to be the single most important factor explaining high fertilizer prices in much of Africa.[188] High costs start with inefficient ports and then quickly rise with distance from port. Kenya's port of Mombasa is the primary port in Eastern Africa, and fertilizer is roughly 20 percent less expensive in Mombasa than in western Kenya and roughly half the price it is in Malawi.[189] Road improvements are therefore valuable.[190] Although roads are also expensive, the International Fertilizer Development Center has argued that substantial fertilizer price reductions could be achieved in parts of Africa by changing port management systems, arranging two-way truck transport, and incorporating some feasible improvements in rail management.[191] Major improvements in road infrastructure in Ethiopia from 1997 to 2011 appear to have played a substantial role in increasing fertilizer use and boosting yields.[192]

Increase the yield benefits of adding more fertilizer

A third set of measures increases the yield effects of adding more fertilizer. Researchers have demonstrated that farmers' decisions to use little fertilizer are often rational in light of the low crop response. For example, in good farmland in western Kenya, the response of maize to fertilizer is high, and farmers use high levels of fertilizer.[193] But in other parts of Kenya and most of sub-Saharan Africa,

crop responses are low, and thus farmers use little fertilizer.[194] As one study emphasizes, "The evidence from agronomic and soil science disciplines indicates that increasingly continuous cultivation, associated soil degradation, low soil organic matter, and soil acidity problems will lock a growing proportion of African farmers into low crop response rates to fertilizer use."[195]

Unfortunately, as we discuss in Chapter 13 on soil and water management, no one has developed a silver bullet for improving soil fertility or otherwise facilitating the use of fertilizer. Options include everything from agroforestry and other measures to improve levels of soil carbon (organic matter), to improved credit access, crop breeding, irrigation, and pest control.[196] Many African governments have developed agricultural investment lists in reports prepared with the African Union as part of the Comprehensive Africa Agriculture Development Programme. But there is no simple, proven list of alternative investments.

In this context, fertilizer subsidies will remain attractive to governments. Even when misused, funds do go directly to large numbers of farmers. In Kenya, despite its success in increasing fertilizer use without the use of subsidies, the government reinstituted subsidies in 2008–9 in response to rising global fertilizer prices at the time and political upheaval following contested election results. These subsidies have continued.[197] Although the research arguments against fertilizer subsidies are strong overall, the case against fertilizer subsidies rests on proof that funds can be better spent elsewhere. Researchers could strengthen their case by costing out specific, alternative agricultural investment strategies and likely results.

Earning Dedicated Climate Funding

At the international climate conference in Copenhagen in 2009, developed countries pledged to provide $100 billion per year in assistance to developing countries, both to adapt to climate change and to mitigate GHG emissions. This funding has been slow to materialize, and the economic downturn in much of the developed world that started in 2008 did not help. To date, developed countries are not on track to meet their goal.[198] But they have begun to raise their funding commitments, some of which they will distribute directly and some of which will pass through the Green Climate Fund (GCF). As of September 2017, the latter had received funding of roughly $10 billion in total for all climate-related work, not merely agriculture.[199] The GCF has adopted policies to allocate roughly half to adaptation and half to mitigation.

Before countries or the GCF distribute large sums of money for mitigation, they demand clear plans showing how funds will be spent and estimates of what will be achieved. Agriculture will probably find itself at a disadvantage compared to other sectors. It is much easier to estimate the GHG emissions savings from a project to replace a coal-fired power plant with a wind power system than it is to estimate the savings from efforts to improve the livestock sector. And it is easier to guarantee construction of the wind farm than to guarantee those livestock improvements. Focusing on energy alone, however, ignores the largest source of emissions for many developing countries.[200]

The best way for agriculture to claim a reasonable share of climate funding for mitigation will be to generate highly specific mitigation plans that are persuasive, detailed enough to guide implementation, and measurable enough to be monitored. Throughout this report, we have highlighted ways to meet these criteria when addressing particular sources of emissions.



CHAPTER 37

STRENGTHENING RESEARCH AND DEVELOPMENT

This report has consistently emphasized the need for additional research to overcome the many obstacles to achieving a sustainable food future. It has also stressed adequate funding to pursue research into the most promising leads. Meeting these needs will require increasing the quantity of funding well beyond what is currently available, putting more effort into the direct application of research, and pursuing critical technological breakthroughs.

Funding for Research and Development in General

The period since 2001 has witnessed some modest growth in agricultural R&D funding. Global public research spending grew from $26.1 billion in 2001 to $31.7 billion in 2008,[201] the last year for which we can obtain truly comprehensive information. Spending on public and nonprofit R&D grew modestly in 30 of 39 countries in sub-Saharan Africa for which data are available. The increase between 2001 and 2014 was roughly 30 percent (from about $800 million to $1.06 million).[202] However, growth has been uneven and spending in many food-insecure regions remains inadequate. Roughly half of the total agricultural R&D growth from 2001 to 2008 occurred in China and India.

Private sector research has also experienced growth. Total private food sector R&D reached $20 billion globally in 2010,[203]and in the United States and Europe the private sector has taken over the incremental improvement and production of many seeds. But globally, only $3.7 billion of these private R&D funds were directed at crop breeding.[204] Abundant evidence indicates that agricultural R&D generally pays off, with estimates commonly in the range of annual returns of 40 percent.[205] China and Brazil, recent global leaders in agricultural R&D, saw their agricultural productivity between 1979 and 2009 increase by 136 percent and 176 percent, respectively.[206]

With agricultural research underfunded in general, and agricultural research related to climate mitigation barely funded at all, the world is unlikely to solve the challenge of achieving a sustainable food future without a large increase in R&D. Viewed more optimistically, the current low levels of research suggest that new investment has a good potential to produce high returns.

A reasonable initial goal would be to raise agricultural R&D in low- and middle-income countries from the current 0.5 percent to 1.0 percent of their agricultural output production value. This would involve an increase of roughly $15 billion per year. The burden of this growth should be shared by high-income countries. The growth should occur in ways designed to guarantee continuity, development of infrastructure, and advancement of partnerships that allow low- and middle-income countries to benefit from newer breeding methods.

Funding the "D" in R&D

Many strategies for boosting agricultural production while reducing GHG emissions require detailed technical assessments of farm practices, land-use characteristics, and infrastructure in a given area. These assessments must be continually updated and improved over time. Such analyses involve science and engineering, not basic research, and are therefore analogous to the "development" portion of "research and development." At this time, however, no entities appear responsible for these assessments, nor are governments funding them at the level of detail required.

For example, our assessment of flooded rice farming (in Chapter 28) found that various strategies for reducing or interrupting the periods of flooding could dramatically reduce emissions, reduce on-farm water use, and potentially boost yields—at least modestly—for most farms. Yet rice farmers cannot practically implement improved management practices unless they can control their water enough to drain and fill fields when needed. The capacity of farmers to do so varies by irrigation district and farming system. Mitigating GHG emissions from rice therefore requires reasonably detailed engineering assessments, irrigation district by irrigation district. Yet to our knowledge no entity is responsible or funded for this task.

Similarly, as we described in Chapter 11 on sustainable intensification of livestock farming, several global studies have shown that beef and dairy systems around the world can greatly reduce their GHG emissions through more efficient feeding and grazing practices, reduced mortality, and improved fertility of pastureland. Yet actually encouraging these changes at the local level requires detailed understanding of the type and location of beef and dairy operations, how feeds are used, how feeds are produced, how cows are managed, and the economic and technical options for improvements. This information can form the basis for changes in infrastructure and new financial incentives to encourage improvements, but such innovations must be tailored to the locale and farm type.

These are just two examples of the type of detailed planning efforts that must occur to take advantage of technical opportunities to boost production and reduce emissions. Reducing land-use change emissions, improving the efficiency of fertilizer uptake

by crops, and improving the water- and land-use efficiency of aquaculture all require these kinds of detailed assessments to animate coordinated efforts. And, as planning moves forward, specific needs for new technologies are likely to become clear—such as a lack of knowledge of soils in a particular location or the lack of an appropriate grass or legume variety necessary to implement a promising grazing system. When a company develops a new product, a university develops a new educational initiative, or a health service addresses a particular public health challenge, they require coordinated planning efforts, technical assessments, and specific studies to address revealed information gaps. Mitigating agricultural emissions while boosting production will require the same type of coordinated effort.

Technical planning efforts may focus on a whole country or on a portion of a country. Based on our assessment of what is needed for detailed decisions on spending and other policies, technical plans should share the following characteristics:

- Start with detailed assessments of representative farm types sufficient to assess farm performance and opportunities.
- Include information about farms and land use that is both disaggregated to the local level and aggregated to the provincial and national levels.
- Assess land use and recent patterns of land-use changes using more detailed and reliable methods that can typically be undertaken at global levels.[207]
- Estimate GHG emissions using methods that are detailed enough to assess how they would change under promising changes in management.
- Include mechanisms for assessing the economics of these management changes, including benefits and costs to farmers and other actors.
- Organize information in easily accessible and understandable formats that allow analysis of improvement scenarios.
- Host online systems that incorporate changing and improved information.
- Integrate work of national and global researchers.

As international development institutions move to support climate-smart agriculture, the lack of funding for this kind of technical planning presents a major obstacle. For example, countries typically use World Bank agricultural loans exclusively for direct agricultural investments and aid. Countries must themselves cover the costs of administering the loans and any technical planning efforts. The World Bank and other funding institutions should develop systems to ensure that at least a small percentage of agricultural project costs support the planning and analytical work necessary to make agricultural plans truly climate-smart. Such systems could include dedicated grant funds or project/loan requirements to apportion, for example, 2–3 percent of funding for this kind of work.

Funding Needed for Breakthrough Technologies

The steady, incremental growth of crop and livestock yields, and recent improvements in input efficiency in developed countries, reflect the continuous development by researchers of a wide range of new seeds, new breeds, and new management techniques. As discussed previously, we assume continued incremental improvement in our 2050 baseline projections. We also call attention to many breeding opportunities to reduce environmental impacts.

In order to achieve a sustainable food future, the world's food system will need to develop and deploy a number of breakthrough technologies as well. Table 37-1 summarizes some of the innovations identified in this report.

These research efforts require dedicated and coordinated funding, directed with intelligence, just as funding institutions support multiyear efforts to cure specific diseases or to develop new energy technologies. Private sector research should be adequate in some areas; developing improved meat substitutes from plant-based ingredients is one such example. But the private sector is unlikely to devote serious funding to most of the items in Table 37-1 and will likely ignore them unless GHG emissions regulations, taxes, or strong financial incentives are in place to assure a market for innovative new products or techniques.

Additional, coordinated funding is therefore needed. In 2009, several governments agreed to form the Global Research Alliance for Agricultural Greenhouse Gas Mitigation precisely because of this need. New Zealand hosted the first meeting and provided much of the motivation, reflecting its commitment to reduce its emissions under the Kyoto Protocol and the fact that almost half of the country's GHG emissions come from agriculture. By 2017, 46 countries had joined, and the alliance now comprises a series of scientific working groups. Although on the right track, the alliance has limited resources. In the absence of additional resources, only limited coordination and development is possible. Another challenge is that in many countries, agricultural agencies are the primary agricultural researchers. Notwithstanding the strong motivations of the individuals involved, these agencies were historically established to promote agricultural production. It will take real effort to expand their missions to include GHG emissions mitigation.

The alliance provides a structure for international coordination but requires additional funds to effectively support the development and deployment of the kinds of breakthrough technologies listed in Table 37-1. In addition, research agencies with a broader mandate than agricultural research should become involved along with climate-focused institutions such as the Green Climate Fund, the World Bank, and international development agencies. International efforts should adopt good research grant-making procedures, such as professional administration and panels of outside scientists to review and rank proposals.

Table 37-1 | **Critical research needs for breakthrough technologies**

SELECTED MENU ITEM	RESEARCH NEED	COMMENT
DEMAND-SIDE SOLUTIONS		
Course 1: Reduce growth in demand for food and other agricultural products		
Reduce food loss and waste	Development of inexpensive methods to prevent decomposition without refrigeration	Companies are investigating a variety of compounds, such as spray-on films that inhibit bacterial growth and hold water in.
Shift to healthier and more sustainable diets	Development of inexpensive, plant-based products that mimic the taste, texture, and experience of consuming beef or milk	The private sector is making significant investments in various plant-based substitutes including imitation beef containing heme, which appears to bleed like real meat.

Table 37-1 | **Critical research needs for breakthrough technologies (continued)**

SELECTED MENU ITEM	RESEARCH NEED	COMMENT
SUPPLY-SIDE SOLUTIONS		
Course 2: Increase food production without expanding agricultural land		
Increase livestock and pasture productivity	Breeding of better, high-yielding forage grasses that can grow in "niche" production areas	In much of Africa and Asia, with limited land available, quality forage for cattle depends on producing high-quality grasses and legumes in restricted land areas, such as underneath forest or banana plantations.
Improve crop breeding to boost yields	Breeding of cereals to withstand higher peak temperatures	Recent research has shown that high peak temperatures, particularly at critical growth periods, can greatly restrict cereal yields, and that climate change may push temperatures to exceed peak thresholds.
Course 4: Increase fish supply		
Improve productivity and environmental performance of aquaculture	Development of fish oil substitutes from microalgae, macroalgae (seaweeds), or oil seeds for aquaculture feeds	Research groups have developed initial breeds of rapeseed containing oils nutritionally equivalent to fish oils and promising seaweed varieties. Work is also proceeding on more economical production of algae.
Course 5: Reduce GHG emissions from agricultural production		
Reduce enteric fermentation through new technologies	Finding feed compounds, drugs, or breeds that lower methane emissions from cows, sheep, and goats	Several research groups are working on feed compounds to reduce methane emissions. After years without promising results, a private company has claimed 30 percent emissions reductions from a cheap compound that does not appear to have significant impacts on animal health or environmental side effects.
Reduce emissions through improved manure management	Development of lower-cost ways to dry and consolidate manure, stabilize nutrients to reduce methane and nitrous oxide emissions, and make them easier to use efficiently with crops	Technologies exist to dry manure and turn it into energy, but costs and leakage rates reduce viability and GHG emissions reduction benefits.
Reduce emissions from manure left on pasture	Breeding of traits into pasture grasses to inhibit formation of nitrous oxide or developing safe, ingestible nitrification inhibitors for livestock	Researchers have discovered one variety of Brachiaria that significantly inhibits nitrification and thus nitrous oxide formation.
Reduce emissions from fertilizers by increasing nitrogen use efficiency	Development of more effective, lower-cost, and integrated compounds such as improved nitrification inhibitors to reduce nitrogen losses associated with fertilizer use and breeding nitrification inhibition into crops	Various compounds exist and appear to be effective but improvements should be possible, including more tailored understanding of which compounds are most effective under precisely which conditions. Researchers have now identified traits to inhibit nitrification biologically in some varieties of all major grain crops that can be built upon through breeding.
Adopt emissions-reducing rice management and varieties	Development of rice varieties that emit less methane	Researchers have shown that some common rice varieties emit less methane than others and have bred one experimental rice variety that reduces methane emissions by 30 percent under scientifically controlled conditions, although its effects on yields are unknown.

Note: This table is not intended to be exhaustive and does not include all courses or menu items.
Source: Authors.

ENDNOTES

1. World Bank (2008).
2. Collier (2008).
3. Farms of more than 500 ha, including pasture, controlled 63% of Brazilian farmland in 2013 but accounted for only 1% by number of Brazilian farms. Farms of more than 500 ha of cropland only accounted for 2% of all farms but generated 50% of production (de Souza Ferreira Filho and de Freitas Vian 2016).
4. Hazell et al. (2007).
5. Collier (2008).
6. World Bank (2008), 91, Figure 3.7.
7. Ser Huay Lee et al. (2014).
8. Lowder et al. (2016).
9. Chand et al. (2011).
10. Chand et al. (2011).
11. SAIN (2011).
12. Fan et al. (2008).
13. Deininger et al. (2011); Ali and Deininger (2014); Larson et al. (2014).
14. Holden and Otsuka (2014).
15. Hazell (2007).
16. Jayne et al. (2016).
17. Place (2009).
18. Chand et al. (2011); Jayne et al. (2016a).
19. Chand et al. (2011).
20. Lowder et al. (2016).
21. Lowder et al. (2016).
22. HLPE (2013).
23. World Bank (2008); Lowder et al. (2016), Table 3.
24. World Bank (2008); Lowder et al. (2016).
25. Jayne et al. (2016a).
26. Ji et al. (2016).
27. Hazell et al. (2007).
28. Hazell (2011).
29. Hazell et al. (2007); Poulton et al. (2010).
30. Harris and Orr (2014).
31. Waithaka et al. (2006).
32. Frelat et al. (2015).
33. Wiggins (2009).
34. World Bank (2008); Holden and Otsuka (2014).
35. World Bank (2008).
36. Borger (2008).
37. The International Institute for Environment and Development has done a large series of investigations and papers on land acquisitions, many of which can be found at http://www.iied.org/understanding-growing-pressures-land-land-grabbing-beyond.
38. Deininger et al. (2011).
39. Rulia et al. (2013), Table 1.
40. GRAIN (2016). GRAIN focused on an important subset of land deals that were initiated after 2006, have not been canceled, are led by foreign investors, are for the production of food crops, and involve large (> 500 ha) areas of land.
41. Information on acquisitions is being acquired by Land Matrix, a cooperative venture of many respected institutions. Members include the International Land Coalition, CIRAD, the Centre for Development and Environment of the University of BERN, GIGA, and GIZ.
42. Land Matrix database, accessed July 2016. This chart shows completed land acquisitions for agriculture. To meet criteria, deals involve land use for any purpose that must "entail a transfer of rights to use, control or ownership of land through sale, lease or concession; have been initiated since the year 2000; cover an area of 200 ha or more; imply the potential conversion of land from smallholder production, local community use or important ecosystem service provision to commercial use." See more at http://www.landmatrix.org/en/about/.
43. As one study explains, estimates vary substantially by research group, which may in part reflect the sources of information and kinds of transactions being counted, which may range from announcements in the press, to applications, to memoranda of agreements, to completed leases (Cotula et al. 2014).
44. Brautigam (2015).

45. According to the most recent figures in Land Matrix, Chinese interests acquired 437,000 ha in Africa. Land Matrix Online DataBase, accessed July 14, 2016.

46. Cotula et al. (2014).

47. Schönweger et al. (2012).

48. Many examples are described in Brautigam (2015); and Pearce (2012).

49. Pearce (2012); Cotula et al. (2014).

50. Cotula et al. (2014).

51. Cotula et al. (2014).

52. Farmland held by large-scale domestic owners is underreported, and anecdotal evidence suggests that national elites and the urban middle class are involved in land acquisitions in several African countries. See, for example, Cotula et al. (2009); Jayne et al. (2016a); Blas and Wallis (2009); and Koussoubé (2013).

53. The 17.3 million ha included 500 deals.

54. German et al. (2011).

55. Rosenbarger et al. (2013).

56. German et al. (2011).

57. Cotula et al. (2014); Pearce (2012).

58. Notess et al. (2018).

59. German et al. (2011); Cotula et al. (2014); Feed the Future (n.d.).

60. Land Matrix database, accessed July 2016.

61. Pearce (2012).

62. An image of land deals around the world is provided by Pearce (2012). For Indonesia, see Obidzinski et al. (2012). For Africa, see Cotula et al. (2014); and German et al. (2011). For Cambodia, see Colchester and Chao (2011).

63. Cotula et al. (2014).

64. Examples include descriptions of land acquisitions in Ethiopia in German et al. (2011).

65. For example, in the Gambella region of Ethiopia, where Saudi and Indian companies have cleared and drained thousands of hectares in part to grow food crops such as rice, maize, and sorghum, the goal of exporting down the Nile appears to have been important (Pearce 2012), 7.

66. German et al. (2010a); German et al. (2011).

67. Schönweger et al. (2012).

68. Schönweger et al. (2012).

69. Veit and Sarsfield (2017); Pearce (2012).

70. Pearce (2012), 55–63.

71. Neville (2015); McVeigh (2011).

72. German et al. (2010b).

73. German et al. (2011).

74. Global databases on land deals do not provide comprehensive summary statistics on existing land use, land cover, and land tenure. Where data are available, they do not clearly and consistently differentiate between cropland and less intensively used land. For example, a Land Matrix newsletter summarized data for September 2015 that covered 38.9 Mha, of which 26.3 Mha had no information on existing land use. Land use was known for deals covering 12.6 Mha, of which 4.2 Mha were former commercial (large-scale) agriculture, about 3.9 Mha were smallholder agriculture, 3.6 Mha were forestry, 0.6 Mha were for pastoralists, and 0.3 Mha were for conservation. Land cover data for these deals indicated 6.4 Mha of forest, 4.5 Mha of cropland, 2.6 Mha of shrubland/grassland, and 1.8 Mha of marginal land. Land cover data were not available for 23.5 Mha.

75. German et al. (2011).

76. Koh and Wilcove (2008).

77. Thomson Reuters Foundation (2017); Hemphill (2017).

78. Deininger et al. (2010); German et al. (2011a); Cotula (2011).

79. Schoneveld et al. (2010).

80. German et al. (2011).

81. German et al. (2010b).

82. German et al. (2010b).

83. Andriani et al. (2011).

84. Larsen et al. (2015). This short paper cites to the underlying studies.

85. Larsen et al. (2015).

86. Larsen et al. (2015); German et al. (2010a).

87. Butler (2009); Budidarsono (2012), 6.

88. There is no good dataset for the compensation typically provided to communities, but extensive contacts between WRI staff and local communities over the years indicate that payments do not approach these estimated oil palm values.

89. German et al. (2011).

90. German et al. (2011); FAO (2010a); FAO (2010b).

91. For further discussion on this report's criteria for a sustainable food future, see the first section of this report, "Scope of the Challenge and Menu of Potential Solutions."

92. Bellemare (2015).

93. For Africa, for example, see Kherallah et al. (2002).

94. As Key and Runsten (1999) noted, "Contract farming has also been critiqued as being a tool for agroindustrial firms to exploit an unequal power relationship with growers. While farmers usually enter into contracts voluntarily, they may, over time, invest fixed resources into production or alter their cropping patterns so as to become overly dependent on their contract crops. When this is the case, growers face limited exit options and reduced bargaining power vis-a-vis the firm and forced to accept less favorable terms."

95. This is a consistent finding of studies and summarized in Ton et al. (2018) among other meta-analyses.

96. Ton et al. (2018).

97. Ton et al. (2018). Minot and Sawyer (2016) found that contract-farming in developing countries improves farm productivity and incomes, with income effects mainly in the range of 25 to 75%. Otsuka et al. (2016) and Wang et al. (2014) also found income and productivity gains in meta-analyses of contract farming in both developed and developing countries. Bellemare and Novak (2017) found benefits for contract farming from six regions in Madagascar. For examples of the variety of experiences even in limited regions, Narayanan (2014) found high variability in the income effects of contract farming in Southern India although average benefits overall.

98. Bellemare (2015).

99. Maertens and Vande Velde (2017) found that benefits from an aid agency promoted effort to support contract farming in Benin. Ragasa and Kufoalor (2018), however, found that donor-supported efforts to promote agricultural intensification of maize in Ghana resulted in higher costs to farmers that were not fully justified by higher prices and production.

100. Minot and Sawyer (2016).

101. For papers on the effects of the Bolsa Família program, see Soares et al. (2006); Vaitsman and Paes-Sousa (2007); and Fernald et al. (2008).

102. For example, Todd et al. (2009) found that cash transfers enable small farmers to increase the diet diversity and nutritional quality of what they grew for themselves.

103. World Bank (2008).

104. World Bank (2008); Place (2009).

105. For China, see Jacoby et al. (2002). For Eastern Europe, see Rozelle and Swinnen (2004). For Latin America, see Deininger and Chamorro (2004); and Fort (2007). For Thailand, see Feder et al. (1988).

106. Place (2011).

107. See the discussion of Tanzania in Notess et al. (2018), 23, Box 3.

108. Peters (2009).

109. Lawry et al. (2014).

110. German et al. (2011).

111. Adedipe et al. (1997); Adekanye et al. (2009).

112. Byamugisha (2013), 1.

113. Veit (2011).

114. Place (2011), paraphrasing Van den Brink (2005).

115. Byamugisha (2013), 8.

116. Deininger et al. (2011); Bezabih and Holden (2010).

117. Marfo et al. (2012).

118. Nolte et al. (2013).

119. Ding et al. (2016).

120. For more on how carbon pricing works, see Kennedy et al. (2015).

121. IPCC (2003); INPE (2009).

122. Tollefson (2016).

123. New Zealand Government (2013).

124. New Zealand Government (2013).

125. A basic description of New Zealand's emission trading system is available at the website of Te Uru Radau at https://www.mpi.govt.nz/growing-and-harvesting/forestry/forestry-in-the-emissions-trading-scheme/ (last accessed August 15, 2018).

126. Examples include Koper (2014); and Parkhurt (2015).

127. De Pinto et al. (2010).

128. The CDM allows European companies responsible for cutting their emissions to obtain credit as an alternative for paying for actions in developing countries that cut their emissions. Only a few potential agricultural practices have qualified under CDM methodologies, mostly including managing of manure or wastes, or planting trees on agricultural land. As of 2011, one study found that agriculture or other land-use projects were expected to generate less than 1% of total CDM projects. Larson et al. (2012).

129. The Alberta system allows offset credits for changes in cropping systems, three ways of increasing feeding efficiencies, various efforts to reduce nitrous oxide, improvements in dairy cow efficiency, and capture of biogas from manure. Stockholm Environment Institute and Greenhouse Gas Management Institute (2011).

130. Vasa and Neuhoff (2011).

131. Haya (2009).

132. Searchinger, Edwards, Mulligan et al. (2015) showed that government models estimating greenhouse gas emissions reductions for grain-based biofuels are estimating large reductions in food consumption, which are the source of the greenhouse gas benefits through reduced breathing out and generation of wastes of carbon by people and livestock.

133. De Pinto et al. (2010).

134. FAO (2012c). This figure is an estimate of the total value of agricultural capital stock.

135. Lowder et al. (2012), Figure 2.

136. FAO (2012c), Figure 8.

137. World Bank (2008).

138. Analysis by the authors from OECD database on agricultural price support. OECD (2016).

139. According to the World Bank, total agricultural value added in 2015 was $3.175 trillion (World Bank 2017e).

140. Smith et al. (2017).

141. GAO (2003).

142. Claassen et al. (2004) estimated that the wetland programs had probably reduced wetland drainage based on the continued status as wetlands of several million acres that the study estimated were profitable to convert. Since that date, there have been no comparable studies offering estimates. USDA/ERS (2017b) also estimated that the erosion control provisions had achieved some reduction of water erosion, and possibly of wind erosion as well.

143. Hart et al. (2017). Farmers are required to follow crop diversification, but that only means they must grow two or three separate crops somewhere on their land. They are required also to devote 5% to ecological focus areas, but that can include any kind of cover crop grown on 5% of their land. Finally, national governments must protect 95% of existing grasslands, which may not result in any restrictions on individual farms.

144. Based on data from the OECD, the combination of funding from the European Union and member states for individual farm payments was roughly 61 billion euros per year in 2014–16, and the two combined provided 19 billion euros for rural development. See Searchinger et al. (2018b).

145. Searchinger et al. (2018b); Hart et al. (2017); Jongeneel et al. (2016); European Network for Rural Development (2017).

146. Huang et al. (2017).

147. Email communication with Jikun Huang, March 2017.

148. Hua et al. (2016) found that plantation forests reestablished in one province actually had less biodiversity value than the forests they replaced. For papers estimating soil carbon gains from the reforestation programs, see Persson et al. (2013); and Song et al. (2014). Anna et al. (2017) found that grassland rehabilitation programs had not consistently sequestered carbon.

149. World Bank (2008).

150. IFPRI (2013).

151. Gulati and Narayanan (2003); Gale (2013).

152. Li et al. (2014).

153. Fan et al. (2007); Morris et al. (2007).

154. Fan et al. (2008); Gulati and Narayanan (2003); Gale (2013).

155. Li et al. (2014).

156. See papers discussed in Jayne and Rashid (2013) finding that African farmers tend to apply fertilizer at rational rates given prices. For China, see Zhou et al. (2010).

157. Zhang et al. (2015b).

158. Gulati and Banerjee (2015).

159. GKTODAY (2012); Himanshu (2015).

160. Gulati and Banerjee (2015).

161. Qiu (2009).

162. See also AGRA (2013).

163. Morris et al. (2007).

164. World Bank (2008), Figure 6.2.

165. Morris et al. (2007) lists this as only one factor, but researchers since have given it an even heavier emphasis.

166. An excellent summary of experience with African fertilizer programs is set forth in Morris et al. (2007). See also Druilhe and Barreiro-Hurlé (2012); and Jayne and Rashid (2013).

167. Future Agricultures Consortium (2008).

168. Jayne and Rashid (2013).

169. Wanzala-Mlobela et al. (2013). Also see Morris et al. (2007).

170. Wanzala and Groot (2013); Lunduka et al. (2013).

171. World Bank (2008), 152.

172. Holden and Lunduka (2012).

173. Jayne and Rashid (2013).

174. A large number of studies are summarized in Jayne and Rashid (2013).

175. Jayne and Rashid (2013).

176. Druilhe and Barreiro-Hurlé (2012).

177. Pauw and Thurlow (2014).

178. Jayne and Rashid (2013).

179. Jayne and Rashid (2013).

180. World Bank (2008).

181. Druilhe and Barreiro-Hurlé (2012).

182. Ariga and Jayne (2011).

183. Morris et al. (2007).

184. Morris et al. (2007).

185. Ariga and Jayne (2011).

186. Druilhe and Barreiro-Hurlé (2012), Figure 1.

187. Ariga and Jayne (2011).

188. Morris et al. (2007), Table 4.7.

189. Druilhe and Barreiro-Hurlé (2012).

190. Kiprono and Matsumoto (2014).

191. IFDC (2013).

192. Bachewe et al. (2015).

193. Morris et al. (2007).

194. One summary of the whole region found a yield of 8 to 24 kg of maize for each kilogram of nitrogen. This estimate means that even if there were a linear relationship and yields responses were toward the high end of the response to nitrogen, an addition of 50 kg of nitrogen on a hectare would only raise yields by 1 ton. Those yield gains would be meaningful but far less than the response to nitrogen use in developed countries. In addition, in Malawi, the poorest households tend to obtain the lowest response, presumably because they have the poorest-quality land. See Ricker-Gilbert and Jayne (2012).

195. Jayne and Rashid (2013). For additional discussion of fertility problems, see Marenya and Barrett (2009a); Marenya and Barrett (2009b); and Giller and Tittonell (2013).

196. When economists analyze farmer willingness to apply fertilizer, they typically assume high discount rates, which means that farmers must anticipate high returns on investment to take the risk of purchasing fertilizer. See, for example, Druilhe and Barreiro-Hurlé (2012). Reducing the riskiness to farmers of these investments by reducing the consequences of crop failure should therefore increase farmer investments in fertilizer. See the discussion of risk and fertilizer use in Morris et al. (2007).

197. Andae (2015).

198. Roberts and Welkmans (2016).

199. Green Climate Fund (2017).

200. WRI (2016).

201. Beintema (2012). The most recent year that we found with available global figures is 2008.

202. This analysis is based on data provided by the Agricultural Science and Technology Indicators downloaded from the IFPRI website in March 2019. This analysis assumed $1 million of spending in Eritrea in 2011, the last year reported, continued in 2014. The omitted additional countries, which lacked reported data from 2001, contributed roughly an additional $90 million of spending in 2014, although the data do not allow assessment of how that changed from 2001.

203. Fuglie et al. (2011).

204. Fuglie et al. (2011), Table 1.1.

205. Alston et al. (2000).

206. Fuglie (2012).

207. The best way to assess land use change is to combine satellite images with use of more detailed aerial photographs, such as those available from Google Earth to verify the findings from satellite images.

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CHAPTER 38

CONCLUSIONS

The challenges of creating a sustainable food future, to some extent, are reflected and addressed in the concept of "climate-smart agriculture." Our menu defines our understanding of that concept, which is less a specific set of practices and more a quality that emerges from highly efficient use of natural resources, innovation in technology and management, and protection of natural lands at a national or landscape level.

Creating a sustainable food future—simultaneously feeding a more populous world, fostering development and poverty reduction, and mitigating climate change and other environmental damage—presents a set of deeply intertwined challenges. Our definition of a sustainable food future overlaps in large measure with the term "climate-smart agriculture" (CSA) but our report offers several insights that differ in direction or emphasis from much prior work (Box 38-1).

The challenge of sustainably feeding nearly 10 billion people by 2050 is substantially greater than commonly presented in land-use or climate mitigation analyses

- **Global challenge:** We believe that many studies to date have failed to take account of the full magnitude and interrelated nature of the challenges ahead. Climate estimates generally pay little attention to rising agricultural emissions and often improperly assume that land-use-change emissions will stop. Some agricultural analyses have overestimated the trends of yield gains because, for example, they base their estimates on compound growth rates. Others have simply assumed that other human activities can convert large areas of pasture or woody savannas without food, carbon, or significant biodiversity effects. But the world is on a course (on existing trend lines) to require more than 50 percent more food per year by 2050, which, in our baseline scenario, would be produced by converting hundreds of millions of hectares of land to agriculture and generating 33 percent more GHG emissions from agricultural production relative to our base year of 2010.

- **Shifts in locations of agricultural land:** Loss of carbon and biodiversity result not merely from net land expansion but also from shifts in agricultural land locations both between and within regions. This shifting adds greatly to the challenge and makes land-use restrictions or pricing of carbon consequences necessary.

BOX 38-1 | The Menu for a Sustainable Food Future and "Climate-Smart Agriculture" (CSA)

Since the term was coined around 2010, CSA has become an important goal of international institutions, such as the World Bank and FAO. FAO identifies three pillars of CSA: sustainably increasing agricultural productivity and incomes, adapting and building resilience to climate change, and reducing and/or removing GHG emissions. The overlap between this broad definition and the goals of this report is clear, which means that our report can help to define and identify priorities for CSA.

One school of thought, which we consider too restrictive, treats CSA as a set of specific practices, with a particular focus on those that build soil carbon. The original hope was that sequestering carbon in soils would provide a cheap method of reducing concentrations of carbon in the air, which factories and utilities might fund for carbon offsets. Measures such as mulching, agroforestry, and no-till farming would simultaneously mitigate climate change by removing carbon dioxide, boost output through the greater productivity of carbon-rich soils, and increase resilience to greater fluctuations in rainfall through the ability of carbon-rich soils to hold water longer.

As we discussed in Chapter 30, soil carbon sequestration in agricultural soils turns out to be far more difficult than previously thought, and several measures were more about moving carbon storage around than increasing total storage. The potential of soil carbon sequestration to mitigate other agricultural emissions is limited and is probably needed just to offset emissions not counted today from soil carbon loss. We believe that measures to build carbon in soils should be thought of not as easy climate mitigation or adaptation measures but rather as challenging yet valuable measures primarily to build agricultural productivity, with relatively modest direct climate mitigation through the carbon dioxide removed—but more potential climate benefits through the potential to reduce land conversion.

For these reasons, the menu items proposed in this report offer a broader set of strategies for climate-smart agriculture. They offer major synergies between productivity gains, greater resilience, and GHG mitigation. They support the goal of "produce, protect, and prosper." The core synergy lies in boosting efficiency in the use of land, animals, and inputs, which can raise agricultural incomes while reducing emissions and the demand for land. Yet because productivity gains can exacerbate shifting in locations of agricultural land, the synergy requires strong measures to prevent agricultural land expansion into natural ecosystems.

Because of this synergy—and even though some specific agricultural practices are necessary to mitigate production emissions, such as feed additives for enteric methane—low-emissions agriculture cannot just be one specific set of agricultural practices. Low-emissions agriculture can only emerge from a combination of strategies deployed at national or, at the least, landscape level.

- **Sub-Saharan Africa:** Sub-Saharan Africa presents a core challenge for a sustainable food future because of its low yields, high rates of malnutrition, rapid population growth, abundant opportunities to convert additional woody savannas and forests, and hundreds of millions of smallholder farmers. Improving the region's crop yields, focusing land expansion on the lowest-environmental-cost lands (above all by controlling the locations of road improvements), and accelerating progress in education and public health are all critical to success.

Productivity gains are critical

Under all scenarios, the growth in crop and pasture yields and other forms of agricultural productivity gains are the prime determinants of future emissions and land-use demands (although this fact can be obscured by the large productivity gains already assumed in baselines).

Productivity gains in land, animal, and chemical inputs already in our 2050 baseline are responsible for closing two-thirds of the GHG mitigation gap and more than 80 percent of the land gap that exist if we assume no improvements in efficiency or output relative to 2010 levels (our "no productivity gains after 2010" scenario). When adding in the various additional productivity gains required to meet our 4 gigaton/year GHG emissions target by 2050, the role of productivity gains must grow even larger. Productivity gains also provide the most important potential synergy between income, food security, and environmental goals.

- **Crops:** Replicating the large increases in chemical inputs and irrigation water associated with the Green Revolution is no longer possible or consistent with environmental goals. Fortunately, advances in molecular biology and related breeding technologies offer great potential for boosting productivity above trend lines—if research efforts receive sufficient financial support.
- **Pasture:** Every hectare of global pasture that is capable of and appropriate for sustainable intensification must be fully exploited to realize its potential to increase milk or meat output several times over.

Slowing the rate of growth in demand for food and other agricultural products is critical too

- **Food loss and waste:** Abundant technical opportunities exist to reduce food loss and waste. The deliberate reduction of food loss and waste, through action by governments, consumers, and food companies, is a newly emerging effort. At this time, it requires commitment, innovation, measurement, and then deployment of promising approaches.
- **Diets:** When properly factoring in the effects of diets on land use, dietary choices have far greater consequence for ecosystems and GHG emissions than typically estimated.
- **Bioenergy:** To date, the primary effect of public policy has been to make the challenge harder by increasing demand for bioenergy, based on mistaken GHG accounting. Because even a small amount of bioenergy from crops or feedstocks that make use of dedicated land requires a large amount of land, plans for more bioenergy could, alone, derail a sustainable food future.
- **Population:** Major economically and socially advantageous opportunities exist to hold down the growth in demand for agricultural products in sub-Saharan Africa. Key strategies are to increase educational opportunities for girls, increase access to reproductive health services, and reduce infant and child mortality. Realizing these opportunities will require major social and financial commitments.

Production of meat and milk from cattle, sheep, and goats needs to be a core focus of both demand-side strategies and productivity gains

- **Forage-based agriculture:** Demand for milk and meat from cattle, sheep, and goats is responsible for most projected future land-use expansion and roughly half of agricultural production emissions. No viable strategy for a sustainable food future exists that does not include huge increases in the efficiency of pasture- and forage-based agriculture and slower growth in demand for ruminant meat.

- **Ruminant meat consumption:** Analyses that have focused inappropriately on human-edible feeds only and have not fully factored in land-use consequences have sometimes masked the enormous role that ruminant meat consumption plays in agricultural land demand. A major effort to shift diets away from high levels of ruminant meat consumption is warranted by several factors. The environmental impacts of ruminant meat production are high, the number of people who consume large quantities of ruminant meats is relatively small, ruminant meats provide only 3 percent of calories and 12 percent of dietary protein even in the United States, and there is a historical precedent for shifting away from beef consumption in the United States and Europe.

Productivity gains must be explicitly linked to protection of carbon-rich ecosystems

- **Link "produce" and "protect":** Productivity gains by themselves cannot stop emissions and ecosystem degradation caused by shifts in the locations of agricultural land. Productivity gains will only solve the land-use challenge if countries simultaneously enforce protection of forests and savannas and—when some agricultural expansion is inevitable—use detailed, spatial plans to locate expansion in the areas with the lowest environmental opportunity costs.
- **Policy instruments:** Governments and private parties should explicitly link efforts to boost yields with ecosystem protection through financing, lending conditions, supply chain commitments, and public policies.
- **Road building:** New roads must be located in ways that minimize the incentives to convert natural areas to agriculture. The forest frontier should be closed to agriculture.

Reforestation of some lands, and restoration of peatlands, should proceed immediately, but larger-scale reforestation depends on technological innovation and changes in consumption patterns

- **Reforestation:** Important but limited opportunities exist today to reforest unproductive or abandoned agricultural lands with little improvement potential. However, the scale of reforestation necessary to fully achieve climate goals requires that more land be liberated from agriculture. Freeing up hundreds of millions of hectares of land can only be achieved through highly successful implementation of the measures proposed in our demand-reducing and productivity-boosting menu items (Courses 1 and 2).
- **Natural forests:** Because agricultural land tends to shift locations, programs that reforest abandoned land only with plantation forests will lead to steady declines in biodiversity and carbon stocks. More reforestation programs therefore need to focus on diverse, native species.
- **Peatlands:** Restoration of drained peatlands is a low-hanging fruit among climate mitigation options. Drained peatlands occupy perhaps 0.5 percent of total agricultural land but produce 2 percent of all human-generated GHG emissions, not merely those from agriculture.

Strategies should support rural livelihoods by helping farmers sell to markets, even as more farmers transition to urban jobs, but should not promote large land acquisitions.

- **Pushing large farms?** Pushing the replacement of small farms, particularly by supporting large acquisitions of communal land or land now farmed by small farmers, is not consistent with poverty reduction or environmental goals and is rarely helpful for productivity gains.

- **Focusing assistance for small farms:** Even so, subsistence agriculture offers poor prospects over the long term, and small farms in many parts of the world are dividing and becoming too small to allow households to avoid poverty without off-farm income. Policy should therefore encourage farming for markets, allow farms to consolidate "organically" through purchases and leases of land, create social welfare systems that reduce the risk inherent in farming for markets or specializing in cash crops, and otherwise support the inevitable shift toward off-farm incomes.

- **Appropriately formalizing property rights:** Formalizing property rights would probably be valuable in many parts of the world, and new geographic information systems make the effort less technically difficult. But the process can lead to greater inequity when controlled by powerful interests. Formalizing rights can even codify inequities such as limitations on property rights for women. Formalization should therefore proceed in ways that respect the variety of traditional uses, carefully safeguard equity, and modify traditional property approaches when necessary to rectify historic inequities.

Regulation and technological innovation will be essential to achieve the most ambitious levels of our menu items.

- **Regulation:** It is hard to reduce emissions and related environmental harms if efforts to reduce them are completely voluntary. Regulations must be crafted to spur innovation while allowing flexibility to develop cost-effective solutions. Regulations should apply mostly to manufacturers of agricultural inputs and to managers of concentrated livestock facilities.

- **Research and innovation:** Several types of innovations are necessary to close the food, land, and GHG emissions gaps. Many already exist but, despite their promise, receive minimal support today. Their further development requires large increases in public funding, which need to come from a variety of public agencies, not just traditional agricultural research agencies.

- **The "D" in R&D:** The actual deployment of low-emissions and productivity-enhancing technologies often requires the development of detailed plans, with regular monitoring and feedback. Today, most aspects of technological deployment receive only a fraction of the attention that is needed. Just as engineering costs are built into construction projects, development plans should be incorporated into virtually all agricultural development funding.

To summarize our conclusions, we believe that the challenge of sustainably feeding nearly 10 billion people by 2050 is greater than commonly appreciated.

Despite the many obstacles to be overcome, we believe that a sustainable food future is achievable. Our 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 benefits 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.

PHOTO CREDITS

Pg. 480 Aditya Basrur.

APPENDIX A. DESCRIPTION OF THE GLOBAGRI-WRR MODEL

Overview of the Model

The GlobAgri-WRR model is a global agriculture and land-use accounting model. It estimates changes in agricultural production, greenhouse gas (GHG) emissions, and land-use demands over time, which result both from changes in demand for agricultural products and changes in production techniques, yields, and systems. Changes in demand may result from changes in population, diets, nonfood uses of crops such as biofuels, and levels of food loss and waste. Changes in production may result from changes in crop yields, livestock efficiencies or a broad range of changes in agricultural production methods. GlobAgri-WRR's primary use is to estimate levels of land-use demand and GHG emissions at various points in the future, particularly 2050, and how various changes in demand or production methods might reduce those land-use requirements and emissions.

As an accounting model, the model estimates ultimate land-use requirements and emissions given a wide variety of parameters that are varied exogenously by the user or programmed into the model. For example, diets, populations, crop yields, nitrogen use efficiencies, and the intensity of livestock systems can all be varied, but the user must set exogenously to run the model for any particular scenario. The model is designed to answer questions such as what the changes will be in land-use requirements and total emissions, both from production methods and land use, if diets, populations, crop yields, and production systems in each country in 2050 follow certain estimates. It is therefore a means of estimating what set of demands and production systems would achieve environmental goals. In the course of doing so, the model also estimates many other parameters, such as nitrogen lost to the environment and changes in terrestrial carbon.

The initial drivers of the model are diets, population, and demand for nonfood agricultural products. The model is calibrated to match statistics from the Food and Agriculture Organization of the United Nations (FAO) for the reference year of 2010 using an average of 2009–11 to avoid overreliance on the results of a single year. These statistics include diets at the country level (set forth in FAO food balance sheets),[1] production, harvested area, cropland, and pasture. Food loss and waste rates are based primarily on a 2011 FAO study,[2] which GlobAgri-WRR adjusts to reflect estimates of processing and transformation losses in FAO food balance sheet data and thereby avoid any double-counting between the 2011 FAO study and the FAO food balance sheets.

The reference year inputs are disaggregated at the country level, including not just demands but the various coefficients that translate demand for agricultural products into production, inputs, and land use, such as levels of waste, calorie balances, and livestock production systems. When the model is "run," which involves solving for trade and some other interactions among countries, these levels are aggregated to a regional level both to avoid excess computation requirements and to smooth out possible data errors at the country level. When coefficients for parameters are missing at the country level, regional estimates are assigned to each country within the region.

Overall, the model can estimate how changes in population, diets, other crop demands, rates of losses and wastes, and/or production techniques within any one country will change production, emissions, and land-use demands regionally and globally. Table A-1 shows how the world's countries and territories are grouped into 11 regions in GlobAgri-WRR: Asia (except China and India), Brazil, China, European Union, Former Soviet Union, India, Latin America (except Brazil), Middle East and North Africa, Organisation for Economic Co-operation and Development (OECD, other countries), sub-Saharan Africa, and the United States and Canada. Because the regional disaggregation is fully flexible, it is also possible to use any individual country as a region, and in the standard operation of the model, Brazil, India, and China are both countries and regions.

At the country level, the model works with the 117 agricultural products that are a part of FAOSTAT commodity balance levels. For specific purposes, in particular trade and nitrogen balances, some products may be further disaggregated into finer agricultural products, which FAO calls supply and utilization account (SUA) commodities. For example, pulses are divided into separate types of beans, and the category of vegetables is divided into separate vegetable products. This further disaggregation is used to analyze trade because FAO reports trade in these products at more detailed levels, and to determine nitrogen contents of crops in order to estimate nitrogen surpluses. By contrast, some derived products are merged with the product they are derived from using energy equivalent quantities and after accounting for processing losses. For example, demand for a certain quantity of beer results in demand for barley with equivalent energy content after accounting for transformation losses.

Although these country-level products are used to calculate land-use demands, GHG emissions, inputs, and other factors, all interactions among countries occur at the regional level both to reduce processing time and to smooth out errors in data that may occur at the country level for some products. In addition, to limit processing time, the more detailed agricultural products are aggregated to 33 product aggregates at this regional level. Some of these aggregates remain as unique products, as is the case for wheat, maize, rice, soybeans, soybean oil, soybean cakes, beef, dairy, and eggs. Feed products not in commodity balances are also included at both the country and regional levels, most prominently grass. For the most part, country-level and commodity-balances parameters can be individually varied, allowing the model to compute model inputs using whatever detail is available at the country and detailed products level.

Table A-1 | Countries, territories, and regions in the GlobAgri-WRR model

COUNTRY OR TERRITORY	GLOBAGRI-WRR REGION
Afghanistan	Asia (except China and India)
Albania	OECD, other countries
Algeria	Middle East and North Africa
American Samoa	Asia (except China and India)
Andorra	OECD, other countries
Angola	Sub-Saharan Africa
Anguilla	Latin America (except Brazil)
Antarctica	Not classified
Antigua and Barbuda	Latin America (except Brazil)
Argentina	Latin America (except Brazil)
Armenia	Former Soviet Union
Aruba	Latin America (except Brazil)
Australia	OECD, other countries
Austria	European Union
Azerbaijan	Former Soviet Union
Bahamas	Latin America (except Brazil)
Bahrain	Middle East and North Africa
Bangladesh	Asia (except China and India)
Barbados	Latin America (except Brazil)
Belarus	Former Soviet Union
Belgium	European Union
Belize	Latin America (except Brazil)
Benin	Sub-Saharan Africa
Bermuda	OECD, other countries
Bhutan	Asia (except China and India)
Bolivia (Plurinational State of)	Latin America (except Brazil)
Bosnia and Herzegovina	OECD, other countries
Botswana	Sub-Saharan Africa
Brazil	Brazil
British Indian Ocean Territory	Not classified
British Virgin Islands	Latin America (except Brazil)
Brunei Darussalam	Middle East and North Africa
Bulgaria	European Union
Burkina Faso	Sub-Saharan Africa
Burundi	Sub-Saharan Africa
Cambodia	Asia (except China and India)
Cameroon	Sub-Saharan Africa
Canada	United States and Canada
Cape Verde	Sub-Saharan Africa
Cayman Islands	Latin America (except Brazil)
Central African Republic	Sub-Saharan Africa
Chad	Sub-Saharan Africa

COUNTRY OR TERRITORY	GLOBAGRI-WRR REGION
Channel Islands	European Union
Chile	Latin America (except Brazil)
China	China
Christmas Island	Not classified
Cocos (Keeling) Islands	Not classified
Colombia	Latin America (except Brazil)
Comoros	Sub-Saharan Africa
Congo	Sub-Saharan Africa
Cook Islands	Asia (except China and India)
Costa Rica	Latin America (except Brazil)
Côte d'Ivoire	Sub-Saharan Africa
Croatia	OECD, other countries
Cuba	Latin America (except Brazil)
Cyprus	European Union
Czech Republic	European Union
Democratic People's Republic of Korea	Asia (except China and India)
Democratic Republic of the Congo	Sub-Saharan Africa
Denmark	European Union
Djibouti	Sub-Saharan Africa
Dominica	Latin America (except Brazil)
Dominican Republic	Latin America (except Brazil)
Ecuador	Latin America (except Brazil)
Egypt	Middle East and North Africa
El Salvador	Latin America (except Brazil)
Equatorial Guinea	Sub-Saharan Africa
Eritrea	Sub-Saharan Africa
Estonia	European Union
Ethiopia	Sub-Saharan Africa
Falkland Islands (Malvinas)	Latin America (except Brazil)
Faroe Islands	OECD, other countries
Fiji	Asia (except China and India)
Finland	European Union
France	European Union
French Guiana	Latin America (except Brazil)
French Polynesia	Asia (except China and India)
French Southern and Antarctic Territories	Not classified
Gabon	Sub-Saharan Africa
Gambia	Sub-Saharan Africa
Georgia	Former Soviet Union
Germany	European Union

Table A-1 | Countries, territories, and regions in the GlobAgri-WRR model (continued)

COUNTRY OR TERRITORY	GLOBAGRI-WRR REGION
Ghana	Sub-Saharan Africa
Gibraltar	OECD, other countries
Greece	European Union
Greenland	OECD, other countries
Grenada	Latin America (except Brazil)
Guadeloupe	Latin America (except Brazil)
Guam	Asia (except China and India)
Guatemala	Latin America (except Brazil)
Guinea	Sub-Saharan Africa
Guinea-Bissau	Sub-Saharan Africa
Guyana	Latin America (except Brazil)
Haiti	Latin America (except Brazil)
Holy See	OECD, other countries
Honduras	Latin America (except Brazil)
Hungary	European Union
Iceland	OECD, other countries
India	India
Indonesia	Asia (except China and India)
Iran (Islamic Republic of)	Middle East and North Africa
Iraq	Middle East and North Africa
Ireland	European Union
Isle of Man	European Union
Israel	Middle East and North Africa
Italy	European Union
Jamaica	Latin America (except Brazil)
Japan	OECD, other countries
Jordan	Middle East and North Africa
Kazakhstan	Former Soviet Union
Kenya	Sub-Saharan Africa
Kiribati	Asia (except China and India)
Kuwait	Middle East and North Africa
Kyrgyzstan	Former Soviet Union
Lao People's Democratic Republic	Asia (except China and India)
Latvia	European Union
Lebanon	Middle East and North Africa
Lesotho	Sub-Saharan Africa
Liberia	Sub-Saharan Africa
Libya	Middle East and North Africa
Liechtenstein	OECD, other countries
Lithuania	European Union
Luxembourg	European Union

COUNTRY OR TERRITORY	GLOBAGRI-WRR REGION
Madagascar	Sub-Saharan Africa
Malawi	Sub-Saharan Africa
Malaysia	Asia (except China and India)
Maldives	Asia (except China and India)
Mali	Sub-Saharan Africa
Malta	European Union
Marshall Islands	Asia (except China and India)
Martinique	Latin America (except Brazil)
Mauritania	Sub-Saharan Africa
Mauritius	Sub-Saharan Africa
Mayotte	Sub-Saharan Africa
Mexico	Latin America (except Brazil)
Micronesia (Federated States of)	Asia (except China and India)
Monaco	OECD, other countries
Mongolia	Asia (except China and India)
Montenegro	OECD, other countries
Montserrat	Latin America (except Brazil)
Morocco	Middle East and North Africa
Mozambique	Sub-Saharan Africa
Myanmar	Asia (except China and India)
Namibia	Sub-Saharan Africa
Nauru	Asia (except China and India)
Nepal	Asia (except China and India)
Netherlands	European Union
Netherlands Antilles	Latin America (except Brazil)
New Caledonia	Asia (except China and India)
New Zealand	OECD, other countries
Nicaragua	Latin America (except Brazil)
Niger	Sub-Saharan Africa
Nigeria	Sub-Saharan Africa
Niue	Asia (except China and India)
Norfolk Island	Asia (except China and India)
Northern Mariana Islands	Asia (except China and India)
Norway	OECD, other countries
Occupied Palestinian Territory	Middle East and North Africa
Oman	Middle East and North Africa
Pacific Islands Trust Territory	Not classified
Pakistan	Asia (except China and India)
Palau	Asia (except China and India)
Panama	Latin America (except Brazil)
Papua New Guinea	Asia (except China and India)
Paraguay	Latin America (except Brazil)

Table A-1 | Countries, territories, and regions in the GlobAgri-WRR model (continued)

COUNTRY OR TERRITORY	GLOBAGRI-WRR REGION
Peru	Latin America (except Brazil)
Philippines	Asia (except China and India)
Pitcairn Islands	Not classified
Poland	European Union
Portugal	European Union
Puerto Rico	Latin America (except Brazil)
Qatar	Middle East and North Africa
Republic of Korea	Asia (except China and India)
Republic of Moldova	Former Soviet Union
Republic of North Macedonia	OECD, other countries
Réunion	Sub-Saharan Africa
Romania	European Union
Russian Federation	Former Soviet Union
Rwanda	Sub-Saharan Africa
Saint Helena	Sub-Saharan Africa
Saint Kitts and Nevis	Latin America (except Brazil)
Saint Lucia	Latin America (except Brazil)
Saint Pierre and Miquelon	OECD, other countries
Saint Vincent and the Grenadines	Latin America (except Brazil)
Samoa	Asia (except China and India)
San Marino	OECD, other countries
São Tomé and Príncipe	Sub-Saharan Africa
Saudi Arabia	Middle East and North Africa
Senegal	Sub-Saharan Africa
Serbia	OECD, other countries
Seychelles	Sub-Saharan Africa
Sierra Leone	Sub-Saharan Africa
Singapore	Asia (except China and India)
Slovakia	European Union
Slovenia	European Union
Solomon Islands	Asia (except China and India)
Somalia	Sub-Saharan Africa
South Africa	Sub-Saharan Africa
Spain	European Union
Sri Lanka	Asia (except China and India)
Sudan	Sub-Saharan Africa
Suriname	Latin America (except Brazil)
Svalbard and Jan Mayen Islands	OECD, other countries
Swaziland	Sub-Saharan Africa
Sweden	European Union
Switzerland	OECD, other countries
Syrian Arab Republic	Middle East and North Africa
Tajikistan	Former Soviet Union
Thailand	Asia (except China and India)
Timor-Leste	Asia (except China and India)
Togo	Sub-Saharan Africa
Tokelau	Asia (except China and India)
Tonga	Asia (except China and India)
Trinidad and Tobago	Latin America (except Brazil)
Tunisia	Middle East and North Africa
Turkey	Middle East and North Africa
Turkmenistan	Former Soviet Union
Turks and Caicos Islands	Latin America (except Brazil)
Tuvalu	Asia (except China and India)
Uganda	Sub-Saharan Africa
Ukraine	Former Soviet Union
United Arab Emirates	Middle East and North Africa
United Kingdom	European Union
United Republic of Tanzania	Sub-Saharan Africa
United States of America	United States and Canada
United States Virgin Islands	Latin America (except Brazil)
Uruguay	Latin America (except Brazil)
Uzbekistan	Former Soviet Union
Vanuatu	Asia (except China and India)
Venezuela (Bolivarian Republic of)	Latin America (except Brazil)
Viet Nam	Asia (except China and India)
Wake Island	Not classified
Wallis and Futuna Islands	Asia (except China and India)
Western Sahara	Middle East and North Africa
Yemen	Middle East and North Africa
Zambia	Sub-Saharan Africa
Zimbabwe	Sub-Saharan Africa

Note: The European Union comprised 27 member states in 2010, the base year used in the model.

Although the core of the model is an elaborate accounting system, the model incorporates results from a variety of submodels that use a range of biophysical processes to estimate emissions or the relationship of inputs to production. These models include the following, which are discussed in further detail below:

- **Land use:** A model to estimate the source of new agricultural lands by region and resulting GHG emissions from land-use change developed primarily by researchers at the European Commission's Joint Research Centre.
- **Livestock:** A model estimating representative production systems, feeds, and emissions at the regional level for beef, milk, sheep and goats, pork, chicken, and eggs developed primarily by researchers at the Commonwealth Scientific and Industrial Research Organisation and the International Institute for Applied Systems Analysis.
- **Aquaculture:** A model to separate aquaculture production by representative production systems within major producing countries or regions, and to estimate land-use demands, feed requirements, and emissions developed by WorldFish.
- **Rice:** A model to estimate GHG emissions from rice production developed primarily by a researcher at the Institute for Soil Science in Nanjing, China.
- **Nitrogen:** A model to estimate nitrogen demand and emissions by different crop types and country developed primarily by researchers at Princeton University.
- **Energy use:** Estimates of emissions from agricultural energy use developed by the U.S. Environmental Protection Agency and by FAO.

Categories of Agricultural Products

The model manages three types of agricultural products:

1. Primary vegetal products, such as wheat, soybeans, or grasses, are grown on land. Based on levels of demand, location or production, and yield, the demands for these products translate into demand for cropland and/or grazing land (and, based on production techniques, into GHG emissions). Demand for these products may be direct, or it may result from demand for transformed products, such as meat. At the regional level, the model aggregates the primary vegetable products into 15 categories of primary vegetal products based on commodity-balances products and three grass products.
2. Transformed products provide a second type of product demand, including vegetable oil, oilseed cakes (sometimes called meals) used for livestock, biofuels, alcohol, and various meats, milk, and eggs. Some of these products are in direct demand, such as the demand for meat and milk or vegetable oil. The demand for some others, such as oilseed cakes, which are used as an animal feed, derives from demand for other products, such as meats and milk, and may depend not only on their levels of demand but also on production systems specified in the model. For example, the amount of soybean cake required will depend not only on the quantity of various livestock products but also on the production systems specified for those products. There are 17 such products at the regional level.
3. The third type of agricultural product does not require land, directly or indirectly. It corresponds to aquatic plant, honey, game, and other such products but also to some livestock by-products, such as offal. These products play a small role, and when diets or livestock production systems call for such products, the model generates them without emissions or land-use costs.

The report refers to "animal-based foods" (and subcategories of such foods) extensively throughout Chapter 6—which are a combination of the second and third types of agricultural products noted above. See Figure A-1 for additional clarification about the different subcategories of animal-based foods modeled in this report.

In each case, the model also uses FAO data to relate calories available as food in each region and country to food quantities produced based on commodity-balance food products information included in food balance sheets. These coefficients vary by country because FAO estimates of the calorie content of final food products differ from country to country (mostly modestly but sometimes to a large degree) and because final products differ in quality and type (for example, the type of beef consumed). The calories-to-quantity coefficients must reflect these different calorie contents. For products that are the result of processing (e.g., alcohol), the relationship of production to consumption must also reflect losses during processing. We describe in more detail how those coefficients are calculated for processed products below.

Overall, one feature of this model that differs from most or all previous global agricultural models is the higher degree of disaggregation into both different food products and their transformed products. This makes it possible to analyze changes in more detailed diets.

Model Computational Structure

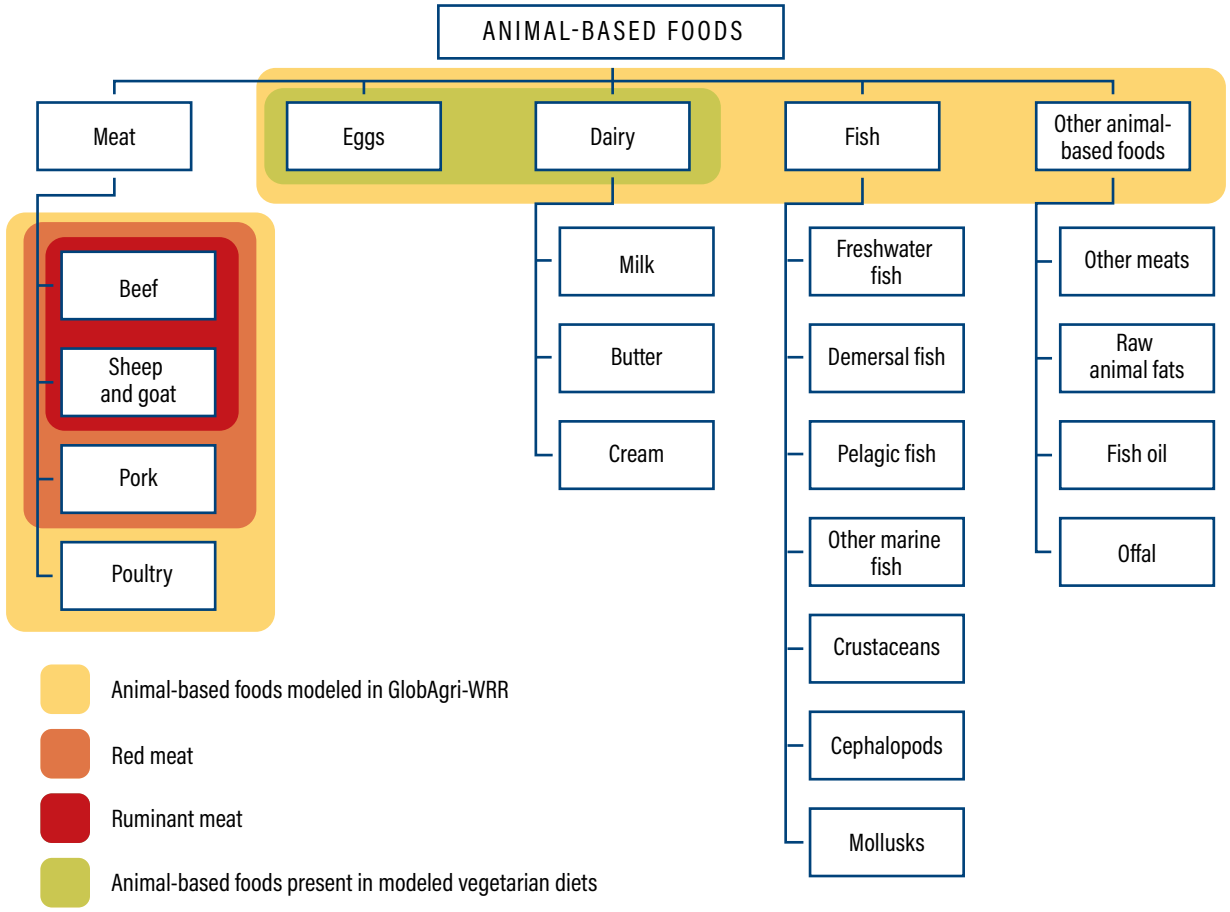
For the most part, the model works like a series of interlocked spreadsheets translating demand for all types of agricultural products into production in different countries and calculating the land use and other inputs required for that production and, from these inputs, the emissions generated during that production. In certain features, however, the model must resolve demand and supply through more complicated algorithms.

Trade

In the base year, imports and exports are specified by FAO data at the country level and aggregated to the regional level using FAO bilateral trade information to remove intraregional trade. From these data, each region's "dependence ratio" and "share in global gross exports" are calculated for each agricultural product. The dependence ratio is the ratio of a region's gross imports divided by the region's demand for domestic consumption. If a region has gross imports of 10 units and consumes 100 units of a product, its dependence ratio is therefore 10 percent. The "share in gross exports" is that country's share of global gross exports. If a country contributes 20 units of total gross exports of a product among all exporting countries, and the world's total trade of that product is 100 units, that country's share in gross exports is 20 percent.

In future scenarios, the baseline assumption preserves both the "dependence ratio" and the "share in gross exports." A region may both import some of the same product and export that product, in general because of different types or qualities of a crop or agricultural product. This system preserves both roles in global markets. To explore future scenarios, the model can be run with different trade shares and dependence ratios.

Figure A-1 | Animal-based foods are split into eight categories in the GlobAgri-WRR model



Note: Offal refers to the entrails and internal organs of an animal used as food. Demersal fish refers to fish living near the floor of a body of water. Pelagic fish refers to fish that exist in the pelagic zone of a body of water, which is neither close to the shore nor close to the bottom. Cephalopods refers to sea life with prominent heads and tentacles, such as squid and octopi.

Source: GlobAgri-WRR model and FAO (2019a).

Land Use

In some scenarios that the model could analyze, there are possibilities for increasing agricultural land-use demands within a country to levels in excess of available land. To avoid this scenario, when a country runs out of agricultural land, the model is programmed to cap production and to meet rising demand by changes in net imports. This cap would only become relevant for extremely high growth scenarios.

We also have special rules regarding dry grazing land. In general, the model assumes that the full range of global production systems meet milk or meat demands in the base year. However, we believe that all or virtually all dry grazing land available in a country is used today, so that increases in grassland areas must come from wetter systems (humid or temperate). We also believe that because dry grazing lands have little alternative use, they would continue to be used even if demand for milk or ruminant meat declined. We therefore program the model so that changes in supply of milk or ruminant meat do not come from increases or decreases in arid grazing systems and instead result in changes in humid and temperate production systems.

By-products, Processing Products, and Coproducts

We take diet consumption in the reference year from FAO commodity balances. FAO reports these data per country. These balance sheets cover a wide variety of products that are derived products, such as sugar and sweeteners, alcohol, vegetable oils and cakes, brans, milled rice, and milk and meats. In addition, some products may be joint products. For example, soybeans generate both soybean oil and cake, and producing milk will result in both milk and some meat production. It is possible to handle these transitions by translating all final products into primary product equivalents. For example, a kilogram of soybean oil can be transformed into a fraction of a kilogram of soybean crop that might correspond to its weight or calorie percentage. An advantage of this approach is that it limits the number of products, and also implicitly accounts for changes in coproduct shares when

demand changes. But a limitation of this approach is that the quantities of processed products may not be physically possible. For example, the percentages of soybean cake and soybean oil consumed may be different from the physical quantities actually produced by a given quantity of soybeans. In part because of the growing dietary importance of vegetable oil, which may come from multiple sources, we wished to have a model that was physically possible for those products. We also wanted to have primary equivalents for other products—namely, sugar and sweeteners, alcohols, and brans. The model therefore establishes rules so that production of a primary product is driven by its largest coproduct by energy value—for example, soybean cake in the case of soybean products. The quantity of soybean oil production is therefore established by the demand for soybean cake for animal feed.

Similarly, the FAO commodity balances show that many products (e.g., crops) are devoted to processing. The finished products that come out, such as alcohol, may derive from different combinations of primary products, such as different grains. During the processing, some product quantities are also lost or transformed into bran and some other products that are typically used for animal feed and that do not show up in food balance sheets. The commodity balances do not directly permit a mapping of processed products to primary products, and such a mapping is not straightforward. One challenge is that FAO estimates of calorie contents of food calories vary by region or country (e.g., a kilogram of beef will have different calories in one country compared to another because the types of beef products are considered to vary). Ultimately, consumed calories in the different product categories have to map consistently and plausibly to primary products, both produced domestically and imported.

Programming in GlobAgri-WRR is designed to address these challenges in a variety of ways. For derived products, such as raw sugar, sweeteners, alcohols, and brans that can be derived from diverse products, we first determine the relative contributions of different processed inputs. There could be more than one solution for the determination of a derived product source. For example, wheat and maize processed in alcohol and sweeteners may be combined in different ways. As one example, all the sweeteners may come from maize and the remaining processed maize could be used as alcohol, then processed wheat would be used to produce the remaining alcohol. However, many other combinations are possible. We use a minimization to find a unique solution by trying to keep the share of input product in derived product similar to the share of processed use in total processed uses for corresponding products. In the example above, if processed maize is twice as high as processed wheat, then two-thirds of alcohol and sweetener will come from maize and one-third from wheat. This calculation is done only for the reference year to set coefficients for the model in general.

Finally, for derived products set forth in use by FAO that are not explicit (brans, sugar, alcohols), we compute the transformation coefficients so that primary products and ultimate products are equivalent. For example, if diets report consumption of alcohol, and some of that alcohol is imported, these demands and imports are transformed into primary products both for calculating diets and imports.
All the computations described above concern commodity balances products and reference year balances and coefficients. Turning to the model resolution, for sugar, brans, and alcohols, all the demands for food and feed are translated into primary products demands, mostly cereals and sugar crops. The model resolution is therefore simple for those products.

For oil and cakes that are joint products of oil crops and meat and milk that are joint products of the dairy sector, a different approach must be used to assure physical consistencies for the reasons discussed above. In the case of oil crops except for oil palm fruit, the quantity demanded is based on the quantity of oilseed cakes required. The oil is treated as a by-product and is the first source of vegetable oil. If more vegetable oil is required, the model estimates that this supply will come from palm oil production because it is the cheapest source of global vegetable oil production. For this assumption to function, palm kernel cake and palm oil are considered to be produced independently so that palm oil demand can be met by increased oil palm production without increasing production of palm kernel cake. Similarly, the quantity of meat produced by the dairy sector depends entirely on the quantity of milk demand, with the meat treated as a coproduct. The remaining meat demand is filled by production systems for beef or small ruminant meat that produce only meat.

Aquaculture

In the case of aquaculture, the model determines feed available from fish (a composite of oil and meal) as a percentage of available wild fish consumption. Because the wild fish harvest has not grown for more than 20 years, we do not believe any additional wild fish consumption is possible and therefore cap the level of fish and fish feed at 2010 levels. We have rules to ensure that additional aquaculture production substitutes oilseeds for wild fish. (For some years, diversion of fish feed from other livestock products may serve as the direct source of additional aquaculture production, but that would require additional consumption of oilseeds by other livestock sectors with the same net result.)

Waste

FAO food balance sheet data provide a category of waste for uses of food, but the category is too small to account for all sources of waste. GlobAgri-WRR therefore incorporates estimates of waste for each product in each region from FAO (2011c). To avoid double-counting waste, we add "waste" in FAOSTAT back into the food available for consumption and then use loss and waste coefficients from FAO (2011c). Because FAOSTAT food balance sheets already assume transformation losses in food that goes through processing, we also do not include "processing and packaging" wastes estimated in FAO (2011c). "Postharvest handling and storage" losses going through local food systems are also accounted for. The result should be actual diets.

One of the issues with FAOSTAT and FAO (2011c) estimates of waste is that resulting actual diets appear likely to remain substantially higher than the calories people probably eat. As reported in Del Gobbo et al. (2015),[3] there is a large discrepancy between the calories FAO data imply that people actually consume even after adjusting for loss and waste estimates, and the calories that people claim to eat based on food surveys around the world. For example, U.S. Department of Agriculture (USDA) food surveys claim that people in the United States on average consumed 2,081 calories per day in 2009–10. By contrast, FAO food balance sheets, which are also based on USDA data, estimate food availability of 3,711 calories per person per day, which according to our calculations translates into 2,922 calories per person per day after adjusting for estimates of waste in the retail and consumer sectors. This difference is part of a broader set of discrepancies. For example, Del Gobbo et al. (2015) found that while the FAO balance sheets estimated much higher food availability than consumption for most foods, they typically underestimated reported consumption of beans and legumes and nuts and seeds.

These discrepancies lack a full explanation. They may represent overestimates of food available by FAO, but they may also reveal underestimates of food consumption by people responding to surveys. One possible explanation for the underestimate of nuts and beans is that FAO may be failing to count some home production or wild-gathered nuts and seeds. Another possibility is that the FAO (2011c) estimates of food losses and waste, as high as they are, underestimate actual food waste, particularly if they fail to count portions of products that many people don't ultimately consume but may not consider waste (such as the interior parts of vegetables, or the fattier parts of meat, that the affluent throw away). For purposes of GlobAgri-WRR, what is most important is that the land (and chemicals) used for agricultural production ultimately correspond properly to diets. If losses and wastes are higher than otherwise estimated in FAO (2011c) and consumption is lower, this relationship between land and inputs and diets will remain accurate. At this time, there is no alternative to using FAO data for this type of analysis.

Land-Use Requirements

The model specifies a production level for each crop and for livestock in each country based on demand and trade. Land area requirements for each crop are then based on specified yields and cropping intensities, which reflects the ratio of total cropland area to harvest. The model uses an average cropping intensity for all crops within a country. These figures are based on FAO data in the reference year. In future years, yields and cropping intensities can be specified as a model input.

For grazing area, the model computes a demand for grazing area forage from the livestock module and in the reference year, an average yield of forage per hectare of grazing land in each of several climate zones. Forage quantities from grazing land are based on the model used for Herrero et al. (2013), discussed below. Grazing areas per climate zone were based on an overlay of the zones as specified by FAOSTAT and maps of grazing area from Bouwman et al. (2006). The climate zones are arid, humid, and temperate within each country. For reasons discussed above, all growth and reductions in livestock grazing areas in future years are estimated to come from humid and temperate zones. Grass yields are therefore specific to those zones. For future years, the model permits specification of percentage changes in grassland yields. Increases in tons of grass consumed per hectare could result either from improved grass growth or more efficient grazing, and the model does not differentiate. (The livestock model also permits specification of improved livestock yields due to more efficient conversion of feed to meat and milk, but that improvement is made through the livestock module.)

Emissions

The model focuses on emissions up to the farm gate, including emissions involved in the production of farm inputs. Emissions from land-use change are also calculated separately and can be combined with production emissions.

Emissions are based on carbon dioxide, nitrous oxide, and methane (and do not include other pollutants such as black carbon and aerosols, or impacts on climate through tropospheric ozone or changes in albedo). In all cases, emissions are counted both in their actual gasses and using global warming potential (GWP) for 100 years. To calculate the GWP of 1 kg of methane, the model uses 34 kg of carbon dioxide equivalent based on the recommendations of the most recent comprehensive assessment of the Intergovernmental Panel on Climate Change (IPCC). These figures contrast with a GWP 100 of methane of 25 under the IPCC's 2006 national reporting guidelines, which most countries and international institutions still use. The GWP 100 of nitrous oxide is 298.

The model computes the following categories of GHG emissions in ways that incorporate several other models as follows:

Livestock emissions (enteric, manure management, and paddocks, range and pasture)

The model estimates both emissions from livestock and types and quantities of feed required using a representation of livestock systems used in Herrero et al. (2013). As part of that exercise, the authors separated the world's ruminant livestock systems into 27 regions, and in each region, into up to eight representative systems based on the Sere-Steinfeld livestock categorization system. Those systems are based on grazing-only systems, mixed systems (combining some grazing and some confined feeding), and "urban," which are entirely confined systems. Grazing and mixed systems were also grouped into arid, humid, and temperate zones, which include tropical highlands. Ruminant systems were also categorized as bovine dairy, bovine meat, small ruminant dairy (sheep and goats), or small ruminant meat. For each system, the team estimated average feed diets and dominant breeds used, and basic herd characteristics (such as fertility and mortality rates). The team then estimated production using the "ruminant model," which is a biophysical model developed by Herrero that simulates ruminant digestion, energy and protein uptake, and their translation through different cow breeds into live weight gain and milk production. The model is sensitive to the precise qualities of animal feeds. Using a number of convergence algorithms, the modelers adjusted the estimates to fit FAO data for livestock numbers, production, and animal feeds tracked by FAO.

The model calculates feed requirements in the following categories: crops, forage from grazing land, forage characterized as "occasional" (forage gathered by cut and carry systems or wastes from agricultural processing), and "stover" (crop residues). (The underlying model also uses types of stover and wastes.) Crops in turn are segregated into barley, corn, pulses, rice, sorghum and millet, soybeans, wheat, other cereals, other oil seeds, canola, and feed from animal products.

Running GlobAgri-WRR does not require running ruminant or the underlying herd model but instead incorporates these results based on the regions and production systems. For each production system, the model incorporates the estimates of feed requirements per kilogram of production and emissions generated per kilogram of production. For the reference year, the model allocates ruminant production in a country to the different systems in proportion to the regional distribution of livestock systems' grass demand estimated by Herrero et al. (2013) for the year 2000, using system-specific grassland areas in countries and regional system grassland yields. For monogastrics, the regional system production shares are used to split country production in the different systems. The quantity of production otherwise calculated by GlobAgri-WRR in a region or country, multiplied by share of a production system, and multiplied by either the feed requirements or GHG emissions per unit of production for that system generates the total feed requirements and emissions in total for that system. GlobAgri-WRR

then sums these feed requirements to the national or regional level, where they determine the production of feeds and trade. GlobAgri-WRR also sums the emissions to the global level.

The ruminant model embedded in this livestock system estimates both methane emissions and the nitrogen content of wastes. Based on system, the overall model estimates the portion of this nitrogen that is deposited on paddocks, range, and pasture (PRP) and the portion that is subject to a form of concentrated manure management. The model then uses Tier 1 coefficients from the IPCC 2006 national GHG reporting guidelines to estimate emissions from nitrous oxide associated with these nitrogen excretions. The ruminant model also estimates quantities of waste. The overlay model determines the manure management system for those systems that involve concentrated production of manure and uses Tier 1 IPCC emissions factors for that management system to estimate methane emissions.

The same paper also generates analyses for pork and poultry systems, divided between egg production and meat. Within each region, pork and poultry production are divided between intensive ("urban") and extensive ("other"). Only crop feeds are individually listed, as other feeds are considered to be wastes and residues of some unspecified type. The authors estimated waste management systems by region. Emissions are based on Tier 1 methods from the IPCC 2006 guidelines.

For future years, GlobAgri-WRR can be run through variations on these livestock systems by estimating changes in the mix of livestock systems within a region or by introducing improvements in livestock systems whose effects are separately estimated using the ruminant model and herd model to generate emissions and feed requirement estimates.

More details about the livestock model components, including a description of the ruminant model, are presented in the published online supplement to Herrero et al. (2013).

Rice methane emissions

Rice methane emissions are based on the model developed and presented in Yan et al. (2009) based on IPCC 2006 methods. According to these methods, rice production from irrigated fields is influenced by the length of period of flooding within the cultivation season, the flooding regime outside of the cultivation period, the types of soil amendments added (particularly crop residues), and whether the in-season flooding is continuous, interrupted once by a drawdown that allows oxygen to penetrate soils, or interrupted by multiple drawdowns. Yan et al. (2009) developed a spreadsheet model based on understanding of these conditions in the rice-growing countries, and which allows for changes in water management conditions and soil amendments. The model can produce average national estimated methane emissions for each hectare of rice production. GlobAgri-WRR incorporates these estimates for the baseline year based on the model per country. For future scenarios, the rice model can be run "off-line" to estimate changes in these average national emissions based on changes in management practices. Such changes can then be incorporated as part of mitigation scenarios.

For this process, we made one change to the version of the model used in Yan et al. (2009). The version for that model built in assumptions of very high levels of single and multiple drawdowns across the world's irrigated rice production based on figures provided in an Asian Development Bank report. These estimates seemed too high to the authors of the World Resources Report rice installment in Adhya et al. (2014). We adjusted these estimates so that one midseason drawdown is assumed to be common only in Japan, China, and South Korea (90 percent of irrigated production), and there is no meaningful rate of multiple drawdowns. In all other countries, only 10 percent of irrigated production is estimated to experience one midseason drawdown.

Nitrogen fertilizer use and nitrous oxide emissions

Nitrous oxide emissions from agricultural soils are a function of all nitrogen applied to soils whether from fertilizer, nitrogen applied in manure, nitrogen deposited on soils by grazing cows, nitrogen fixed or absorbed by crops and left in crop residues, or nitrogen deposition. For cropland and for the portion of nitrogen applied to pasture from fertilizer, the model is now programmed primarily to generate emissions using an IPCC Tier 1 emission factor for direct and indirect nitrous oxide emissions of 1.425 percent of applied nitrogen. An exception is that nitrogen for irrigated rice production is based on the IPCC emission factor of 0.3 percent, because of the extensive evidence that flooding reduces nitrous oxide emissions. The model can easily be run using alternative emissions coefficients. The model can also estimate nitrous oxide emissions based on nitrogen surplus (the excess of applied nitrogen over nitrogen removed in crops, according to a formula estimated by van Groenigen et al. 2010).

Total nitrogen application rates, including nitrogen from synthetic fertilizer, manure, biological nitrogen fixation, and nitrogen deposition, are based on a database presented in Zhang et al. (2015b) and described in its supplement. This database was developed using data from a variety of sources, with particular reliance on data sets established by the International Fertilizer Association (IFA) and FAO. The nitrogen database in Zhang et al. (2015b) provides estimates on nitrogen input rate from four different sources, namely fertilizer, manure, biological nitrogen fixation, and deposition, by country and crop type for the period 1961–2011. The database covers 153 crop types and over 190 countries, which account for more than 99 percent of the global total nitrogen input to cropland. The nitrogen fertilization rates are estimated based on reports by IFA and FAO on fertilization rates by country and crop types for recent years (namely, 2000, 2006, 2007, and 2010). Nitrogen deposition rates for each country and crop type are estimated based on maps of nitrogen deposition and crop distribution. The projected deposition rates in 2050 are estimated based on the projection in Bouwman et al. (2013) and the crop distribution map around year 2000. Nitrogen fixation rates by leguminous crops are estimated based on the crop type and yield following methodologies used in Van Grinsven et al. (2015).

In addition, this database provides information on nitrogen removed from cropland in the form of food product, and consequently the nitrogen use efficiency (NUE) by crop type and country (or region), which is defined as the ratio of nitrogen removed by harvested crops divided by total nitrogen inputs. Along with nitrogen inputs from other sources, fertilizer demand can be estimated over time as a function of NUE, crop production, and crop yields. By estimating changes in NUE, various potential mitigation options can be analyzed.

For nitrogen from manure, to ensure consistency with the livestock model and potential changes in livestock production, we replaced the manure estimates in Zhang et al. (2015b) with manure estimates from the livestock model adapted from Herrero et al. (2013). In addition, because nitrogen in crop residues is not explicitly accounted for, a coefficient is used that links nitrous oxide emissions from residues to other sources of nitrous oxide emissions based on FAOSTAT emissions data.

Energy Use

Energy use emissions come from two categories: energy used on farms to run machinery, and energy used to produce fertilizer and pesticide inputs. Emissions for energy use on farms are taken from FAOSTAT and are assigned within a country by hectare of harvested area. Emissions for pesticides are based on quantities of pesticides used by hectare and country using the same methodology as the U.S. Environmental Protection Agency (EPA) for a 2009 rulemaking for the Renewable Fuels Standard expressed in a worksheet included in the docket for a rulemaking published on March 26, 2010, titled EPA-HQ-OAR-2005-0161-3175.17.[4] The analysis also includes estimated emissions and quantities for the production of phosphorus, potash, and potassium, which are also estimated per hectare for each of 11 crop types using IFA data. For nitrogen use, the model uses the nitrogen model subcomponent to estimate quantities of synthetic nitrogen used and then estimated emissions factors associated with synthetic nitrogen synthesis from the EPA document.

Land-Use Emissions

Emissions from land-use change are based on a model developed by researchers at the European Commission Joint Research Centre (JRC), originally described in Hiederer et al. (2010). This land-use model estimates the quantity of GHG emissions that will be generated by land-use change for a specified quantity of hectares of a particular type of crop within a specific region. It does so by identifying existing croplands and areas devoted to specific crops (Ramankutty et al. 2008; Monfreda et al. 2008) and identifying potentially suitable land for each specific crop that is not in crop production from the GAEZ/FAO model, and then a variety of mapped products to identify different landscape types. After excluding land within a cell that is not suitable for production of a particular crop, the model then selects lands within a cell that are not cropland. In each cell with crops of any particular type, the assumption is that cropland expands into remaining ecosystem types in proportion to those types. This analysis is based on an assumption but grounded in extensive empirical evidence that agricultural expansion tends to work outward from existing agricultural areas.

Expansion of cropland results in levels of vegetation and soil carbon stocks falling from those found under natural vegetation to those found under cropping systems. To estimate carbon stocks, the model uses vegetative carbon stocks based on the IPCC 2006 default values for different ecosystems as synthesized in the guideline for the European Commission Directive on Renewable Energy (European Commission 2010). The IPCC provides values for a broader range of ecosystems than our five land-use categories.[5] The JRC model uses these different land-use categories to estimate carbon stocks and changes but groups changes into five broader land-use categories: open forest (less than 30 percent canopy cover), closed forest (30 percent to 100 percent canopy cover), scrubland (woody plants lower than 5 meters not having clear aspects of trees), grassland, and sparse vegetation. Soil carbon stocks within the top meter were estimated based on the Harmonized Soil and Water Database (version 1.1).[6] The GlobAgri-WRR model assumes that cropland conversion causes the loss of one quarter of soil carbon from the top meter, while conversion to grazing land does not alter soil carbon stocks.

In GlobAgri-WRR, the quantity of grazing land is dictated by demand for livestock and livestock systems. If the JRC model estimates that cropland would expand into grassland used for grazing, the area of grazing land would have to expand further. The JRC model can also be run to estimate land-use types converted for grazing. When the model estimates that cropland would expand on to grazing land, we therefore substitute for that grazing land a mix of land-use types that would be converted for expanded grazing. Because little of the world's true native grassland (as opposed to scrubland or woody savanna) is not already used for grazing, we assume that all grassland conversion for crops reduces grazing land and therefore triggers this second-order conversion to replace the grazing land. This second-order conversion comes from ecosystem types that the model estimates would supply new grazing land in proportions based on the cell-by-cell analysis, but those sources of potential grazing land are restricted by GlobAgri-WRR to scrublands, open forest, and closed forest on the grounds that existing native grazing land is already used.

These calculations result in average carbon emissions for each hectare of land expansion in each country for pasture or for each type of crop. The central features of GlobAgri-WRR use these estimated emissions rates per hectare if the model estimates a change in demand for a type of crop or pasture within a country. Although the precise rate of emissions per hectare varies for each run of the model, typical average conversion rates for global changes in diets are around 85 tons of carbon per hectare, including both vegetation and soil carbon. These average emission factors are slightly higher than the average emissions per hectare used by the U.S. EPA for biofuel regulations (for the 2017 case) of roughly 76 tons of carbon per hectare.[7] One likely reason is that the EPA analysis used an international model focused on cropland expansion, which did not require that all converted grazing land be replaced. As a result, substantial areas of relatively low-carbon grazing land could be converted to crops without any further conversion of higher-carbon forest and savanna. Under the accounting approach in GlobAgri-WRR, a reduction in grazing land due to crop conversion requires an increase in pasture area for the same level of production, and this pasture land requires a further conversion of savanna, scrubland, or open or closed forest. All net increases in agricultural land can therefore only come from these land covers. The EPA model also did not account for the high carbon losses associated with peatland conversion for palm oil production in Southeast Asia.

One challenge in calculating emissions from land-use change is that methods such as those employed by our model typically ignore the forgone carbon sequestration that would occur in forests, and some savannas and scrublands, if the land were not converted to agriculture. Carbon stock estimates are typically based on existing forests, not undisturbed forests. Many and probably most of the world's forests and woodland/savannas have been subject to forest harvest, whether for commercial production or firewood, and have depleted carbon levels. In satellite mapping systems, many lands that appear as savannas and open forest are actually abandoned agricultural lands regenerating with wood, or mixed-use landscapes. If not converted to cropland, some of these lands would increase their carbon stocks, and others might continue to be used but would contribute wood or even agricultural products that help meet human needs. If carbon stocks are taken as fixed, the model neither picks up this forgone sequestration or the loss of biomass for human uses that might be replaced elsewhere. Put another way, the full opportunity cost of converting this land is not captured. Data limitations frustrate attempts to estimate these costs more fully because regeneration and harvest rates are unknown. At this time, our model in this way underestimates the costs of land conversion. Many other assumptions are uncertain because of the uncertainties

about the precise lands that will be converted, soil carbon losses, and existing carbon stocks. However, GlobAgri-WRR can be easily run with adjustments to these carbon stocks to represent alternative scenarios.

Land-use conversion will also typically result in nitrous oxide emissions during decomposition of soil carbon, as well as nitrous oxide and methane emissions if fire is used for clearing. Although the JRC model estimates nitrous oxide emissions from soils in this way,[8] the estimated emissions are typically only around 2 percent of carbon losses, and we omit them here.

Aquaculture

Levels of aquaculture production, feed demand, and emissions are based on a study and model developed by WorldFish and described in Hall et al. (2011b). This study first characterized aquaculture production in all of the world's major aquaculture-producing countries (plus other regions where aquaculture rates are lower) by major fish type and into three levels of production systems: extensive, semi-intensive, and intensive. For each system, the modelers estimated direct land-use demands (ponds), chemical and feed inputs, production, and emissions from direct energy use. (WorldFish modelers also estimated indirect emissions and land-use requirements associated with feed production, but for use in GlobAgri-WRR, these quantities were stripped from the model to avoid double-counting, as GlobAgri-WRR estimates these emissions and land-use requirements directly given type and quantity of feed demand.) We aggregated fish production by country into commodity balance products based on the present mix, with associated average feed, direct land-use demands, and direct energy emissions (including chemical inputs). Using the WorldFish spreadsheet model, we developed alternative scenarios for future aquaculture production both in type of fish produced (allowing us to vary such factors as herbivores, omnivores, or carnivores), and changes in production methods. These scenarios, some of which are intended to explore mitigation techniques, are run "offline" and then fed into GlobAgri-WRR as alternative production and demand scenarios.

Because aquaculture has provided all increases in global fish consumption for more than two decades, the model assumes that all future fish consumption will come from aquaculture. Presently, the model is also programmed to assume that uses of wild fish meals and oils are constant to the 2010 base year, so that increases in aquaculture production will require oilseeds to replace fish meal and oil.

Biomass burning

At this time, GlobAgri-WRR model does not estimate emissions from biomass burning. Biomass burning typically attributed to agriculture falls into two categories: burning of savannas and grasslands for improved grazing, and burning of crop residues. We do not include the former because the extent to which human burning of grasslands and savannas increases methane and nitrous oxide above natural conditions of these fire-prone ecosystems remains unclear. Residue burning has not yet been incorporated into the model, but it is small.

Diets

To analyze diets in the reference year, GlobAgri-WRR generally adjusts diets provided by FAO food balance sheets after adjustment for wastes as specified in the papers describing the diets. For vegetarian diets in developed countries, there is little information available about what vegetarians actually consume. One exception is a set of surveys from 1993 to 1999 of vegetarians and vegans in the United Kingdom conducted by EPIC-Oxford. These data were the basis for an analysis of differential GHG emissions in Scarborough et al. (2014), which compared emissions from diets using analogous lifecycle calculations that included not just farmgate emissions, which are the focus of GlobAgri-WRR, but also processing, retailing, and consumption emissions. For the vegetarian analysis in GlobAgri-WRR, the authors of that study provided access to the dataset showing the reported intakes of each of 289 different foods for all 55,504 EPIC-Oxford participants. Those food items included final, processed food categories. We extracted the reported dietary intakes of each item by the vegetarians and vegans for both men and women and, using other data provided by the authors of that study, transformed the final food diets into calories of the types of foods analyzed by FAOSTAT. The resulting reported calorie consumption per person was significantly lower than that implicit in the FAOSTAT food balance sheets. That imbalance may occur because balance sheet diets, as discussed above, tend to be substantially more calorie-rich than self-reported diets whether by vegetarians or omnivores, but vegetarian calorie consumption may also be lower because vegetarians were likely a healthier subset of the UK population. To identify the benefits of vegetarian diets themselves rather than changes in calorie consumption, we rescaled vegetarian diets in each region in which we applied these diets (generally wealthier countries) to the average per capita calorie consumption.

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APPENDIX B. FINDINGS OF PREVIOUS STUDIES OF THE ENVIRONMENTAL CONSEQUENCES OF SHIFTING DIETS

Table B-1 summarizes papers that examine the implications of reducing meat and dairy consumption in diets. They have consistently found large reductions in land use and GHG emissions, although effects on water use can depend on the level of fruit, vegetable, and nut consumption. Because each of the studies discussed in this list uses a different approach, and because some include GHG emissions from food processing and retail and not merely production-related emissions at the farm, their results are not directly comparable to each other or to GlobAgri results.

The GlobAgri-WRR model builds on previous studies and addresses some of their limitations. Many other studies are based not on one consistent model but on average results from multiple lifecycle assessments performed by different researchers of different foods. This approach can introduce inconsistencies due to the widely varying methods and assumptions of different lifecycle assessments. Moreover, some modeling analyses, such as Eshel et al. (2014), focus only on one country. GlobAgri-WRR applies a single modeling approach to production of foods throughout the world. It is most similar in basic approach to Bajzelj et al. (2014) and Hedenus et al. (2014). A principal difference is that GlobAgri-WRR is substantially more disaggregated. It can therefore estimate, for example, not just broad global shifts in diets, but diet shifts only in regions where people consume large quantities of animal-based foods. It can also examine the regional consequences of these shifts and interactions with more possible changes in production methods.

Table B-1 | Summary of findings by previous studies examining the implications of shifting toward lower meat and dairy consumption

PREVIOUS STUDIES	SUMMARY OF FINDINGS
Eshel et al. (2009)	Found that the average U.S. diet (which includes animal-based foods) required 3–4 times as much land and 2–4 times as much nitrogen fertilizer as alternative vegan diets.
Stehfest et al. (2009)	Modeled a "healthy diet" scenario, based on recommendations by the Harvard Medical School for Public Health, that included reducing consumption of beef, poultry/eggs, and pork to 52%, 44%, and 35% of global projected consumption levels (respectively) in 2050. The scenario freed up enough existing agricultural land to allow substantial reforestation and sequestering of carbon, and reduced GHG mitigation costs by more than 50% for the period 2005–50.
Eshel et al. (2014)	Found that beef production requires 28 and 11 times more land and irrigation water, respectively, and produces 5 and 6 times more GHG emissions and reactive nitrogen impacts, respectively, than the average of the other livestock categories (dairy, poultry, pork, and eggs). The paper also found that these other livestock categories, in turn, involved 2 to 6 times more land, GHG emissions, and nitrogen impacts than staple plant-based foods, although irrigation requirements were comparable.
Bajzelj et al. (2014)	Examined the effects of shifting to "healthy diets" that reduce consumption of sugar, oil, meat, and dairy while increasing consumption of fruits and vegetables. Found that shifting to "healthy diets" reduced global cropland demand by 5%, pastureland demand by 25%, GHG emissions by 41%, and irrigation water demand by 3% relative to 2050 baseline projections.
Hedenus et al. (2014); Bryngelsson et al. (2016)	Found that reducing ruminant meat and dairy consumption—in addition to improving agricultural productivity and efficiency and reducing GHG emissions from fossil fuels and deforestation—is a necessary strategy to meet EU and global emissions targets to limit global warming to 2°C.
Scarborough et al. (2014)	Analyzed the GHG impacts of UK diets and found that vegetarian diets produce only two-thirds of the GHGs and vegan diets only produce one-half of the GHGs relative to the average UK diet.
Tilman and Clark (2014)	Predicted that global average per-capita dietary GHG emissions would increase by nearly one-third between 2009 and 2050 as incomes rise. Estimated that, relative to the projected 2050 global-average diet, per-capita dietary GHG emissions would be 30%, 45%, and 55% lower under Mediterranean, pescatarian (vegetarian diet with fish), and vegetarian diets, respectively.

PREVIOUS STUDIES	SUMMARY OF FINDINGS
Tyszler et al. (2014)	Modeled a diet for the Netherlands that both met nutritional requirements and lowered environmental impacts by reducing consumption of meat, cheese, and milk to 30%, 40%, and 84% (respectively) of the average Dutch diet, while raising consumption of fruits, vegetables, nuts, and seeds. The modeled diet provided a 38% reduction in GHG emissions and a 40% reduction in land use relative to the average Dutch diet.
Westhoek et al. (2014, 2015)	Predicted that halving consumption of meat, dairy, and eggs in the European Union would reduce nitrogen emissions by 40% and GHG emissions by 25–40%. Also predicted a 23% reduction in domestic cropland needed to feed each EU citizen.
Tom et al. (2015)	Found that shifting from the current U.S. diet to one that reduced overall caloric intake and also followed U.S. dietary guidelines actually increased energy use by 38%, blue water footprint by 10%, and GHG emissions by 6%. However, the scenario modeled included not only a 25% decrease in meat consumption but also a 78% increase in dairy consumption—leading to an overall 13% increase in animal-based food consumption.
Springmann, Godfray, et al. (2016a)	Found that transitioning to more plant-based diets in line with standard dietary guidelines could reduce food-related GHG emissions by 29–70%, relative to a reference scenario in 2050, along with health and economic benefits.
Erb et al. (2016)	Found that many options exist to meet the global food supply in 2050 without further deforestation, even at low crop-yield levels—including all scenarios with a fully vegan world population, and 94% of scenarios with a fully vegetarian population.
Springmann et al. (2018); Willett et al. (2019)	Found that a "healthy reference" diet reduced GHG emissions from agricultural production by roughly half (relative to 2050 business as usual), although cropland use and blue water use remained similar to business as usual.

ENDNOTES

1. FAO (2019a).
2. FAO (2011c).
3. Del Gobbo et al. (2015) provides a comparison of national estimates implied by FAOSTAT and a separate Global Dietary Database. Although this paper does a great service by compiling data on food surveys and analyzing differences with FAO, the authors did not adjust FAO food availability for estimated losses and waste in households and at the retail level. As a result, the size of the discrepancies the paper discusses are higher than those implied by the FAO data and estimates of losses and waste, but our analysis indicates that the discrepancies remain even after adjusting for estimates of retail and household losses and waste.
4. The guide to the rulemaking can be found at https://www.epa.gov/renewable-fuel-standard-program/renewable-fuel-standard-rfs2-program-amendments-2010.
5. We corrected one element of the directive carbon stock estimates, which were those for open forest. As discussed in Carré et al. (2010), vegetative soil carbon estimates were based on an assumption that an open forest would have vegetative carbon stocks relative to closed forests in proportion to their canopy cover (e.g., that a forest with 20% canopy cover would hold 20% of the vegetation of a closed forest). This calculation incorrectly assumes that closed forests all have 100% canopy cover, while closed forest carbon stocks are estimated for forests with between 30% and 100% canopy cover. The result was open forest carbon estimates far lower than those estimated by others. To correct this figure, we increased the carbon content of closed forests by 50%, which is probably still conservative as it left our figures for open forests lower than those estimated in Gibbs et al. (2008) (supplement) for average open forests using IPCC methodology.
6. FAO/IIASA/ISRIC/ISSCAS/JRC Harmonized World Soil Database (version 1.1), http://www.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML.
7. Plevin et al. (2010).
8. Carré et al. (2010).

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ACKNOWLEDGMENTS

We are pleased to acknowledge our institutional strategic partners, who provide core funding to WRI: Netherlands Ministry of Foreign Affairs, Royal Danish Ministry of Foreign Affairs, and Swedish International Development Cooperation Agency.

The authors are grateful to the following peers who provided critical reviews and helpful suggestions to this report: Mitch Aide (University of Puerto Rico), Gary Atlin (Bill and Melinda Gates Foundation), Tobias Baedeker (World Bank), Erin Biehl (Johns Hopkins University Center for a Livable Future—JHU-CLF), Robert Boddey (Embrapa), Randall Brummett (World Bank), Rebecca Carter (WRI), Tim Christophersen (UNEP), Ed Davey (WRI), Chris Delgado (WRI), Adriana Dinu (UNDP), Natalie Elwell (WRI), Karlheinz Erb (Universität für Bodenkultur Wien), Jamison Ervin (UNDP), Roger Freedman (2Blades Foundation), Halley Froehlich (University of California, Santa Barbara), James Gaffney (DuPont), Tess Geers (Oceana), Laura German (University of Georgia), Charles Godfray (Oxford Martin Programme on the Future of Food), Patricio Grassini (University of Nebraska), Hidayah Hamzah (WRI), Nancy Harris (WRI), Mario Herrero (Commonwealth Scientific and Industrial Research Organisation), Jillian Holzer (WRI), Lisa Johnston (WRI), Doyle Karr (DuPont), Kelly Levin (WRI), David Lobell (Stanford Center on Food Security and the Environment), James Lomax (UN Environment), Jared Messinger (WRI), Charles McNeill (UNEP), Joseph Monfort (DuPont), James Mulligan (WRI), Carlos Nobre (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior), Lily Odarno (WRI), Mark Peterson (DuPont), Michael Phillips (WorldFish), Frank Place (International Food Policy Research Institute), David Powlson (Rothamsted Research), Becky Ramsing (JHU-CLF), Raychel Santo (JHU-CLF), Frances Seymour (WRI), Fred Stolle (WRI), Guntur Subbarao (Japan International Research Center for Agricultural Sciences), Rod Taylor (WRI), Philip Thornton (International Livestock Research Institute), Robert Townsend (World Bank), Peter Veit (WRI), Sara Walker (WRI), Arief Wijaya (WRI), Stefan Wirsenius (Chalmers University of Technology), Christy Wright (DuPont), Graham Wynne (WRI), and Edoardo Zandri (UNEP).

The authors extend a special thanks to Nikos Alexandratos (FAO) and Jelle Bruinsma (FAO), who were generous in providing information and guidance about the FAO agricultural projections to 2050; Michael Obersteiner (IIASA), who provided information about the GLOBIOM model; Tom Kram Fam (Netherlands Environmental Assessment Agency), who provided information for analyzing the IMAGE model results, and Benjamin Bodirsky (Potsdam Institute for Climate Research) for his thorough review of the GlobAgri-WRR model.

The authors thank all the peer reviewers who provided critical reviews and helpful suggestions for improvement to each of the 11 working papers that underpin much of this report. They include:

- *The Great Balancing Act (Installment 1):* Philip Angell (WRI emeritus), Mary Allen Ballo (SahelEco), Manish Bapna (WRI), Malcolm Beveridge (WorldFish), Randall Brummett (World Bank), Peter Dewees (World Bank), Francis Gassert (WRI), Daniel van Gilst (Norad), Debbie Hellums (International Fertilizer Development Center), Bente Herstad (Norad), Kelly Levin (WRI), Mike McGahuey (USAID), Jennifer Morgan (WRI), Michael Phillips (WorldFish), Chris Reij (WRI and VU), Tony Rinaudo (World Vision), Sara Scherr (EcoAgriculture Partners), Jane Swira (Ministry of Environment and Climate Change, Malawi), Juergen Voegele (World Bank), Peter Weston (World Vision), and additional anonymous reviewers at UNDP.
- *Reducing Food Loss and Waste (Installment 2):* Mark Barthel (WRAP), Camelia Bucatariu (FAO), Betty Bugusu (Purdue University), Stamatios Christopolous (UNDP), Laura Draucker (WRI), George Gordon (Tesco), Estelle Herszenhorn (WRAP), Jess Lowenberg-DeBoer (Purdue University), Emma Marsh (WRAP), and Robert van Otterdijk (FAO).
- *Achieving Replacement Level Fertility (Installment 3):* Athena Ballesteros (WRI), Mary Allen Ballo (SahelEco, Mali), Manish Bapna (WRI), Terry Brncic (WRI), Jason Bremner (Population Reference Bureau), Daniel van Gilst (Norad), Norbert Henninger (WRI), Mary Kent (formerly with Population Reference Bureau), Shelley Snyder (USAID), Jane Swira (Ministry of Environment and Climate Change, Malawi), and one anonymous reviewer.
- *Improving Land and Water Management (Installment 4):* Jens Aune (Norwegian University of Life Sciences), William Critchley (Sustainable Land Management Associates, Ltd.), Craig Hanson (WRI), Norbert Henninger (WRI), Rattan Lal (Ohio State University), Tim Searchinger (WRI and Princeton), Melinda Smale (Michigan State University), and Peter Veit (WRI).
- *Improving Productivity and Environmental Performance of Aquaculture (Installment 5):* Dalal Al-Abdulrazzak (UNDP), Lauretta Burke (WRI), George Chamberlain (Global Aquaculture Alliance), Christopher Delgado (WRI), Stephen Hall (WorldFish), Craig Hanson (WRI), Andrew Hudson (UNDP), Melanie King (Global Change Institute, University of Queensland), David Little (Institute of Aquaculture, University of Stirling), Aaron McNevin (WWF), Tim Searchinger (WRI and Princeton), Mark Spalding (The Ocean Foundation), David Tomberlin (WRI), and Hua Wen (WRI). Special thanks go to Markus Klinger (DuPont Nutrition & Health) for contributing research and writing assistance on fish oil alternatives, nutrient content of wild and farmed fish, and integrated multitrophic aquaculture.
- *Indicators of Sustainable Agriculture: A Scoping Analysis (Installment 6):* Lauretta Burke (WRI), Daryl Ditz (WRI), Francis Gassert (WRI), Angel Hsu (Yale University), Mike McGahuey (USAID), Lars Christian Oxe (Danish Ministry of Foreign Affairs), Stephen Russell (WRI), Johann Scharr (WRI), Tim Searchinger (WRI and Princeton), David Spielman (International Food Policy Research Institute), Richard Waite (WRI), and Robert Winterbottom (WRI).
- *Crop Breeding: Renewing the Global Commitment (Installment 7):* Nourollah Ahmadi (INRA), Jean-Marc Bouvet (CIRAD), Keith Fuglie (U.S. Department of Agriculture), Jean-Christophe Glaszmann (CIRAD), Charles Godfrey (Oxford University), Janet Ranganathan (WRI), Richard Waite (WRI), and Robert Winterbottom (WRI).

- *Wetting and Drying: Reducing Greenhouse Gas Emissions and Saving Water from Rice Production (Installment 8):* To Phuc Tuong (International Rice Research Institute), Chris van Kessel (University of California at Davis), Ben Macdonald (Commonwealth Scientific and Industrial Research Organization), Christopher Delgado (WRI), Craig Hanson (WRI), and Richard Waite (WRI).

- *Avoiding Bioenergy Competition for Food Crops and Land (Installment 9):* Manish Bapna (WRI), Craig Hanson (WRI), Nancy Harris (WRI), Dario Hidalgo (WRI), Charles Kent (WRI), Brian Lipinski (WRI), Chris Malins (International Council on Clean Transportation), Alex Perera (WRI), Janet Ranganathan (WRI), John Sheehan (Colorado State University), Robert Winterbottom (WRI), and one anonymous reviewer.

- *Limiting Crop Expansion to Lands with Low Environmental Opportunity Costs (Installment 10):* Ezra Berkhout (PBL Netherlands Environmental Assessment Agency), Ben ten Brink (PBL Netherlands Environmental Assessment Agency), Chris Delgado (WRI), Eric Dinerstein (Resolv), Jenny Goldstein (University of California, Los Angeles), Nancy Harris (WRI), Lisa Johnston (WRI), Agnieszka Latawiec (International Institute for Sustainability-Brazil), Denise Leung (WRI), Brian Lipinski (WRI), David McLaughlin (WWF), Moray McLeish (Price Waterhouse Coopers-Indonesia), Aurelio Padovezi (WRI-Brasil), Anne Rosenbarger (WRI-Indonesia), Nirarta Samadhi (WRI-Indonesia), Fred Stolle (WRI), Bernardo Strassburg (International Institute for Sustainability-Brazil), Carl Wahl (Concern Worldwide), Richard Waite (WRI), Peter Veit (WRI), and Robert Winterbottom (WRI).

- *Shifting Diets (Installment 11):* Neal Barnard (Physicians Committee for Responsible Medicine), Rachel Biderman (WRI), Benjamin Leon Bodirsky (Potsdam Institute for Climate Impact Research), T. Colin Campbell (Cornell University), Christopher Delgado (WRI), Tara Garnett (Food Climate Research Network, University of Oxford), Craig Hanson (WRI), Susan Levin (Physicians Committee for Responsible Medicine), Jacqui Macalister (IKEA Food Services AB), Joanne Lupton (Texas A&M University), Charles McNeill (UNDP), Miriam Nelson (Friedman School of Nutrition Science and Policy, Tufts University), Barry Popkin (Nutrition Transition Research Program, University of North Carolina, Chapel Hill), Matthew Prescott (Humane Society of the United States), Anne Roulin (Nestlé), Ryan Sarsfield (WRI), William Hua Wen (WRI), Deborah Zabarenko (WRI), and Li Zhou (Chinese Academy of Social Sciences).

In addition, the authors thank several WRI colleagues who provided research, data, analysis, and editing services in support of this report: Abraar Ahmad, Austin Clowes, Ayesha Dinshaw, Tyler Ferdinand, Rutger Hofste, Tara Mahon, Cecelia Mercer, Gerard Pozzi, Yangshengjing Qiu, Paul Reig, and Anna Spiller. We thank our colleague Liz Goldman for preparing several of the maps in the report.

Creating a Sustainable Food Future: Interim Findings underpins many portions of this report. The authors would like to extend their gratitude to those who helped make the *Interim Findings* a stronger publication:

- The following members of the Creating a Sustainable Food Future's technical advisory group provided valuable suggestions, reviews, and other contributions: Tapan Adhya (Kalinga Institute of Technology), Ken Cassman (University of Nebraska), Julian Chara (CIPAV), Cyprian Ebong (Rwanda Agricultural Research Board), Charles Godfray (Oxford University), Peter Grace (University of Queensland), Mario Herrero (CSIRO), Chris van Kessel (University of California at Davis), Xeujuan Liu (China Agricultural University), Alexandre Meybeck (FAO), Charles McNeill (UNDP), Michael Peters (CIAT), David Powlson (Rothamsted Research), Pete Smith (University of Aberdeen), Bernardo Strassburg (Instituto Internacional para Sustentabilidade), and Xiouyuan Yan (China Institute for Soil Science).

- Reviewers and data providers include: Walid Ali (UNDP), Philip Angell (WRI emeritus), Mary Allen Ballo (SahelEco), Manish Bapna (WRI), Malcolm Beveridge (WorldFish), Randall Brummett (World Bank), Stamatios Christopoulous (UNDP), Joseph Corcoran (UNDP), Chris Delgado (World Bank), Peter Dewees (World Bank), Joao Fernando (UNDP), Daniel van Gilst (Norad), Debbie Hellums (International Fertilizer Development Center), Bente Herstad (Norad), Alioune Badara Kaere (UNDP), Dearbhla Keegan (UNDP), Carola Kenngott (UNDP), Markus Klinger (DuPont Nutrition & Health), Kelly Levin (WRI), Chris Malins (Cerulogy), Mike McGahuey (USAID), Marc Metian (Stockholm Resilience Centre), Jennifer Morgan (WRI), Eija Pehu (World Bank), Michael Phillips (WorldFish), Chris Reij (WRI and VU), Nick Remple (UNDP), Tony Rinaudo (World Vision), Marc Sadler (World Bank), Sara Scherr (EcoAgriculture Partners), Mark Spalding (The Ocean Foundation), Jane Swira (Ministry of Environment and Climate Change, Malawi), Albert Tacon (Aquatic Farms Ltd.), Robert Townsend (World Bank), Pia Treichel (UNDP), Stefania Vannuccini (FAO), Juergen Voegele (World Bank), Peter Weston (World Vision), and additional anonymous reviewers at UNDP.

This report was improved by the careful review of its framing and argumentation by Emily Matthews, Daryl Ditz, Laura Malaguzzi Valeri, and Liz Goodwin. The report was shepherded through the publication process by WRI's experienced publications team, particularly Emily Matthews and Maria Hart. We thank Alex Martin and Bob Livernash for their careful copyediting and LSF Editorial for proofreading. We thank Carni Klirs for report design and layout. In addition, we thank Bill Dugan, Billie Kanfer, Julie Moretti, Sarah Parsons, Romain Warnault, and Lauren Zelin, for additional design, strategy, and editorial support.

WRI is deeply grateful for the generous financial support for this report—and for the series of working papers underlying this report—from the Norwegian Ministry of Foreign Affairs, the United Nations Development Programme, the United Nations Environment Programme, the World Bank, and the institutional strategic partners listed above. In addition, we would like to thank the Bill & Melinda Gates Foundation for supporting background research on the "improving soil and water management" menu item. Thank you for your generous and patient support.

This report represents the views of the authors alone. It does not necessarily represent the views of the World Resources Report's funders.

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Natural resources are at the foundation of economic opportunity and human well-being. But today, we are depleting Earth's resources at rates that are not sustainable, endangering economies and people's lives. People depend on clean water, fertile land, healthy forests, and a stable climate. Livable cities and clean energy are essential for a sustainable planet. We must address these urgent, global challenges this decade.

Our Vision
We envision an equitable and prosperous planet driven by the wise management of natural resources. We aspire to create a world where the actions of government, business, and communities combine to eliminate poverty and sustain the natural environment for all people.

Our Approach

COUNT IT
We start with data. We conduct independent research and draw on the latest technology to develop new insights and recommendations. Our rigorous analysis identifies risks, unveils opportunities, and informs smart strategies. We focus our efforts on influential and emerging economies where the future of sustainability will be determined.

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ISBN: 978-1-56973-963-1
Library of Congress Control Number: 2019907466