WORLD RESOURCES INSTITUTE

WORLD RESOURCES REPORT

CREATING A SUSTAINABLE FOOD FUTURE

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

SYNTHESIS REPORT, DECEMBER 2018

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CREATING A SUSTAINABLE FOOD FUTURE: SYNTHESIS REPORT

This synthesis report summarizes the findings of the World Resources Report *Creating a Sustainable Food Future*, a multiyear partnership between World Resources Institute, the World Bank Group, United Nations Environment, 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 full report will be published in the spring of 2019. Previously published installments analyzing many of the issues covered in this report in greater detail are available at https://www.wri.org/our-work/project/world-resources-report/publications.

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

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NOTES

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

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

All tons are metric tons unless otherwise indicated.

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

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

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

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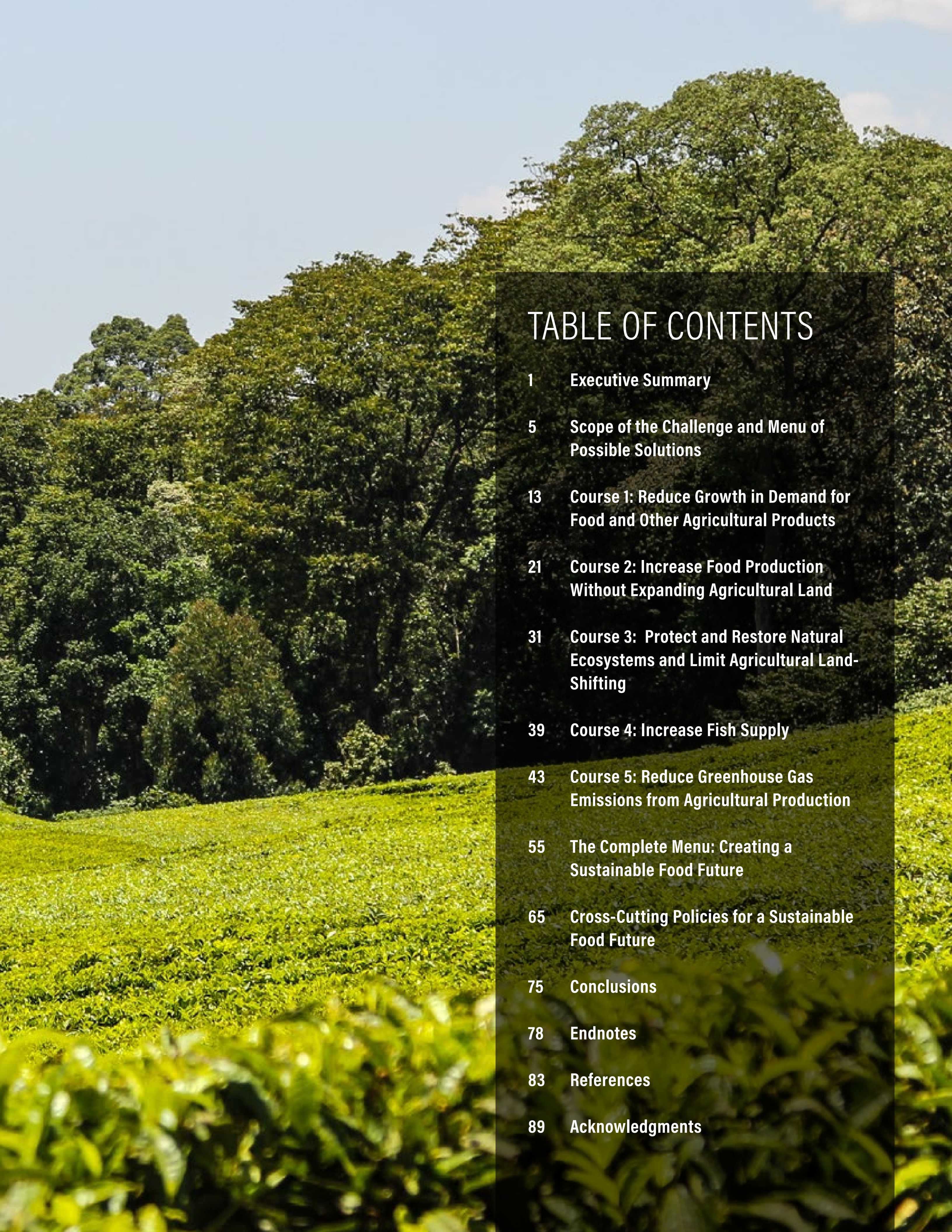

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EXECUTIVE SUMMARY

As the global population grows from 7 billion in 2010 to a projected 9.8 billion in 2050, and incomes grow across the developing world, overall food demand is on course to increase by more than 50 percent, and demand for animal-based foods by nearly 70 percent. Yet today, hundreds of millions of people remain hungry, 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 synthesis 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 7,400 trillion calories, or 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 required in 2050 even if crop and pasture yields continue to grow at past rates. We estimate this gap to be 593 million hectares (Mha), an area nearly twice the size of India.
- **The GHG mitigation gap—**the difference between the annual GHG emissions likely from agriculture and land-use change in 2050, which we estimate to be 15 gigatons of carbon dioxide equivalent (Gt CO_2e), and a target of 4 Gt that represents agriculture's proportional contribution to holding global warming below 2°C above pre-industrial temperatures. We therefore estimate this gap to be 11 Gt. Holding warming below a 1.5°C increase would require meeting the 4 Gt target plus reforesting hundreds of millions of hectares of liberated agricultural land.

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) exploit reduced demand on agricultural land to protect and restore forests, savannas, and peatlands; (4) increase fish supply through improved wild fisheries management and aquaculture; and (5) reduce greenhouse gas 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 maintain existing carbon storage. 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, economic, and environmental 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 merely expanding but shifting from one region to another (e.g., from temperate areas to the tropics) and within regions. The resulting land-use changes increase GHG emissions and loss of biodiversity. To ensure that food production is increased through yield growth (intensification) and not expansion, and productivity gains do not encourage more shifting, governments must explicitly link efforts to boost crop and pasture yields with legal protection of 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. Ruminant meat demand 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. 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.

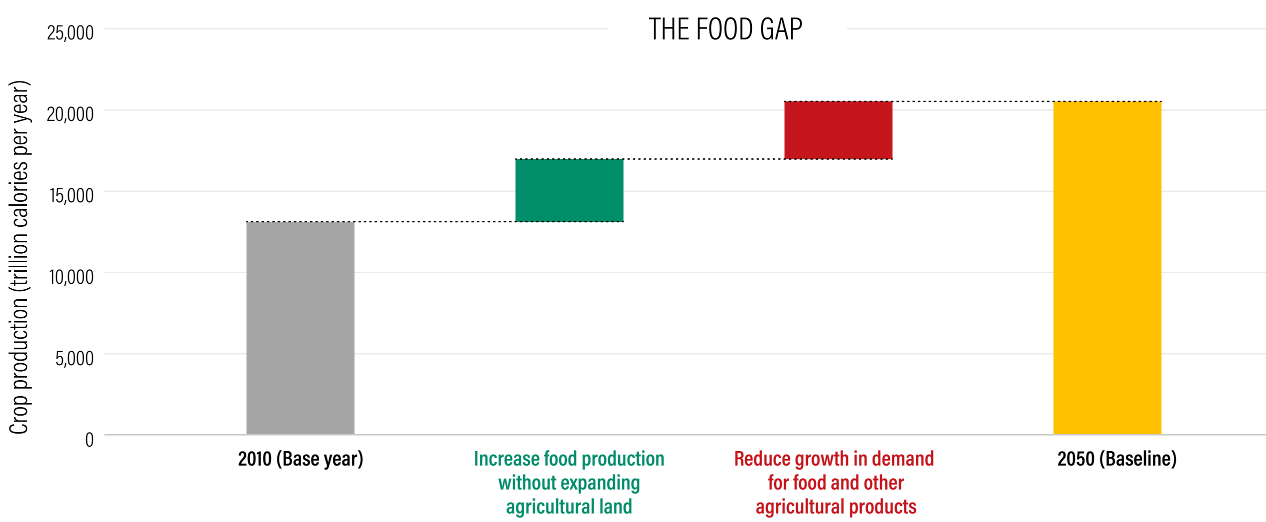
- **Target reforestation and peatland restoration.** Rewetting lightly farmed, drained peatlands that occupy only around 0.3 percent of global agricultural lands provides a necessary and cost-effective step toward climate change mitigation, as does reforesting some marginal and hard-to-improve grazing 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.

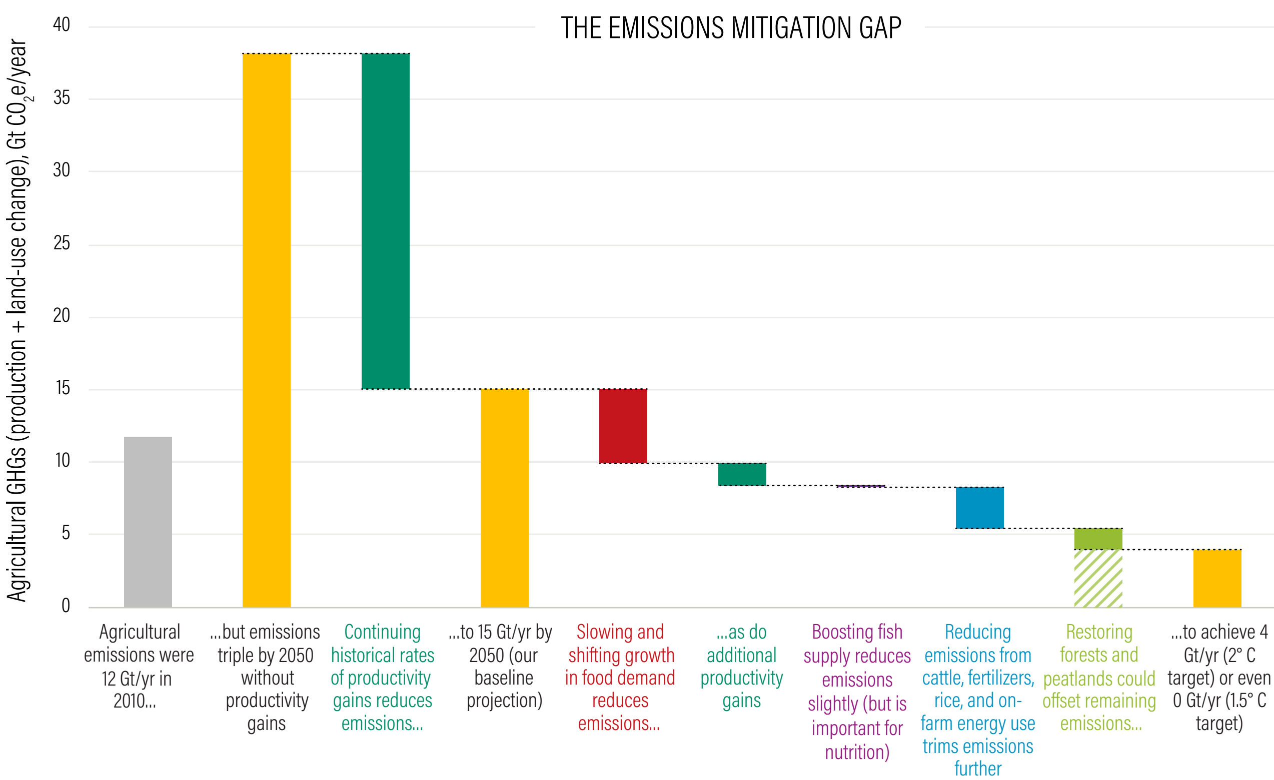
- **Require production-related climate mitigation.** Management measures exist to significantly reduce GHG emissions from agricultural production sources, particularly enteric fermentation by ruminants, manure, nitrogen fertilizers, and energy use. These measures require a variety of incentives and regulations,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

- **Spur technological innovation.** Fully closing the 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. Figure ES-1 illustrates how our five courses of action could feed the world and hold down global temperature rise. Although a formidable challenge, a sustainable food future is achievable if governments, the private sector, and civil society act quickly, creatively, and with conviction.

Figure ES-1 | **Ambitious efforts across all menu items will be necessary to feed 10 billion people while keeping 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 POSSIBLE 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?

A Recipe for Change

The challenge of creating a sustainable food future involves balancing many 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.

We quantify the core of the challenge in terms of the need to close three "gaps": in food production, agricultural land area, and greenhouse gas (GHG) mitigation. To measure the size of these gaps, we use a new model, GlobAgri-WRR, developed in a partnership between Le Centre de coopération internationale en recherche agronomique pour le développement (CIRAD), L'Institut national de la recherche agronomique (INRA), World Resources Institute (WRI), and Princeton University (Box 1).

BOX 1 | OVERVIEW OF THE GLOBAGRI-WRR MODEL

This global accounting and biophysical model quantifies food production and consumption from national diets and populations, 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-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 for crops and livestock in different countries. The model by itself does not attempt to analyze what policies and practices will achieve those systems; that is the focus of this synthesis report and the full report. For this reason, GlobAgri-WRR does not attempt to analyze economic feedback effects but concentrates on more biophysical detail. 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, benefitting from the detail available from other researchers' work.

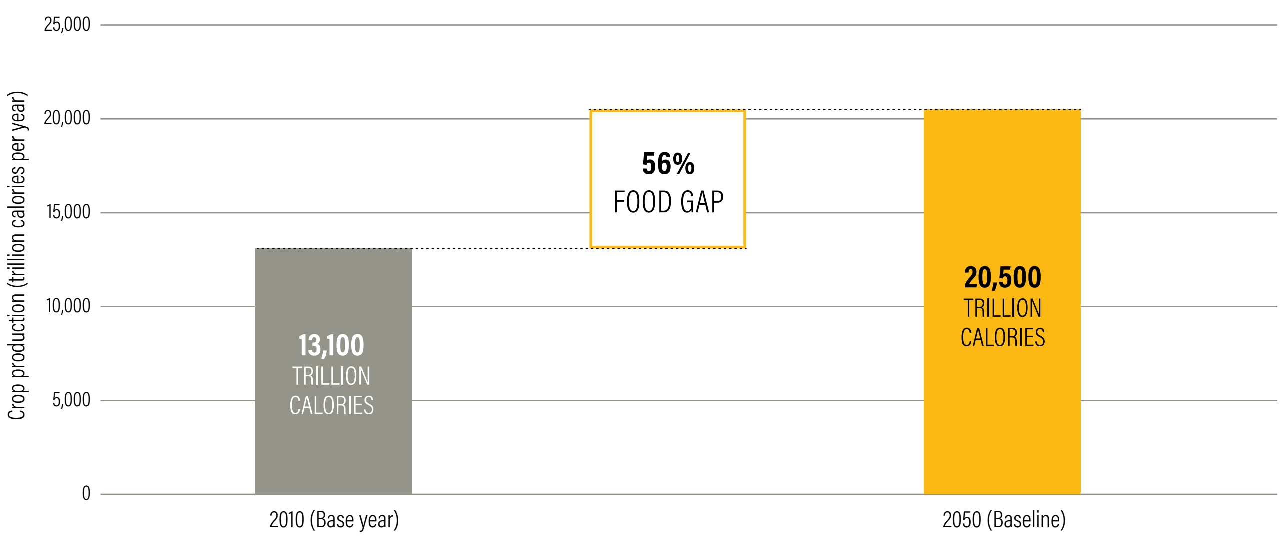
The Food Gap

The food gap is the increase above the amount of food (measured as crop calories)[1] produced in 2010, the base year for our analysis, to the amount that the world will require in 2050, based on projected demand (Figure 1). Rising food demand over this period—leading to this 56 percent food gap—will be driven by population growth (from 7 billion to 9.8 billion people)[2] and by increasing demand for more resource-intensive foods, particularly animal-based foods, as incomes grow.[3] Consumption of milk and meat—foods that rely heavily on pasture for their production—is likely to grow by 68 percent. These rates of growth exceed those that prevailed from 1962 to 2010.

The food gap can be closed both through measures that decrease the rate of unnecessary demand growth 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.

Frequent claims that the world already has an overabundance of food and could meet future needs without producing more food[4] are based on an unrealistic, even if desirable, hypothetical. It presumes that the world not only consumes fewer animal products per person, as this report encourages, but by 2050 eliminates nearly all meat consumption; that people shift from meat to vegetables and legumes and consume the same high-yield crops now used for animal feed; that all food loss and waste is eliminated; and that food is distributed just enough and no more than to meet nutritional needs of every person in the world.

Figure 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.
Source: WRI analysis based on FAO (2017a); UNDESA (2017); and Alexandratos and Bruinsma (2012).

The Land Gap

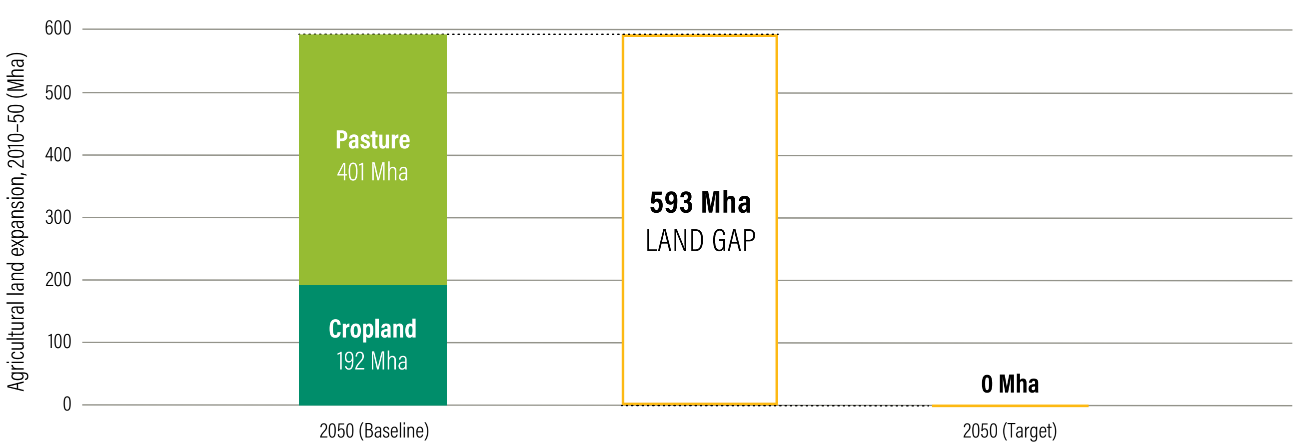
One strategy to close the food gap could be to clear more land for agriculture—but at the cost of great harm to forests and other ecosystems and the people who depend on them, and large releases of stored carbon from vegetation and soils. Today, croplands and pasture occupy roughly half of all vegetated land.[5] Between 1962 and 2010 alone, almost 500 million hectares (Mha) of forests and woody savannas were cleared for agriculture.[6] More land clearing would exacerbate a biodiversity crisis driven heavily by land-use change. And virtually all strategies for stabilizing the climate assume no net releases of carbon from land clearing between now and 2050, while many require net reforestation.

Our target is to hold agricultural land area—cropland and pastureland—to the area used in 2010. The land gap is thus the difference between the projected area of land needed to meet global food demand in 2050 and the amount of land in agricultural use in 2010.

The size of the land gap depends on how quickly crop and livestock yields can be improved. If the world were to experience no gains in crop and pasture yields and no moderation in demand for food (what we call our "no productivity gains after 2010" scenario), agricultural land would expand by 3.3 billion hectares, virtually eliminating the world's forests and savannas. In our baseline projection, we use estimated yields from the Food and Agriculture Organization of the United Nations (FAO), which projects that crop yields will increase, on average, at roughly the same rate as they did between 1961 and 2010. Livestock and pasture productivity gains are from the GlobAgri-WRR model. These gains hold down the expansion of agricultural areas to 593 Mha (Figure 2). However, if future crop yields grow at the somewhat slower rates experienced more recently (1989–2008), and pasture and livestock productivity also grow more slowly than in our baseline scenario, agricultural areas could instead expand by 855 Mha by 2050.

Future yield growth is uncertain, but the key lesson is that the world faces an unprecedented challenge. Crop and pasture yields must increase at rates even faster than those achieved between 1961 and 2010—a period that included the widespread synthetic fertilizer and scientifically bred seeds and a doubling of irrigated area—to fully meet expected food demand and to avoid massive additional clearing of forests and woody savannas.

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



Note: "Cropland" increase includes aquaculture ponds.
Source: GlobAgri-WRR model.

The Greenhouse Gas Mitigation Gap

The GHG mitigation gap is the difference between agriculture-related GHG emissions projected for 2050 and an agricultural emissions target for 2050 that is necessary to help stabilize the climate at globally agreed targets.[7]

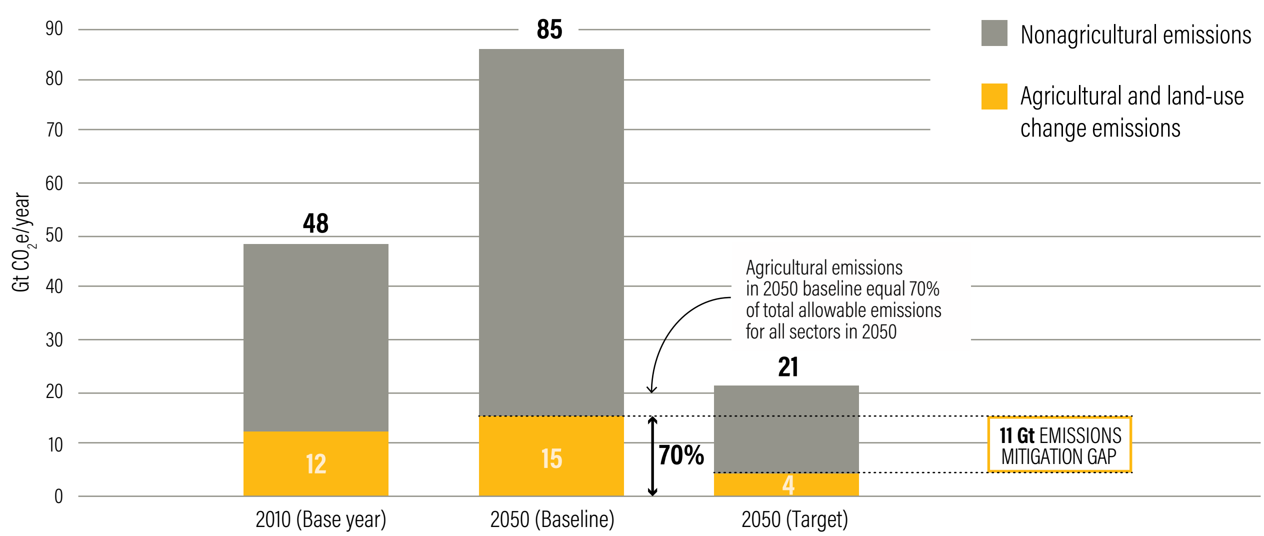
Agriculture and land-use change contributed one-quarter of total human-caused GHG emissions in 2010—roughly 12 gigatons (Gt) measured as carbon dioxide equivalent (CO_2e).[8] Of this total, a little more than half resulted from agricultural production, including such sources as methane from livestock production and rice cultivation, nitrous oxide from nitrogen fertilizer, and carbon dioxide released by fossil fuels used in agricultural production.[9] A little less than half of the emissions resulted from land-use change (vegetation clearing and soil plowing) as agriculture expanded. The land-use category includes 1.1 Gt released annually by the ongoing degradation of cleared peatlands, which are carbon-rich soils that decompose and sometimes catch fire once drained for agriculture.[10]

Using the GlobAgri-WRR model, we project total agricultural GHGs to be roughly 15 Gt per year in 2050–9 Gt of annual emissions from agricultural production and an annual average of 6 Gt between 2010 and 2050 from agricultural expansion and drained peatlands.[11] What are the implications of this estimate? Modeled strategies for holding climate warming to the global target of 2 degrees Celsius (2°C) (3.6 degrees Fahrenheit) above preindustrial levels typically require that total emissions from all human sources in 2050 amount to no more than around 21 Gt and decrease rapidly thereafter.[12] Although agriculture is likely to generate less than 2 percent of global GDP, it alone would fill about 70 percent of the allowable "emissions budget" in 2050 (15 of 21 Gt), leaving almost no space for emissions from other economic sectors and making achievement of even the 2°C target impossible (Figure 3).

Reflecting this dilemma, we define a GHG mitigation gap of 11 Gt: the difference between the 15 Gt of likely annual emissions in 2050 and a target of 4 Gt. The gap represents a nearly 75 percent reduction from the projected level—a reduction in line with the principle of "equal sharing" required from all sources to keep global warming to well below 2°C.

To limit warming to 1.5°C (2.7 degrees Fahrenheit), typical scenarios contemplate similar levels of emissions from agricultural production but require extensive reforestation to offset other emissions. We therefore also explore options for liberating agricultural land to provide such offsets.

Figure 3 | **Agricultural emissions are likely to be ~70 percent of total allowable emissions for 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).

A Menu of Solutions

To close these three gaps, we develop a "menu for a sustainable food future"—a menu of actions that can meet these challenges if implemented in time, at scale, and with sufficient public and private sector dedication (Table 1). We analyze the potential of the menu items to sustainably close the food, land, and GHG mitigation gaps by 2050. 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

A dominant theme of all menu items is the need to increase the efficiency in use of resources, whether through changes in consumption patterns or uses of land, animals, and other agricultural inputs.

In addition to helping close the three gaps, we impose three additional sustainability criteria on the menu items:

- To reduce poverty and hunger, the menu must neither inflate food prices significantly nor deny agricultural opportunities for small and poor farmers, even as they transition to alternative employment as economies develop.
- Because women's gains in income disproportionately reduce hunger for the entire household, the menu must provide opportunities for women farmers, who contribute the majority of agricultural labor in many countries and whose productivity has been hampered by unequal access to resources.
- To avoid further overuse and pollution of fresh water, the menu must contribute to pollution control, avoid increases in large-scale irrigation, and conserve or make more efficient use of water wherever possible. Agriculture accounts for roughly 70 percent of global fresh water withdrawals and is the primary source of nutrient runoff from farm fields.[13]

Table 1 | **The 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.

Table 1 | **The menu for a sustainable food future: five courses (continued)**

MENU ITEM	DESCRIPTION
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.
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 cropland 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 into 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, disease control, and changes in production systems.
Course 5: Reduce greenhouse gas 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) or through breeding 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 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.

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 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.

MENU ITEM: Reduce Food Loss and Waste

Of all the food produced in the world each year, approximately one-third by weight and one-quarter by calories is lost or wasted at various stages between the farm and the fork (Figure 4).[14] Globally, food loss and waste results in nearly $1 trillion in economic losses,[15] contributes to food insecurity in some developing countries, squanders agricultural land and water resources, and generates roughly one-quarter of all agricultural GHG emissions.[16]

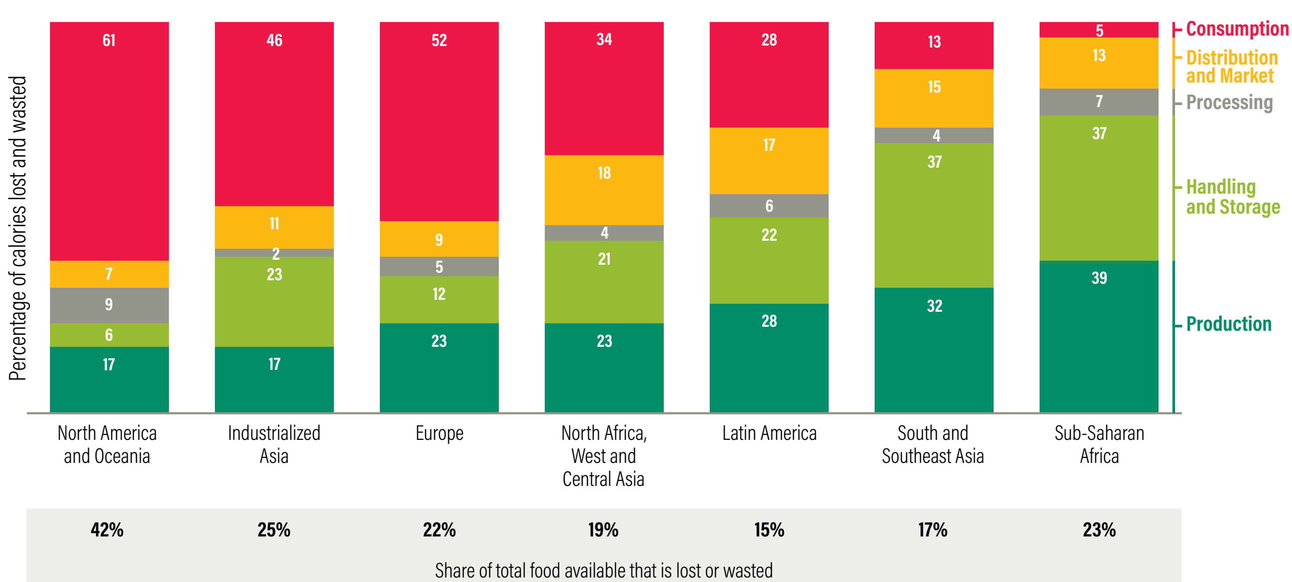
Reducing food loss and waste in developed countries relies heavily on subtle "nudges" to change consumer behavior, such as eliminating the use of trays in cafeterias or streamlining product date labels. Many retail operations can reduce waste through improved inventory management and purchasing agreements that allow suppliers to plan better. Such strategies enabled the United Kingdom to reduce retail and consumer food waste by 21 percent between 2007 and 2012 (and overall food loss and waste by 14 percent).[17] In developing countries, better harvesting equipment can reduce losses, as can agricultural practices that ripen crops for harvesting at more consistent times or produce food with more consistent qualities. Low-technology systems also exist to improve storage, including evaporative coolers and specially designed, low-cost plastic storage bags.

Despite these opportunities, large reductions globally are challenging because food loss and waste arises at so many different stages in the food chain, each one contributing only a small fraction of the whole. The complexity of food loss and waste sources leads us to propose three basic strategies:

- **Target**. Governments and companies should adopt food loss and waste reduction targets aligned with Sustainable Development Goal Target 12.3, which calls for reducing food loss and waste by 50 percent by 2030.
- **Measure**. Major actors in the food supply chain should more carefully measure sources of food loss and waste to identify hotspots, devise actions to reduce them, and assess progress.
- **Act and Innovate**. Many food producers, processors, and vast numbers of consumers will need to take a variety of actions. Many technological innovations will be needed, such as new methods that slow food degradation even without refrigeration and improved handling equipment that reduces damage.

Reducing food loss and waste by 25 percent globally would reduce the food calorie gap by 12 percent, the land use gap by 27 percent, and the GHG mitigation gap by 15 percent.

Figure 4 | **Food loss and waste primarily occurs closer to the consumer in developed regions and closer to the farmer in developing regions**



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

MENU ITEM: Shift to Healthier and More Sustainable Diets

We project consumption of animal-based foods to rise 68 percent between 2010 and 2050, with an 88 percent increase in consumption of ruminant meat (meat from cattle, sheep, and goats). These trends are a major driver of the food, land, and GHG mitigation gaps. For every food calorie generated, animal-based foods—and ruminant meats in particular—require many times more feed and land inputs, and emit far more greenhouse gases, than plant-based foods (Figure 5).

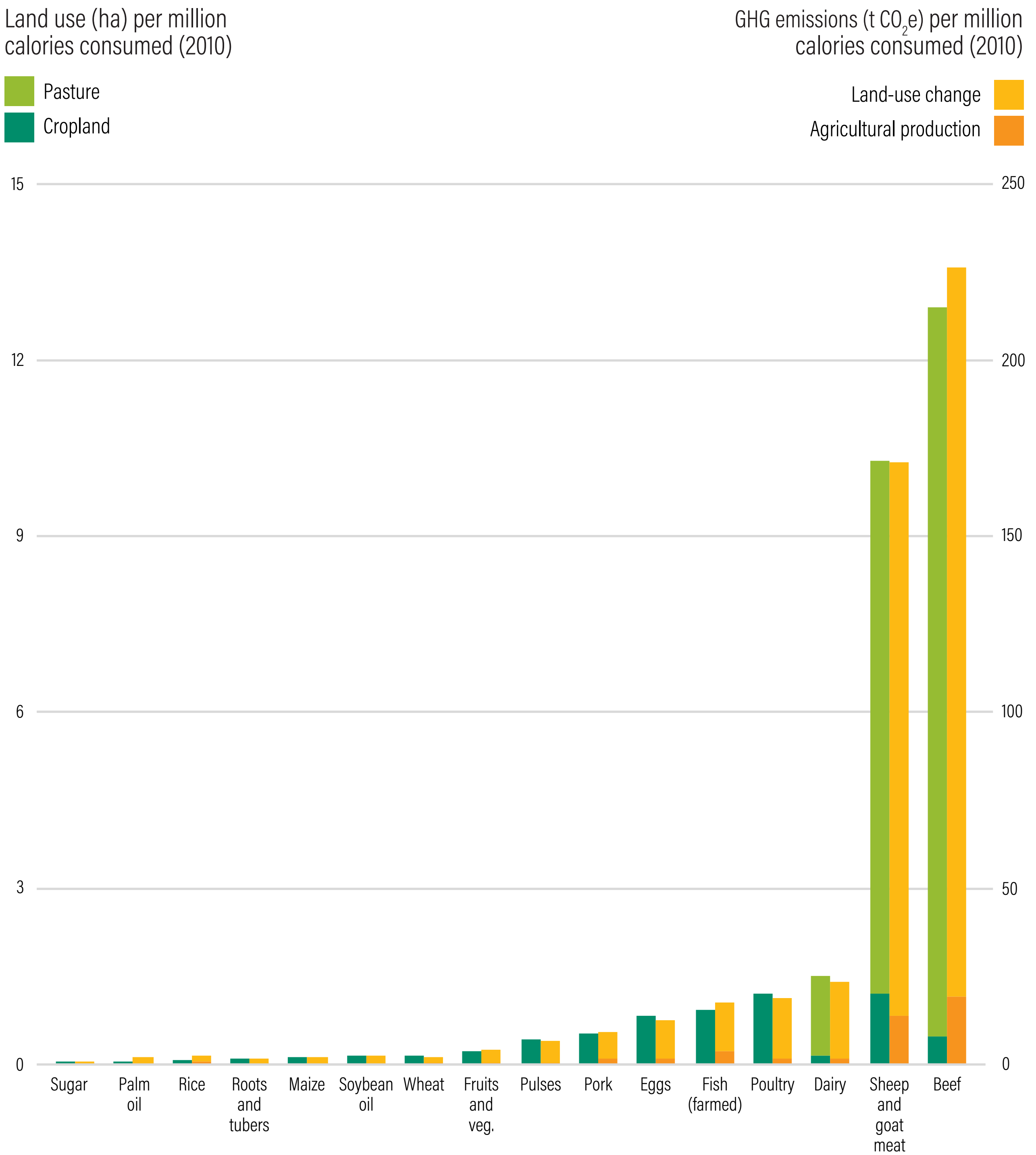
As nations urbanize and incomes rise above poverty levels, diets tend to become more varied and "Western"—high in sugar, fats, refined carbohydrates, meat, and dairy. Although modest consumption of meat and dairy by the world's poor supplies critical micronutrients, the large global rise in consumption of animal-based foods is both unnecessary and unhealthy. Half of the world's population already consumes 50 percent more protein than needed[18] and, contrary to popular understanding, plant proteins can readily meet protein requirements in balanced diets that contain enough calories.[19] New research downplays health risks from cholesterol and other saturated fats but has now identified processed meats as carcinogenic and red meat as probably carcinogenic.[20]

Researchers have long presented the environmental case for shifting high-meat diets toward plant-based foods, but achieving large global benefits is harder than often suggested, for two reasons. First, a common assumption is that, if people reduce meat consumption, they will instead consume much of the food formerly fed to animals (feed grains and oilseeds).[21] However, in practice, people often shift from meat to dairy products, legumes, and vegetables.[22] As shown in Figure 5, the land use and GHG emissions impacts of dairy products actually match or exceed those of pork and chicken and, while beans and vegetables are more environmentally efficient than meat, they are not as efficient as animal feeds. Second, a 10 percent global cut in consumption of all animal-based foods relative to the 2050 baseline, achieved by reducing consumption in wealthy regions, would be necessary just to allow 6 billion people across Asia and Africa to consume even half of Europe's present consumption of such foods while staying within total consumption levels estimated in our baseline projection.[23]

Despite these cautions, by properly factoring in the consequences of diets on land use we find the potential of shifting diets to be even more consequential for GHG mitigation than commonly estimated. In a world where population and demand for food are growing, and yield gains are not keeping pace, agricultural land is expanding. Each person's diet requires additional land-use change equal to the total land area needed to produce that diet, requiring conversion of forests and woody savannas to croplands and pasture. The effects on carbon are typically ignored. By counting the carbon dioxide released by that land-use change, and amortizing that amount over 20 years, we estimate that the average U.S. diet causes emissions of nearly 17 tons of CO_2e per year—an amount on par with per capita emissions from energy use in the United States.[24]

Beef accounts for roughly half of land use and emissions associated with U.S. diets, but it provides just 3 percent of the calories. Major environmental benefits would therefore result simply from shifting from beef toward chicken or pork (Figure 5). If global consumers shifted 30 percent of their expected consumption of ruminant meat in 2050 to plant-based proteins, the shift would, by itself, close half the GHG mitigation gap and nearly all of the land gap. Such a shift would require roughly 2 billion people in countries that today eat high amounts of ruminant meats to reduce their consumption, on average, by 40 percent below 2010 levels to 1.5 servings per person per week—equivalent to 2010 consumption levels in the Middle East and North Africa (Figure 6). In China, the challenge would be to moderate the growth of ruminant meat consumption. The substantial shifts from beef toward chicken that have already occurred in U.S. and European diets since the 1970s suggest that such shifts are feasible.[25] This shift would still allow global consumption of ruminant meats to grow by one-third (instead of the 88 percent growth in the baseline scenario) between 2010 and 2050.

Figure 5 | **Animal-based foods are more resource-intensive than plant-based foods**



Note: Data presented are global means. 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 (2017a). "Fish" includes all aquatic animal-based foods. Estimates are based on a marginal analysis of additional agricultural land use and emissions per additional million calories 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. Estimates of land use and greenhouse gas emissions for beef production are based on dedicated beef production, not beef that is a coproduct of dairy. Dairy figures are lower in GlobAgri-WRR than some other models because GlobAgri-WRR assumes that beef produced by dairy systems displaces beef produced by dedicated beef-production systems.
Source: GlobAgri-WRR model.

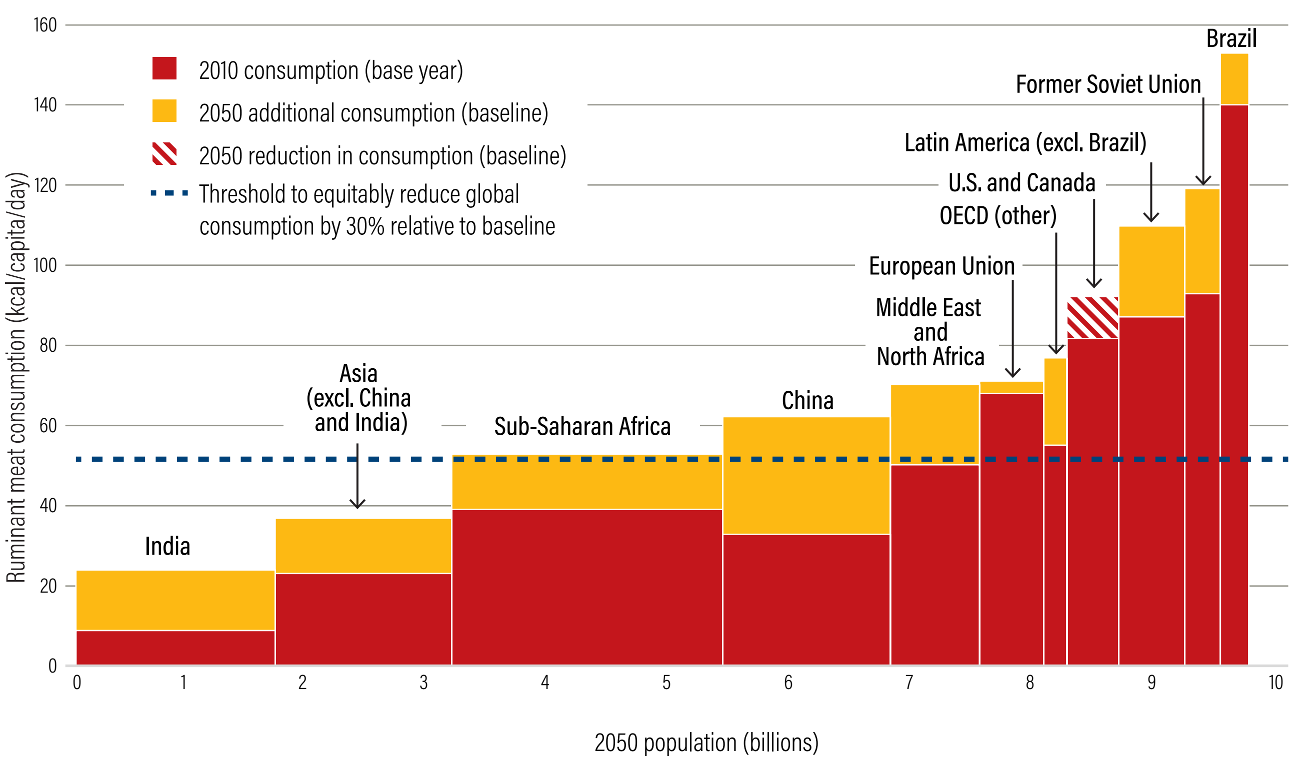
Three strategies will be necessary to shift consumption toward healthier and lower-impact diets:

- **Product innovation**. Businesses should continue to increase investment in development of meat substitutes (e.g., plant-based meats) and blended meat-plant products until they satisfy consumers who still want to enjoy the taste and experience of eating meat at less cost.

- **Promotion and marketing**. Businesses, government, and civil society need to move beyond relying solely on information and education campaigns to shift diets. Rather, they should improve marketing of plant-based foods and plant-rich dishes. A suite of more sophisticated behavior-change strategies, including minimizing disruption to consumers, selling a compelling benefit, maximizing awareness, and evolving social norms, has proven successful in shifting consumption patterns in other food and nonfood products.[26]

- **Policy and pricing**. Governments can support diet shifts through their own food procurement practices and policies that shape the consumption environment (e.g., marketing, display). Once the quality and price of nonmeat alternatives rival that of meat, retail-level taxes on meats or other animal-based foods might become politically acceptable.

Figure 6 | **Limiting ruminant meat consumption to 52 calories per person per day in all regions reduces the greenhouse gas mitigation gap by half and nearly closes the land gap**



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

MENU ITEM: Avoid Competition from Bioenergy for Food Crops and Land

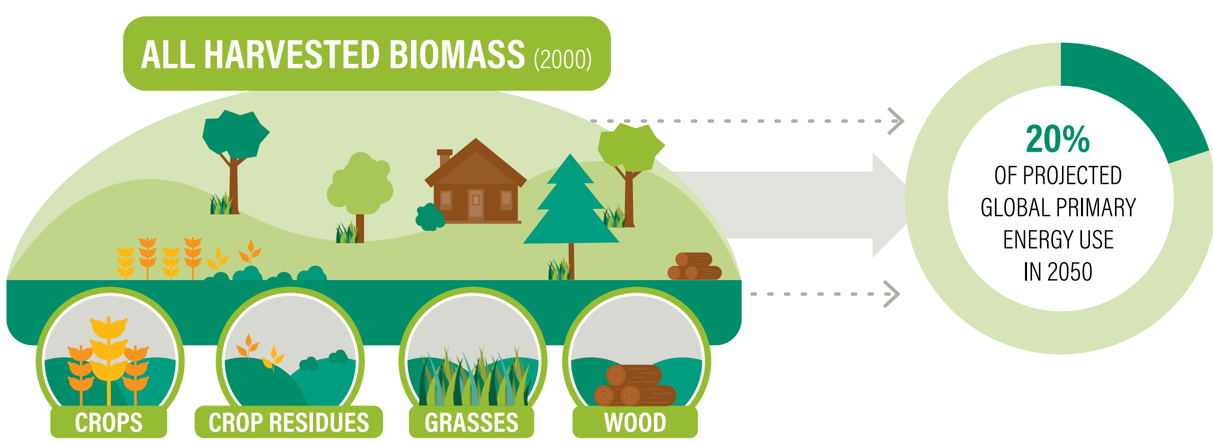
Bioenergy is produced mainly from food and energy crops grown on dedicated land, which increases global competition for land and widens the food, land, and GHG mitigation gaps. Our 2050 baseline projection assumes that the share of biofuels from crops in transportation fuel remains at 2010 levels, but many governments have adopted goals to increase biofuel's share fourfold or more.[27] Such an increase globally would supply about 2 percent of total energy use in 2050 but would increase the food gap from 56 to 78 percent. Still more ambitious goals—to supply 20 percent of world energy from bioenergy by 2050—would require a quantity of biomass equal to all the world's harvested crops, crop residues, forage, and wood in 2000 (Figure 7).

Bioenergy creates so much potential competition for food and carbon storage because bioenergy converts only a fraction of 1 percent of energy from the sun into usable energy. Food or energy crops also require well-watered, productive land. By contrast, solar photovoltaic (PV) cells today can use drylands and they produce at least 100 times more useable energy per hectare than energy crops are likely to produce in the future, even when grown on well-watered lands.[28]

Burning (and refining) biomass also emits more carbon per unit of energy generated than burning fossil fuels. Claims that bioenergy reduces GHG emissions rely on the assumption that this carbon does not "count" because burning plants only returns carbon to the air that growing plants absorb. But diverting land to produce bioenergy comes at the cost of not using this land and the plants it grows for other purposes, including food production and carbon storage. To provide bioenergy without losing these other services, people must either grow additional plants or use organic waste as a feedstock. Some low-carbon bioenergy is available from wastes and possibly from winter cover crops. But claims of large bioenergy potential to reduce GHG emissions ignore the alternative uses of land and plants, in effect assuming they can continue to serve other needs even when dedicated to bioenergy.

Avoiding increased use of bioenergy from energy and food crops is critical to a sustainable food future. Phasing out existing levels of biofuel use would reduce the crop calorie gap from 56 to 49 percent. Governments should phase out subsidies currently in place for bioenergy that is grown on dedicated land. Governments also need to correct "flawed accounting" in renewable energy directives and emissions trading laws that treat bioenergy as "carbon-neutral."

Figure 7 | **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).

MENU ITEM: Achieve Replacement-Level Fertility Rates

Expected population growth of 2.8 billion people between 2010 and 2050[29] drives the majority of expected growth in food demand. Roughly half of this population increase will occur in Africa, and one-third will occur in Asia. Overall, most of the world—including Asia—is close to achieving replacement-level fertility (~2.1 children per woman) and will achieve or even dip below it by 2050.[30]

Sub-Saharan Africa is the notable exception, with a total fertility rate above 5 in 2010–15 and a projected rate of 3.2 in 2050. As a result, sub-Saharan Africa's population, which was 880 million in 2010, is projected to reach 2.2 billion by 2050 and 4 billion by 2100.[31] This population growth risks exacerbating food insecurity in a region that is already home to 30 percent of the world's chronically hungry people.[32]

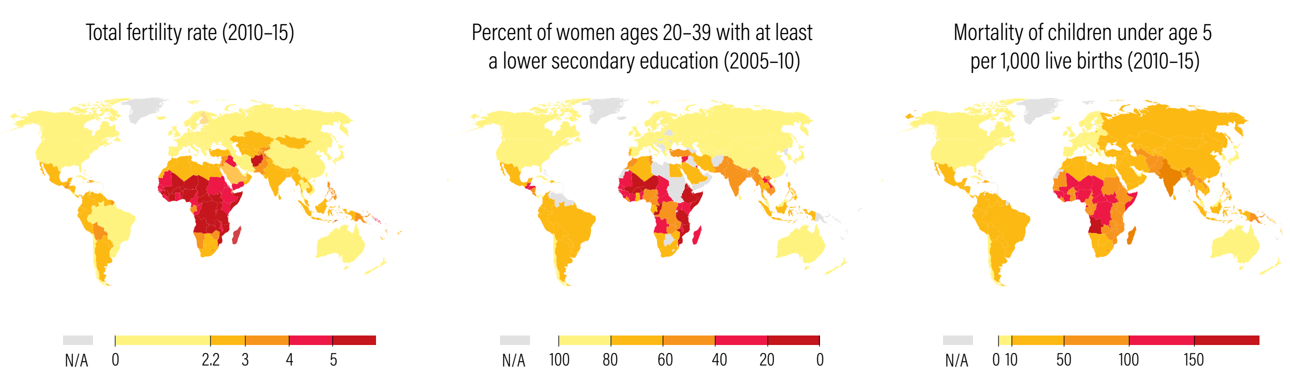
Given the choice, people worldwide have voluntarily chosen to greatly reduce their fertility rates—even in extremely poor countries and across religions and cultures—wherever countries have achieved three forms of social progress:

- **Increased educational opportunities for girls**, ensuring they get at least a lower secondary education (i.e., some high school). The longer girls stay in school, the later they typically start bearing children and the fewer children they bear.
- **Increased access to reproductive health services**, including family planning, to ensure couples can have the family sizes they desire and reduce maternal mortality.
- **Reduce infant and child mortality**, so parents do not need to have many children to ensure survival of the desired number.

Reducing fertility also tends to produce strong economic dividends. Unfortunately, sub-Saharan Africa lags behind in these measures (Figure 8). Most African countries have adopted a goal of reducing population growth, so the challenge is to direct adequate resources to these strategies, develop the necessary administrative and technical capacity, and mobilize civil society.

If sub-Saharan Africa could move toward replacement-level fertility rates by 2050, its population would grow to only 1.8 billion. The regional growth in crop demand would then decline by nearly one-third relative to our baseline projection. The region's farmers would need to clear only 97 Mha of forests and savannas for agriculture rather than the 260 Mha in our baseline projection, closing one-quarter of the global land gap. The global GHG mitigation gap would decline by 17 percent.

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



Sources: UNDESA (2017); Harper (2012); World Bank (2017a).

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, under realistic scenarios, improvements in crop and pasture productivity must exceed historical rates of yield gains.

Assessing the Challenge of Agricultural Land Expansion

The single most important need for a sustainable food future is boosting the natural resource efficiency of agriculture, that is, producing more food per hectare, per animal, per kilogram of fertilizer, and per liter of water. Such productivity gains reduce both the need for additional land and the emissions from production processes. Without the large crop and livestock productivity gains built into our baseline (based roughly on trends since 1961), land conversion would be five times greater by 2050 and GHG emissions would be more than double the level projected in our baseline (Figure 9).

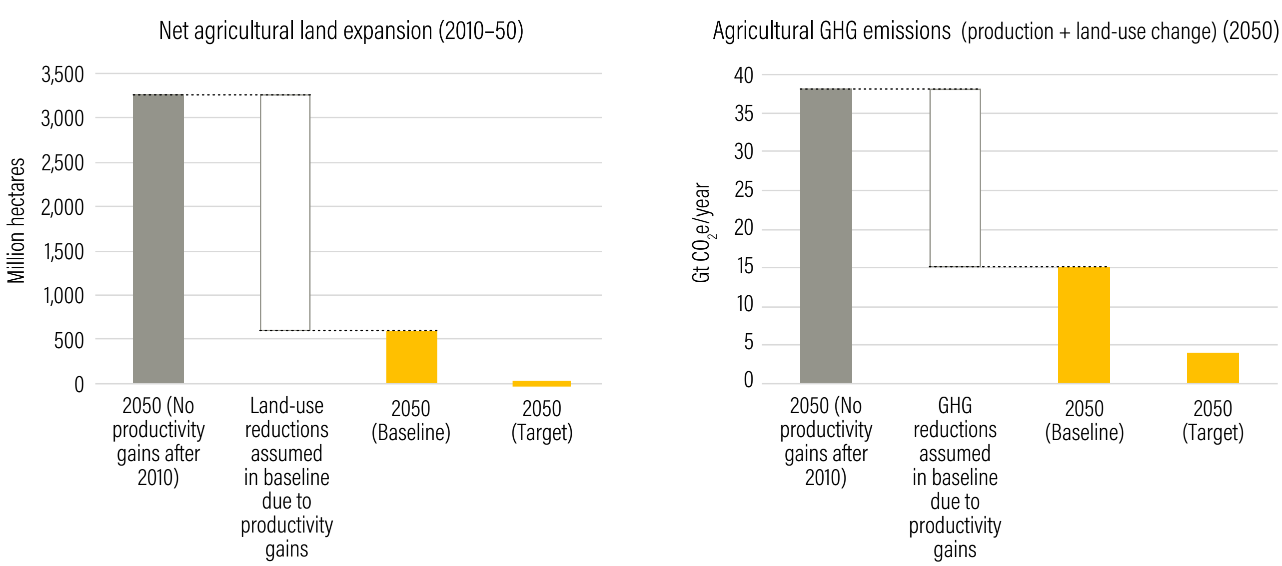
In some mitigation analyses, including reports by the Intergovernmental Panel on Climate Change (IPCC), agricultural productivity gains are barely mentioned, for reasons that are unclear. Even under our baseline projection, with its large increases in crop and livestock yields, we project that agricultural land will expand by 593 Mha to meet expected food demand. Unless projected growth in demand for food can be moderated, to avoid land expansion both crop yields and pasture-raised livestock yields will have to grow even faster between 2010 and 2050 than they grew in previous decades.

Arguments can be made for both pessimism and optimism:

- Studies have projected that farmers could achieve far higher yields than they do today. However, methods for estimating these "yield gaps" tend to exaggerate gap sizes and farmers can rarely achieve more than 80 percent of yield potential. The most comprehensive study suggests that fully closing realistic yield gaps is unlikely to be enough to meet all food needs.
- The massive yield gains of the 50 years from 1960 to 2010 were achieved in large part by doubling irrigated area and extending the use of scientifically bred seeds and commercial fertilizer to most of the world. Only limited further expansion of these technologies remains possible.
- Optimistically, farmers have so far continued to steadily boost yields by farming smarter in a variety of ways, and new technologies are opening up new potential.

Whatever the degree of optimism, the policy implications are the same: Going forward, the world needs to make even greater efforts to boost productivity than in the past to achieve a sustainable food future.

Figure 9 | **Improvements in crop and livestock productivity already built into 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.

MENU ITEM: Increase Livestock and Pasture Productivity

Demand for milk and meat from grazing ruminants is likely to grow even more than demand for crops. Because pasture makes up two-thirds of all agricultural land, the productivity of livestock will critically affect future land use and emissions. Large productivity improvements for pork and poultry are unlikely in developed countries because of biological limits.[33] In developing countries, because traditional backyard systems make use of waste and scavenging, shifts to modern systems increase output but do not reduce land-use demands and emissions.

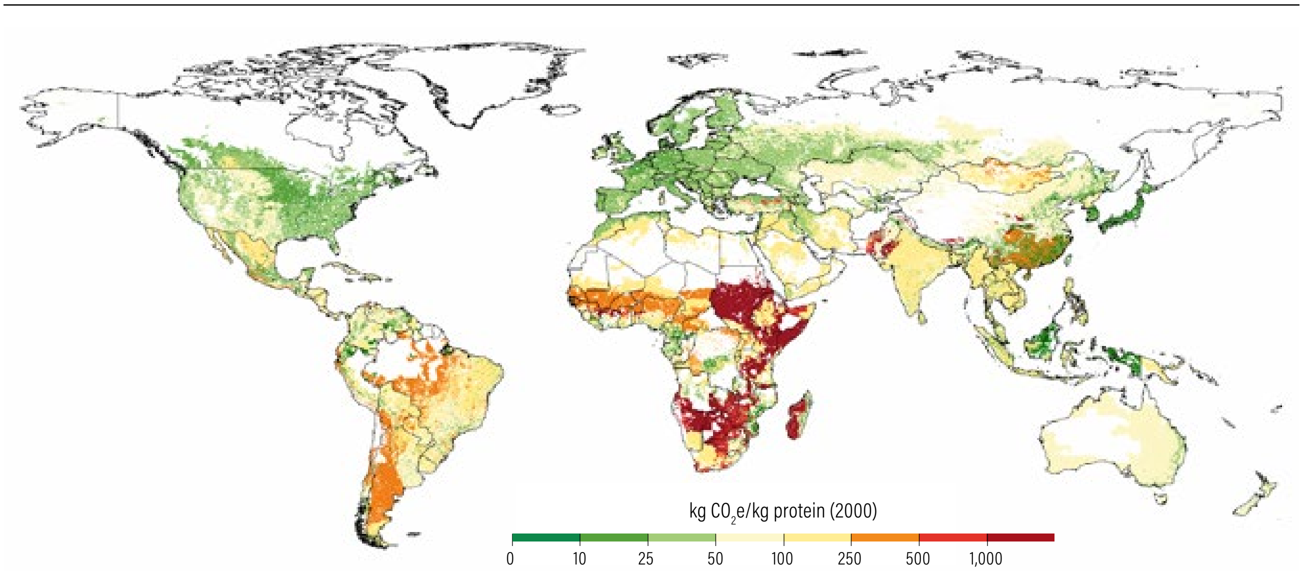
By contrast, ruminant systems have greater potential to improve, as suggested by the wide range in productivities across countries. The GHG emissions that result from producing each kilogram of beef—a good proxy for all aspects of productivity—are far higher in some countries than in others (Figure 10). Land-use requirements can be 100 times greater,[34] and the quantity of feed 20 times greater.[35]

Higher ruminant productivity can be achieved by increasing output per animal through improved food quality, breeding, and health care; and by increasing feed output per hectare. Neither requires a shift to feedlots. On pastures with good rainfall, productivity can be increased by proper fertilization, growing legumes, rotational grazing, and adding supplemental feeds in dry seasons and during the last few months of "finishing." In the "cut and carry" systems that predominate in Africa and Asia, farmers can grow a wide variety of improved forage grasses and shrubs with high protein leaves.

The real challenge lies in the scale of improvement required. Because much grazing land is too dry or too sloped to support large feed improvements, almost every hectare of wetter, accessible, and environmentally appropriate land would need to achieve close to its maximum productive potential to meet expected global demand without the need for further land conversion.

- Most ruminant farmers need to shift from low-management operations, which take advantage of cheap land, toward careful, intensive grazing and forage management using more labor and inputs.
- Governments in developing countries, which are home to the great majority of ruminants, should establish livestock productivity targets and support them with greater financial and technical assistance.
- Implementation of systems to analyze improvement potential and track changes in different areas and on different types of farms would help guide these investments and monitor their effects.

Figure 10 | **Inefficient beef production systems result in far higher greenhouse gas emissions per unit of meat output**



Source: Herrero et al. (2013).

MENU ITEM: Improve Crop Breeding to Boost Yields

Breeding of improved crops is generally credited for half of all historical yield gains. Breeding can both increase the potential yield of crops under ideal conditions and help farmers come closer to those potential yields by better coping with environmental constraints. Countries that have invested more in recent years in crop breeding, such as Brazil and China, have seen vast improvements in their yields.

"Incremental" crop breeding has been the primary driver of yield gains through assessment and selection of the best performing existing crops, followed by purification, rebreeding, production, and distribution. In the United States, improved maize varieties are released every three years. Speeding new crop cycles would boost yield growth in many countries such as Kenya and India, where new grain varieties are released typically every 13 to 23 years.[36]

Much debate has focused on genetically modified organisms (GMOs), which involve insertion of genes from one plant into another. The debate has centered overwhelmingly on two types of traits that assist pest control through glyphosate resistance and expression of Bt (*Bacillus thuringiensis*), a biological pesticide. Some bona fide debate is appropriate about whether the ease of use and relatively lower toxicity provided by these traits in the short term, and their potential value to small farmers without access to pesticides, justifies the longer-term risks of building resistance in weeds, worms, and insects—potentially leading to more pesticide use in the future. There is no evidence that GMOs have directly harmed human health.[37]

Gene editing has far greater potential. Sometimes new genes can provide the only viable mechanisms for crops to survive new diseases. New genes may also play a major role in combating environmental challenges by making crops more efficient at absorbing nitrogen or suppressing methane or nitrous oxide emissions.

The CRISPR-Cas9[38] revolution since 2013 dramatically increases opportunities to improve breeding through genetic manipulation. CRISPR enables researchers to alter genetic codes cheaply and quickly in precise locations, insert new genes, move existing genes around, and control expression of existing genes. CRISPR follows a related genomics revolution, which makes it cheap to map the entire genetic code of plants, test whether new plants have the desired DNA without fully growing them, and purify crop strains more rapidly.

According to the most recent assessments, global public agricultural research is roughly $30 billion per year for all purposes, and private crop-breeding research is around $4 billion, which we consider modest. The vast opportunities created by new technologies warrant large and stable increases in crop-breeding budgets.

MENU ITEM: Improve Soil and Water Management

Revitalizing degraded soils, which may affect one-quarter of the world's cropland,[39] provides another opportunity to boost crop yields. Degradation is particularly severe in drylands, which cover much of Africa and where low soil fertility is a direct threat to food security. Loss of organic matter is a special concern because soils then hold less water and are less responsive to fertilizers, making fertilizer use less profitable.

Agencies in recent years have encouraged African farmers to adopt "conservation agriculture," which relies on no or reduced tillage (plowing) of soils and preserving crop residues.[40] These practices can limit soil erosion and may help boost yields modestly in particularly dry areas, but farmers are often reluctant to avoid tillage because of the increased need for weeding or herbicides, and because they often need to use crop residues for livestock feed.[41]

Some of the more promising approaches involve agroforestry, often using nitrogen-fixing trees. Farmers have helped regenerate trees in farm fields across 5 Mha in the Sahel, boosting yields.[42] Commitments to agroforestry made by many African governments would benefit from more systematic evaluation of which systems work economically, and where. Microdosing crops with small quantities of fertilizer and trapping water on farms through various blocking systems also shows promise in drylands.[43]

Strategies to improve soils will need to address the real obstacles facing farmers. Rebuilding soil carbon may require diversion of land, labor, or residues needed for food production and will therefore need financial support.[44] Efforts to grow more legumes to fix nitrogen in African soils must overcome high rates of disease, which requires breeding plants with improved disease resistance. Enhancing soil carbon also requires that farmers add or fix enough nitrogen to meet crop needs and those of soil-building microbes, so cheaper fertilizers must be available.

- In drylands like the Sahel, governments and international aid agencies should increase support for rainwater harvesting, agroforestry, farmer-to-farmer education, and reform of tree-ownership laws that can impede farmers' adoption of agroforestry.
- Elsewhere, governments and aid agencies need to explore new models for regenerating soils. One option may be to provide financial help to farmers to work incrementally on their farms, improving one small piece of land at a time. If one small area can be improved quickly to the point where it generates large yield gains, the economic return may come soon enough to motivate farmer efforts.

MENU ITEM: Plant Existing Cropland More Frequently

FAO data indicate that more than 400 Mha of cropland go unharvested each year, suggesting that this amount of land is left fallow.[45] FAO data also indicate that farmers plant roughly 150 Mha twice or more each year (double cropping).[46] The ratio of harvests each year (harvested area) to quantity of cropland is known as the "cropping intensity," a ratio that FAO currently estimates at 82 percent. Planting and harvesting existing cropland more frequently, either by reducing fallow land or by increasing double cropping, could in theory boost food production without requiring new cropland.

Some analysts have interpreted FAO data to suggest a large recent increase in cropping intensity, but these claims are mostly undercut by local satellite studies. Using relatively crude criteria, other studies have suggested a substantial theoretical potential to increase double cropping on rainfed lands. But roughly half of double-cropped land today is irrigated, and farmers probably plant two crops a year on only 6 percent of rainfed area. Practically and economically, the prospects for expanding double cropping on rainfed lands must therefore be limited, as is expanding double cropping on irrigated land because of water constraints.

In addition, there are significant environmental costs in some regions to planting fallow croplands more frequently because some fallow lands are either in very long-term rotations or are in the early stages of abandonment. Typically, they will revert to forest or grassland and help store carbon and provide other ecosystem services. Planting them more frequently sacrifices these benefits.

Despite difficulties, there are opportunities for progress. Raising cropping intensity is a promising option, particularly in Latin America, where double cropping has been growing. Our baseline assumes a 5 percent increase in cropping intensity to 87 percent. If cropping intensity were to increase another 5 percent, the land gap would shrink by 81 Mha, or 14 percent.

Strategies to encourage higher cropping intensity require scientists to conduct more detailed and spatially explicit analyses to determine realistic potential increases in cropping intensity. Studies should account for limitations on irrigation water availability and build in at least some basic economics. Governments and researchers will then be better able to determine which improvements in infrastructure or crop varieties can contribute to economically viable increases in cropping intensity.

MENU ITEM: Adapt to Climate Change

The global impacts of climate change on agriculture are sufficiently uncertain that we did not attempt to model them in our 2050 baseline. Although earlier analyses suggested that effects on crop yields by 2050 might even be beneficial, by the time of the 2014 IPCC report, models projected on average that, without adaptation, global crop yields were "more likely than not" to decline by at least 5 percent by 2050—with even steeper declines by 2100.[47]

Many estimates are even larger, and uncertainty should be a cause for greater concern because "medium" impacts are not more likely.[48] We modeled one plausible estimate of a 10 percent decline in crop yields due to climate change without adaptation. Cropland would need to expand overall by 457 Mha (increasing the total land gap by 45 percent).

Climate change will benefit some crops, at least in the short term, as higher concentrations of carbon dioxide increase the efficiency of photosynthesis. Warmer temperatures will extend the growing season in colder countries and regional shifts in rainfall patterns will make some locations wetter.[49] But some areas will also become drier and hotter. Higher temperatures will harm crops by drying soils, accelerating water loss, and increasing pest damage.[50] Extreme heat events will harm maize, wheat, coffee, and many other crops by interfering with reproduction.[51] Growing seasons in parts of sub-Saharan Africa could become too short or too irregular to support crops (Figure 11), contributing to major food security concerns.[52]

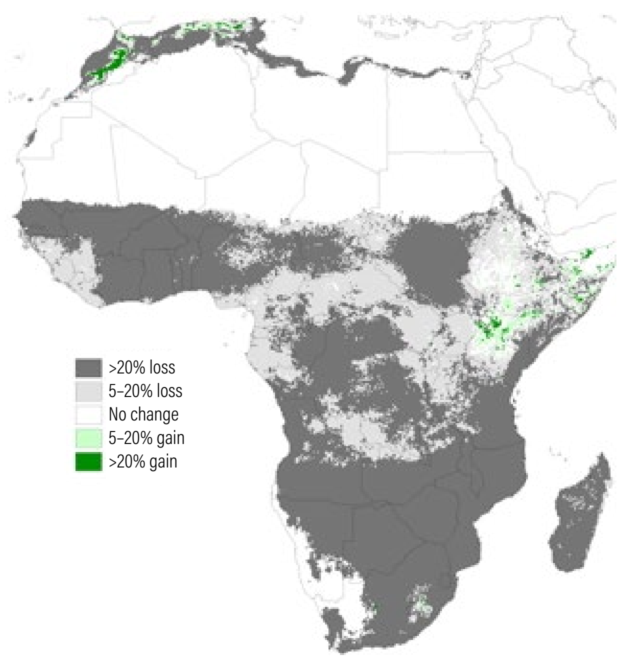
The evidence from crop models indicates significant but uncertain capacity to adapt using tailored crop varieties. Uncertainties about local climate change suggest broad "no regrets" strategies, many of them already included in our other menu items. For example, closing yield gaps in Africa and India would increase incomes and provide a buffer against adverse climate impacts, forest protection could increase resilience through improved local hydrology, while safety net programs for the rural poor will better equip small farmers to deal with future variability.

Some climate effects, however, are sufficiently clear to emphasize the need for new measures or expanded effort on other menu items:

- Farmers need effective regional crop-breeding systems that enable them to select alternative crop varieties specifically adapted to local conditions.
- Small-scale irrigation and water conservation systems will help farmers cope with rainfall variability.
- Research organizations and companies must breed new traits to overcome highly likely big climate challenges such as high temperature effects on maize, wheat, rice, and coffee.
- Governments must help fund adaptation to those major physical changes that are clearly predictable, such as altering production systems in areas that will be affected by sea level rise.

Figure 11 | **Climate change could shorten growing seasons in much of sub-Saharan Africa by more than 20 percent by 2100**

Length of growing period in the 2090s compared with the 2000s



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

How Much Could Boosting Crop and Livestock Productivity Contribute to Closing the Land and Greenhouse Gas Mitigation Gaps?

The menu items in Course 2 are needed first merely to achieve our baseline. As Figure 9 and Table 2 show, the productivity gains assumed in our baseline projection close more than 80 percent of the land gap (and approximately two-thirds of the GHG mitigation gap) that would result if agricultural efficiency did not improve at all after 2010. We also modeled more optimistic scenarios to 2050, where, relative to the baseline projection, we assume a 25 percent faster rate in ruminant livestock productivity gains, 20 and 50 percent faster rates of growth in crop yield gains, and a 5 percent additional increase in cropping intensity.

Even these additional improvements leave significant land and GHG mitigation gaps (Table 2). This is why closing the land gap completely will require demand-side measures (Course 1) and action to protect and restore natural ecosystems (Course 3), and why closing the GHG mitigation gap completely will require action across all courses.

Table 2 | **Higher crop and livestock productivity could reduce agricultural land area and greenhouse gas emissions in 2050**

SCENARIO	EXPANSION IN AGRICULTURAL LAND, 2010–50 (MILLION HA)			TOTAL ANNUAL EMISSIONS, 2050 ($Gt\ CO_2e$)			GHG MITIGATION GAP ($Gt\ CO_2e$)
	PASTURE LAND	CROP-LAND	TOTAL	AGRI-CULTURAL PRODUCTION	LAND-USE CHANGE	TOTAL	
No productivity gains after 2010	2,199	1,066	**3,265**	11.3	26.9	**38.2**	34.2
2050 Baseline (crop yields grow by 48%, cropping intensity by 5%, and output of meat or milk per hectare of pasture by 53–71% between 2010 and 2050)	401	192	**593**	9.0	6.0	**15.1**	11.1
Scenario variations relative to 2050 baseline							
Failure to adapt to climate change (10% decline in total crop yields)	402	457	**859**	9.3	8.2	**17.6**	13.6
25% faster rate of output of meat and milk per hectare of pasture (58–76% growth between 2010 and 2050)	291	182	**473**	8.8	5.1	**13.9**	9.9
20% faster increase in crop yields (crop yields grow by 56% between 2010 and 2050)	401	100	**501**	8.9	5.3	**14.3**	10.3
5% additional increase in cropping intensity (10% growth between 2010 and 2050)	401	110	**512**	9.0	5.4	**14.4**	10.4

Notes: "Cropland" includes cropland and aquaculture ponds. Numbers not summed correctly are due to rounding.
Source: GlobAgri-WRR model.

COURSE 3: PROTECT AND RESTORE NATURAL ECOSYSTEMS AND LIMIT AGRICULTURAL LAND-SHIFTING

This course focuses on the land-management efforts that must complement food demand-reduction efforts and productivity gains to avoid the harms of agricultural land expansion. One guiding principle is the need to make land-use decisions that enhance efficiency for all purposes—not just agriculture but also carbon storage and other ecosystem services. Another principle is the need to explicitly link efforts to boost agricultural yield gains with protection of natural lands.

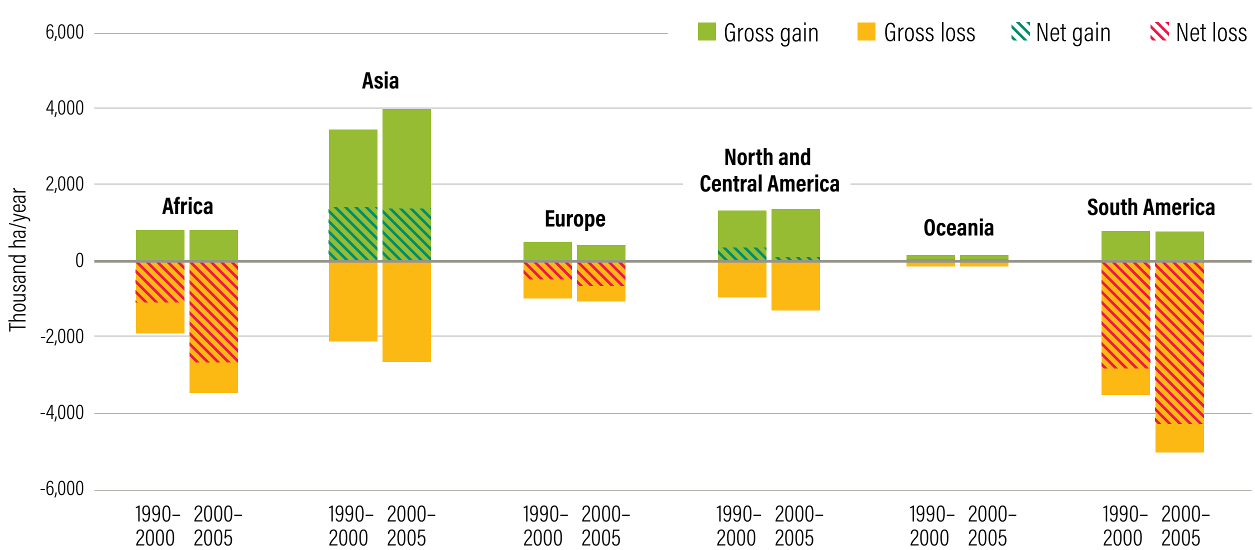
The Causes and Consequences of Shifting Agricultural Land

Merely eliminating the need for a net expansion of agricultural land will not avoid all carbon and ecosystem losses because agricultural land is not merely expanding, it is also shifting. At a regional level, agricultural land is shifting from developed to developing countries.[53] One reason is that growth in population and food demand is mostly occurring in developing countries. Rising food demand in sub-Saharan Africa, for example, is likely to drive cropland expansion of 100 Mha between 2010 and 2050, even allowing for high estimated yield gains in the region and continued importation of roughly one-fifth of staple foods. Another reason is growing global demand for some highly traded crops that developing countries have learned to grow well, such as soybeans and palm oil.

Agricultural land is also shifting within regions and countries, particularly from less productive and more sloped lands to flatter, more productive, more densely vegetated lands. These shifts result in gross forest losses that are much larger than net losses (Figure 12). Many abandoned agricultural lands do reforest but, unfortunately, the trade-off when native forests are replaced with planting or regrowing forests elsewhere is not environmentally neutral. Conversion of natural ecosystems, which is occurring mostly in the tropics and neotropics, tends to release more carbon per unit of food[54] and harm more biodiversity than reforestation of abandoned land offsets elsewhere. The losses of carbon during land conversion also occur quickly, whereas rebuilding carbon in vegetation and soils occurs gradually over longer time periods, exacerbating climate change in the interim.[55] The common tendency of countries to replant abandoned land as forest plantations also reduces carbon and biodiversity benefits.

A sustainable food future therefore requires efforts to reduce agricultural land-shifting, minimize the environmental consequences of inevitable expansion in some countries, and more actively reforest abandoned agricultural land. Under the Bonn Challenge—a global effort to bring 350 Mha into restoration by 2030—47 national and subnational actors have now committed to restore over 160 Mha.[56]

Figure 12 | **Gross forest losses are far greater than net forest losses because agricultural lands are shifting**



Source: FAO (2012a).

MENU ITEM: Link Productivity Gains with Protection of Natural Ecosystems

Although yield gains are critical to achieving food security and reducing the need for global agricultural land expansion, yield gains may increase profitability locally, which may encourage conversion of natural landscapes to increase export share. New roads and other infrastructure can also make it profitable to convert new lands. Governments today have plans for major new roads in Africa and Latin America that would likely lead to extensive conversion to agriculture and loss of habitat in many biodiversity hotspots.[57] If the world is to reap the benefits of productivity gains while protecting natural ecosystems, efforts to do both must be explicitly linked.

Experience has shown that, given political will and sufficient enforcement, governments can protect forests and other natural landscapes. In many countries, governments own the majority of natural lands. They can control how and where private parties may claim ownership or rights to develop public lands though, in some cases, a difficult balance must be struck between enforcement of land-use restrictions and the needs of impoverished smallholders.[58] Where farmers have clear title to their land, governments can combine enforcement with support for agricultural improvement on existing farmland to build social support. Modern monitoring techniques can now provide a powerful foundation for accountability and enforceability of forest protection laws. Not least, governments can designate natural and Indigenous Peoples' protected areas that recognize local rights and protect forests. Researchers have found that recognizing indigenous lands has significantly reduced forest clearing and disturbance in the Amazon.[59]

Linking agricultural improvement and ecosystem protection has potential to attract additional aid and investment from parties interested in either goal. Governments, financiers, and other parties should pursue such linkages and make them as explicit as possible through a variety of mechanisms:

- **International finance.** Development assistance should explicitly link programs to improve agriculture production with forest (or other natural ecosystem) protection. Also, international private financiers should give preferential access to finance for investments that make the linkage to protection explicit.

- **Agricultural loans.** National governments should learn from Brazil's example by legally linking credit and other agricultural improvement assistance to protection of native habitats.
- **Supply chain commitments.** Buyers and traders of agricultural commodities should set purchasing contracts conditioned on the commodity not being linked to natural ecosystem conversion.
- **Land-use planning.** International agencies should help national governments develop detailed spatial tools that guide agricultural zoning and roadbuilding away from natural ecosystems.

All of the above could be integrated in a "jurisdictional approach" at a national or subnational level, motivated by REDD+ finance or other means. An example from Brazil is Mato Grosso's "Produce, Conserve, and Include" development plan, which aims to promote sustainable agriculture, eliminate illegal deforestation, and reduce GHG emissions.[60]

MENU ITEM: Limit Inevitable Cropland Expansion to Lands with Low Environmental Opportunity Costs

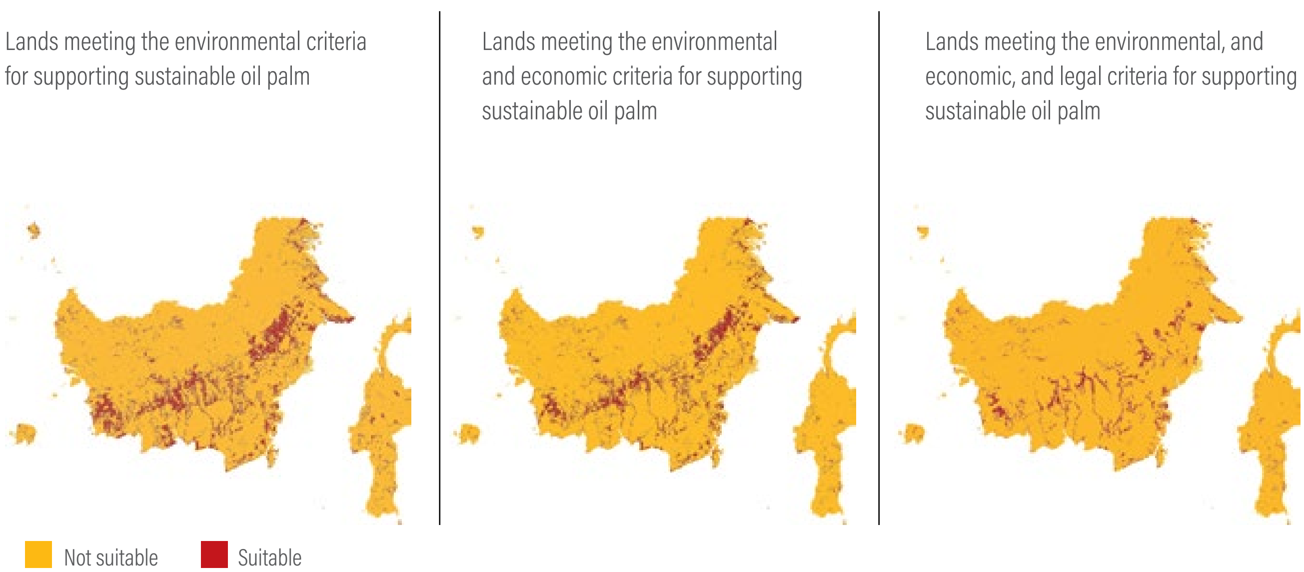
In some countries, preventing all agricultural land expansion is not feasible. For example, rising food demand in Africa will realistically require some land expansion, as will global demand for vegetable oil in Southeast Asia. In countries where expansion or shifts of agricultural land are inevitable, countries need to identify and facilitate expansion only where it would cause less environmental harm.

The goal is to find lands with relatively low environmental (and other) opportunity costs but with good productive potential. These opportunities involve trade-offs (Figure 13). Evaluation of land conversion requires assessing not only the loss of existing carbon but also the forgone carbon sequestration on lands that would otherwise regenerate, for example, on cut-over areas. It should also require analysis of the carbon and biodiversity losses per ton of crop (not per hectare) to minimize total environmental costs while meeting food needs.

This menu item requires above all a commitment by national governments, but it also requires tools that international aid agencies should help fund and that could also help link agricultural improvement and natural landscape protection more generally:

- Tools and models must estimate likely yields and effects on biodiversity and carbon of different development patterns, incorporate information on various obstacles, and allow a wide range of stakeholders to explore acceptable alternatives. A tool developed for Zambia, for example, showed how balancing production and environmental goals could come close to maximizing yield potential while holding down transportation costs, carbon losses, and adverse effects on biodiversity.[61]
- Integrating such tools with analyses of agricultural potential and current farming systems on existing agricultural land could help target use of agricultural improvement funds. Tools that are useful at the farm level and then aggregate to the regional and national level have the greatest potential because their use should improve the quality of analysis over time.
- Governments will need to use such assessment tools to guide land-use regulations, plan road routes, and manage public lands.

Figure 13 | **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).

MENU ITEM: Reforest Abandoned, Unproductive, and Liberated Agricultural Lands

Because some agricultural land will inevitably shift, maintaining forest and savanna area will require reforestation of abandoned agricultural land or restoration to other natural or seminatural ecosystems.[62] History shows that regeneration typically occurs naturally, though governments have assisted the process by subsidizing tree planting. But planting often creates single-species forest plantations with little biodiversity and less carbon than natural, diverse forests. Because of land-shifting, such plantations can contribute to global loss of natural forest cover.

The potential for reforestation is sometimes overestimated.[63] For example, some studies assume that wetter pasturelands, particularly those that were originally forest, are simply available for planting forests, without recognizing the important role they play in producing milk or meat or the fact that their intensification will be necessary just to keep pasture area from expanding. Larger-scale reforestation to mitigate climate change will be possible only if agricultural land is "liberated" through highly successful efforts to slow growth in food demand and intensify production on existing land.

Pending such success, because of growing global food needs, reforesting land in agricultural use for climate purposes should generally be limited to land that is producing little food and has low potential for agricultural improvement. Prime examples are many of the degraded and low-productivity pastures of Brazil's Atlantic Forest region, which are hard to improve because of steep slopes but which could recover into carbon-rich and biologically diverse forests.[64]

Governments should commit more efforts to natural reforestation of marginal or abandoned agricultural land and should give greater emphasis to establishing diverse natural forests. These efforts will require new funding and they would be a good use of international climate funds. Once commitments in this direction are made, they should take account of practical lessons that have already become clear:

- Governments and other actors can sometimes keep costs down by pursuing "assisted natural regeneration," which involves keeping fire, livestock grazing, or other disturbances away from land targeted for reforestation.
- Governments can provide lines of concessional credit for replanting trees within traditional agricultural loans.
- Governments can help fund nurseries of native tree species.
- Governments can monitor progress, in part to determine the need for midcourse corrections and in part to enforce forest protection for newly reforested areas as well as older forests.

MENU ITEM: Conserve and Restore Peatlands

The highest priority for immediate restoration should be the world's 26 Mha of drained peatlands. This small area is responsible for roughly 2 percent of annual human-caused GHG emissions, according to our estimates. The best evidence indicates that roughly half of these peatlands have little or no agricultural use or are used only for grazing.

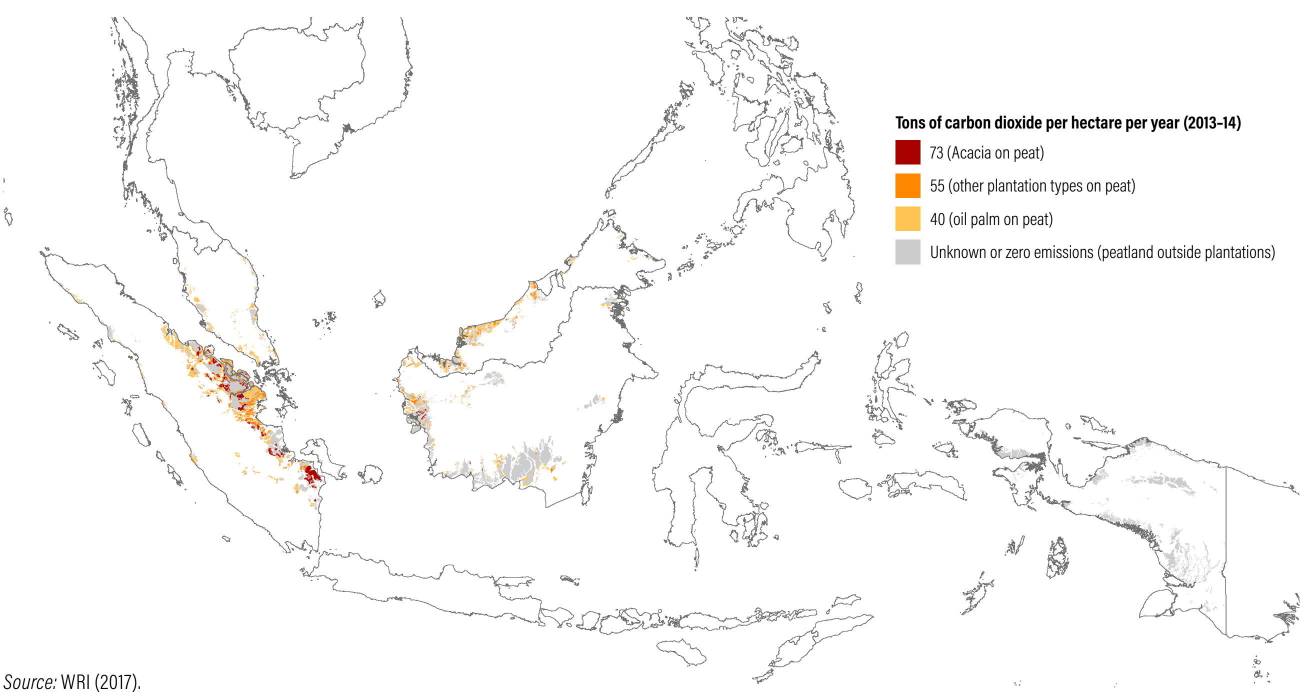
Peatlands are wetlands that built up massive carbon-rich soils over hundreds or thousands of years.[65] Their conversion for agriculture and plantation forestry typically requires drainage, which causes the soils to decompose and sometimes burn, releasing large quantities of carbon into the atmosphere (Figure 14). Rewetting peatlands by blocking drainage ditches can typically eliminate emissions.

Peatlands appear to be far more extensive than previously thought, suggesting high risk of further losses. Researchers have recently discovered the world's largest tropical peatland in the heart of the Congo rainforest in central Africa.[66] It stores an estimated 30 gigatons of carbon, equivalent to roughly 20 years of U.S. fossil fuel emissions. Other large peatlands probably exist in Latin America.

Modest efforts at restoration have occurred in Russia.[67] The president of Indonesia has announced a broad restoration goal, and the country reported 200,000 hectares of peatland restoration between 2017 and 2018.[68] Yet the global effort to restore peatlands is minimal compared to the need. Eliminating half of peatland emissions would close the global GHG emissions gap by 5 percent, while eliminating 75 percent would close the GHG mitigation gap by 7 percent. A series of actions is required:

- Restoration efforts require more funding both to perform the physical restoration and to compensate farmers and communities who must forgo other uses, even if relatively modest. Ideally, assistance would be used to boost productivity on farms outside peatlands.
- Peatland conservation and restoration require better mapping, especially because peatlands cannot be identified from satellite imagery. Mapping and data collection should be a priority for national governments, international agencies, and even private parties.
- Strong laws must protect peatlands to prevent their conversion to agriculture.

Figure 14 | **Greenhouse gas emissions from drained peatlands are ongoing in Indonesia and Malaysia**



Source: WRI (2017).

COURSE 4: INCREASE FISH SUPPLY

Fish, including finfish and shellfish, provide only small percentages of total global calories and protein, but they contribute 17 percent of animal-based protein,[69] and are particularly important for more than 3 billion people in developing countries.[70] We project fish consumption to rise 58 percent between 2010 and 2050, but the wild fish catch peaked at 94 million tons in the mid-1990s and has since stagnated or perhaps declined.[71] This course proposes ways to improve wild fisheries management and raise the productivity and environmental performance of aquaculture.

MENU ITEM: Improve Wild Fisheries Management

According to FAO, 33 percent of marine stocks were overfished in 2015, with another 60 percent fished at maximum sustainable levels (Figure 15). One World Bank study found that world fishing effort needs to decline by 5 percent per year over a 10-year period just to allow fish stocks to rebuild.[72]

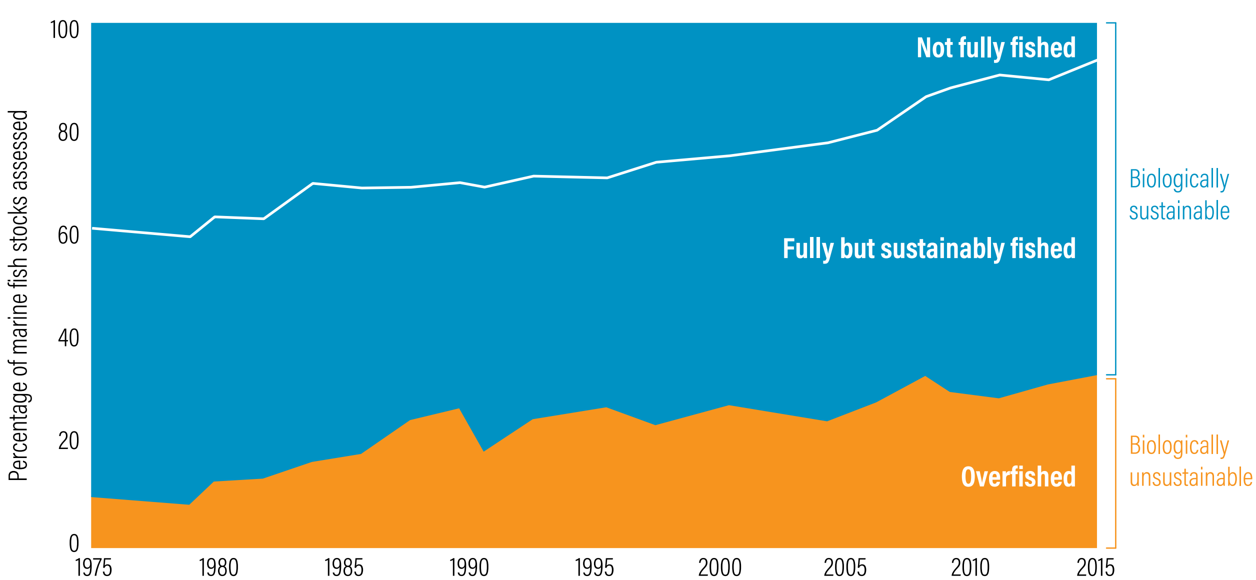
Solutions to curb overfishing are well-known and documented. They focus on principles including limiting catches to a level that allows the fish population to reproduce, limiting the number of fishers to an economically sustainable level, protecting habitat, and avoiding harvest during important breeding times or in important breeding areas.

The challenges to implementing these solutions are largely political and social. Wild fish are a public resource that individual fishers have incentives to exploit before others can do so. Other challenges reflect power imbalances, where foreign fleets from richer countries often are able to obtain agreements to fish in the waters of poorer countries with weaker laws and enforcement capacity. Solutions require mechanisms for persuading fishers to support reductions in fish catch levels:

- Catch shares limit total fish catch and allocate shares of the catch among fishers, who then have a long-term interest in preserving the health of the fishery.
- Where oversight is weaker, 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.
- Removing perverse subsidies—estimated at $35 billion annually[73]—could dramatically reduce overfishing.

Because reducing overfishing is hard, we assume a 10 percent reduction in wild fish catch between 2010 and 2050 in our baseline scenario, and even that goal requires major reforms. A scenario in which fisheries are rebuilt enough to maintain the 2010 level of fish catch in 2050 would have little effect on our gaps but would supply an additional 9 Mt of fish (relative to our 2050 baseline) and would avoid the need to convert 5 Mha of land to supply the equivalent amount of fish from aquaculture ponds.

Figure 15 | **The percentage of overfished stocks has risen over the past 40 years**



Source: FAO (2018).

MENU ITEM: Improve Productivity and Environmental Performance of Aquaculture

Growth in world fish supply since the 1990s has come from aquaculture (fish farming). Aquaculture production would need to more than double between 2010 and 2050 to meet projected fish demand in our baseline (Figure 16).

Aquaculture is a relatively efficient means of supplying animal-based protein. Although efficiencies vary by type of fish and production method, average land-use demands are on par with poultry production (Figure 5) and can even be zero for certain species (e.g., bivalve mollusks). Greenhouse gas emissions from aquaculture are similar to those of poultry and pork production, and much less than those of ruminant meats.

Yet aquaculture presents a range of environmental challenges, which vary by production system. They include conversion of valuable wetland habitats (such as mangroves), use of wild-caught fish in feeds, high freshwater demand, water pollution, and effects of escaped farm fish on wild fish. Aquaculture ponds occupied an estimated 19 Mha in 2010, while an additional 27 Mha was used to grow crop-based fish feed. The total land-use demands roughly double in our 2050 baseline projection.

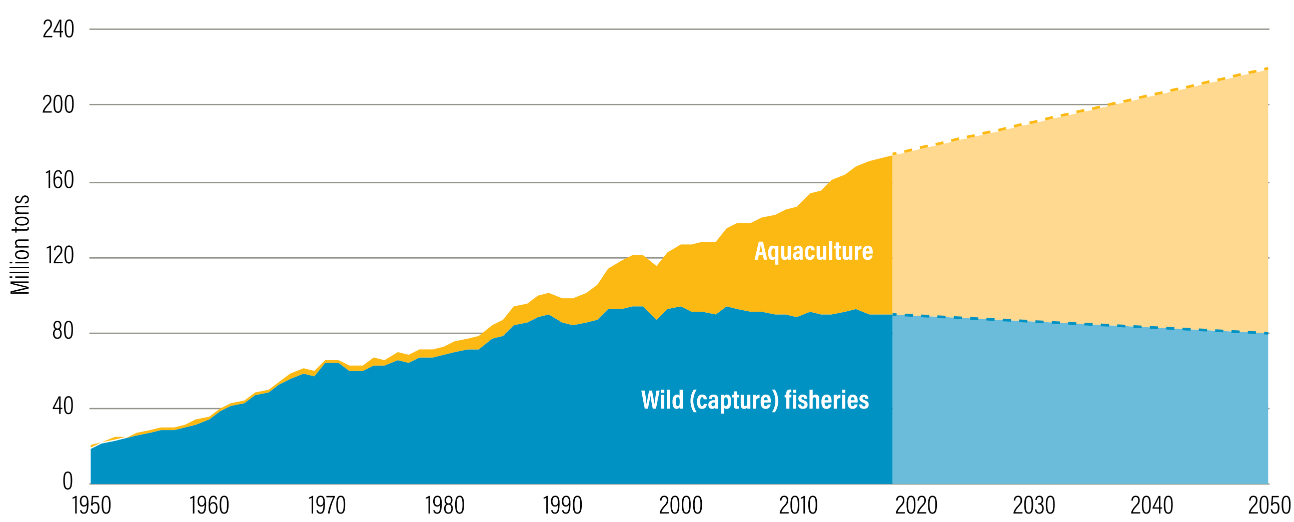
Aquaculture must become more land-efficient, especially because available land is constrained in Asia, where nearly 90 percent of aquaculture production occurs.[74] Shifting to deeper ponds with water recirculation will be necessary to increase production while limiting land expansion. Opportunities also exist to expand aquaculture in marine waters, possibly further offshore.

Aquaculture growth will require development of feed substitutes to replace oil from wild fish because this source is already near or above ecological limits. Promising alternatives include microalgae-based feeds and uses of genetically engineered yeasts or oilseeds bred to produce the omega-3 fatty acids that characterize wild fish oil. Aquaculture must also overcome significant rates of fish disease.

Several strategies can help aquaculture grow sustainably to help meet rising fish demand:

- Selective breeding for improved fish growth rates and conversion efficiencies.
- Technological developments in fish oil alternatives, other feed improvements, and disease control.
- Use of water recirculation and other pollution controls.
- Use of spatial planning to optimize aquaculture siting.
- Expansion of marine-based systems.

Figure 16 | **Aquaculture production must continue to grow to meet world fish demand**



Source: Historical data, 1950–2016: FAO (2017b) and FAO (2018). Projections to 2050: Calculated at WRI; assumes 10 percent reduction in wild fish catch from 2010 levels by 2050, linear growth of aquaculture production of 2 Mt per year between 2010 and 2050.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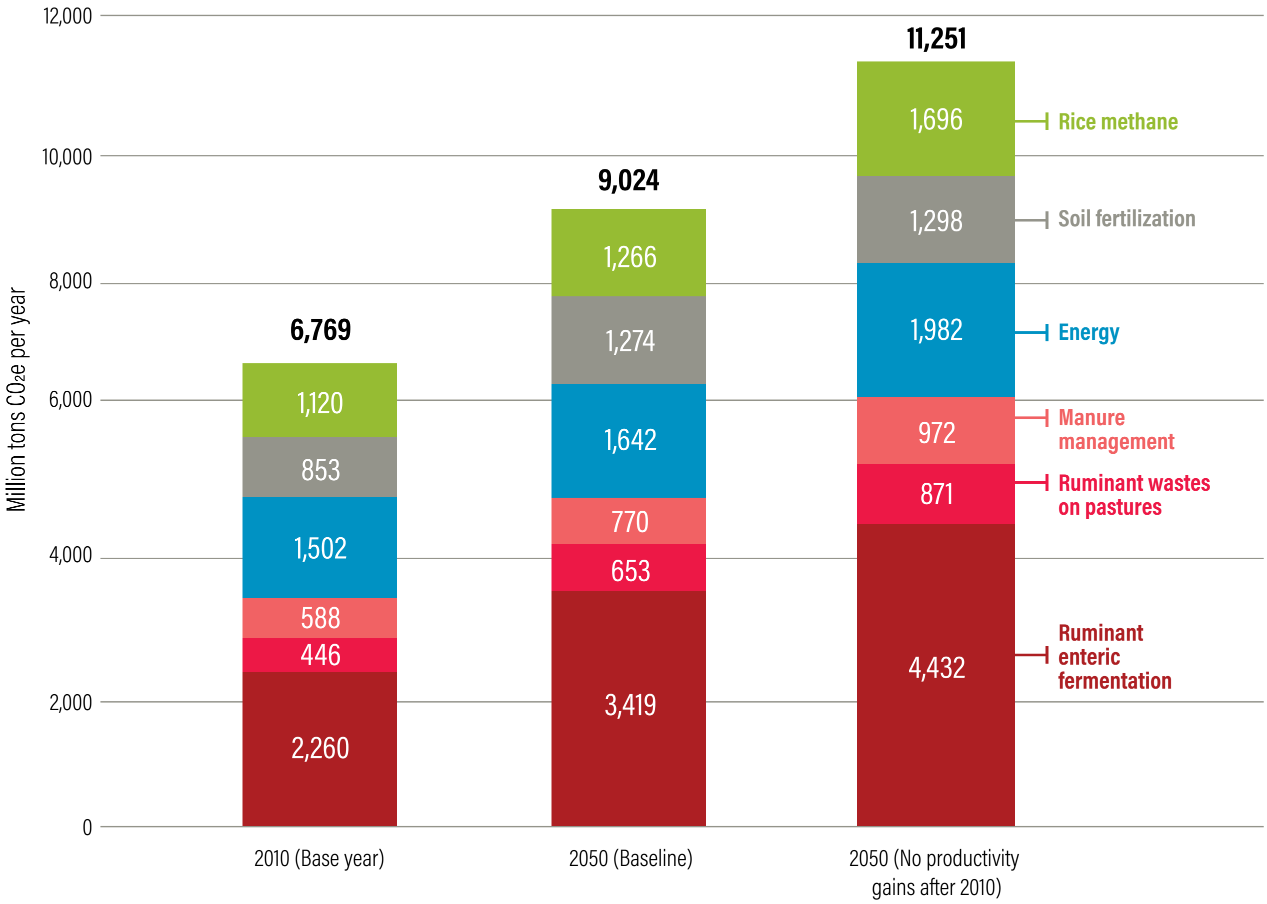
COURSE 5: REDUCE GREENHOUSE GAS EMISSIONS FROM AGRICULTURAL PRODUCTION

Agricultural production emissions arise from livestock farming, application of nitrogen fertilizers, rice cultivation, and energy use. These production processes are traditionally regarded as hard to control. In general, our estimates of mitigation potential in this course are more optimistic than others', partly because many analyses have not fully captured the opportunities for productivity gains and partly because we factor in promising potential for technological innovations.

Even with Large Productivity Gains, We Project Production Emissions to Rise

Annual emissions from agricultural production processes (i.e., excluding emissions from land-use change) reach 9 Gt in our 2050 baseline (Figure 17), leaving a 5 Gt GHG mitigation gap relative to our target emissions level of 4 Gt. The baseline already incorporates large productivity gains, without which the gap would rise to 7 Gt. Most production emissions take the form of two trace gases with powerful warming effects, nitrous oxide and methane.

Figure 17 | **Annual agricultural production emissions reach 9 gigatons in our 2050 baseline projection**



Source: GlobAgri-WRR model.

MENU ITEM: Reduce Enteric Fermentation through New Technologies

Ruminant livestock (mainly cattle, sheep, and goats) generate roughly half of all agricultural production emissions. Of these emissions, the largest source is "enteric methane," generated by microbes in ruminant stomachs.

The same measures needed to increase productivity of ruminants and reduce land-use demands will also reduce methane emissions, mainly because more milk and meat is produced per kilogram of feed. Because the improvements are greatest when moving from the worst-quality feeds to even average-quality feeds, the greatest opportunities to reduce emissions exist in poorer countries. Improving highly inefficient systems causes emissions per kilogram of meat or milk to fall very sharply at first as output per animal increases (Figure 18).

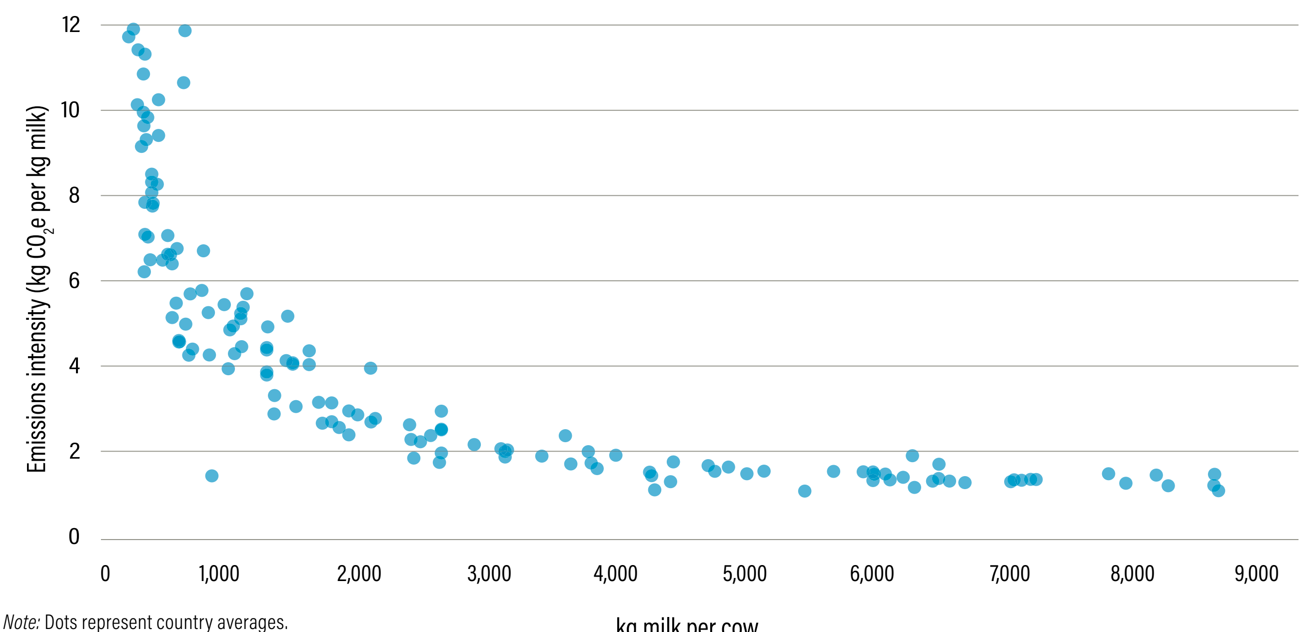
Other strategies to reduce enteric methane emissions rely on manipulating microbiological communities in the ruminant stomach by using vaccines; selectively breeding animals that naturally produce fewer emissions; or incorporating special feeds, drugs, or supplements into diets. These efforts have mostly proved unsuccessful. For example, despite testing thousands of compounds, researchers have found that methane-producing microbes quickly adapt to drugs that initially inhibited them.[75]

More recently, at least one highly promising option has emerged that persistently reduces methane emissions by 30 percent, and may also increase animal growth rates.[76] So far, this compound—called 3-nitrooxypropan (3-NOP)—requires daily feeding at a minimum, so it is not feasible today for most grazing operations unless dosing can be refined.

Enteric fermentation, atypically, is receiving a reasonable level of R&D funding. It is possible that 3-NOP could eventually pay for itself through reduced feed needs or increased productivity, but these benefits are not guaranteed. However, because the compound will be highly cost-effective for GHG mitigation, we recommend that governments consider three policies:

- Provide incentives to the private sector by promising to require use of 3-NOP or other compounds if and when they are proven to mitigate emissions at a reasonable cost.
- Fund large-scale 3-NOP or related demonstration projects in the short term.
- Maintain public research into compounds to reduce methane from enteric fermentation.

Figure 18 | **More efficient milk production reduces greenhouse gas emissions dramatically**



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

MENU ITEM: Reduce Emissions through Improved Manure Management

Manure is "managed" when animals are raised in confined settings and farmers remove the manure and dispose of it. (Manure that ruminants deposit directly on fields is considered "unmanaged" and is addressed in the next menu item.) Managed manure generates both methane and nitrous oxide emissions. Pigs generate roughly half of these emissions, dairy cows just over one-third, and beef cows roughly 15 percent.[77]

The majority of manure is managed in "dry" systems, which account for 40 percent of total managed manure emissions despite low emissions rates.[78] Estimates of mitigation potential tend to be low, in part because management costs tend to be high per ton of emissions. Even so, the use of dry systems is desirable because emissions from "wet" systems (where farmers do not attempt to dry out manure before storage) can be 20 times higher per ton of manure.[79] We also believe that separating liquids from solids has underappreciated potential to reduce emissions. Separation technologies range from simple gravity systems to sophisticated chemical treatments. They also reduce hauling costs and make manure more valuable as fertilizer.

Per ton of GHGs reduced, existing wet systems are easier to mitigate because the manure is generating high levels of emissions. Even an extremely sophisticated system for managing pig manure in North Carolina (United States), using a series of treatment tanks to eliminate virtually all air and water pollution, would cost only an estimated $22 per ton of mitigation (CO_2e).[80] This system would add only around 2 percent to the retail price of pork.[81]

Digesters, which convert manure into methane for energy use, come in high-technology forms that produce electricity in developed countries and simpler household versions used extensively across Asia. They can help reduce emissions but only if manure would otherwise be managed in wet form, and if strong safeguards are in place to keep methane leakage rates low.

Improving manure management will address a range of environmental pollution, human health, and nuisance concerns. Because measures to mitigate emissions would typically contribute to addressing these other concerns, the mitigation may even be "free" from a socioeconomic perspective. Promising strategies are available:

- Phased regulation of facilities, extending from larger to smaller farms, to encourage innovation.
- Government-funded programs, using competition, to develop the most cost-effective technologies.
- Establishment of government programs to detect and remediate leakages from digesters.

MENU ITEM: Reduce Emissions from Manure Left on Pasture

According to standard emissions factors used by the IPCC, nitrogen deposited in feces and urine turns into nitrous oxide at roughly twice the rate of nitrogen in fertilizer. Our 2050 projection already incorporates productivity improvements that lower emissions intensity from manure on pasture by 25 percent compared to 2010, but further increases in feed efficiency could lead to additional modest emissions reductions.

Other studies typically estimate little to no global potential to mitigate this diffuse source of emissions. We are cautiously optimistic, given further development of two nascent technologies. Both work by inhibiting the ability of microorganisms to turn nitrogen from other molecular forms into nitrate, whose further breakdown can release nitrous oxide.

One method involves chemical nitrification inhibitors, which have been found to be quite effective when applied two or three times per year to pastures in New Zealand[82] and—in a very small number of experiments—when ingested by cows. The other involves biological nitrification inhibition, based on findings in Latin America that manure deposited on one variety of the productive *Brachiaria* grass generates almost no nitrous oxide emissions.[83] To exploit this property more broadly, breeders would have to breed this trait into other planted grasses.

These techniques may be more practicable than they appear. Newer research on nitrogen levels in the atmosphere suggests that current emissions factors for unmanaged manure may be too high and that emissions rates are much higher in some fields (usually in wetter areas) than others.[84] This difference in emissions would allow more economical targeting of these techniques toward wetter, more intensively grazed fields.

Research funding to address this challenge is vanishingly small. Far greater efforts and resources must be devoted to exploring an array of potential solutions:

- Governments and research agencies should substantially increase research funding into methods for reducing nitrification of manure.
- Governments should commit in advance to implement regulatory or financial incentives to implement these techniques when they do become available, to encourage research and development by the private sector.

MENU ITEM: Reduce Emissions from Fertilizers by Increasing Nitrogen Use Efficiency

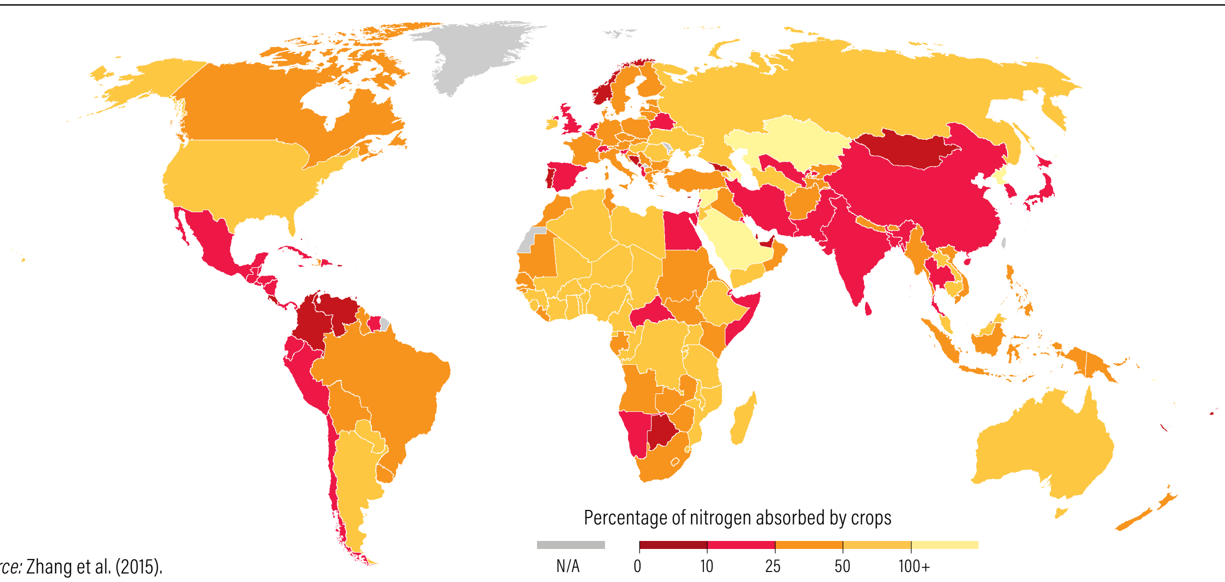
Fertilizers applied to crops and pastures (mostly synthetic fertilizers but also manure and other sources) were responsible for estimated emissions of 1.3 Gt CO_2e in 2010. Nearly all these emissions result from the manufacture, transportation, and application of nitrogen. We project that these emissions will rise to 1.7 Gt by 2050 in our baseline scenario. Globally, crops absorb less than half the nitrogen applied to farm fields. The rest runs off into ground or surface waters, causing pollution, or escapes into the air as gases, including the potent heat-trapping gas nitrous oxide. Countries, and individual farms, vary greatly in their rates of nitrogen application per hectare and in the percentage of nitrogen that is absorbed by crops rather than lost to the environment (known as "nitrogen use efficiency," or NUE) (Figure 19).

Mitigation strategies focus on changing agronomic practices. Technically, extremely high rates of efficiency are possible if farmers are willing to assess nitrogen needs and apply nitrogen frequently in just the required amount over the course of a growing season. The challenge is that such intensive management is expensive while nitrogen fertilizer is cheap. Therefore, we believe innovations are required. Nitrification inhibitors and other "enhanced efficiency" fertilizers can increase NUE, reduce nitrous oxide emissions, and increase yields. But they are used with only 2 percent of global fertilizers,[85] probably because of wide variability in performance and because fertilizer manufacturers today spend little money to improve them. Biological nitrification inhibition is another promising option for crops and pasture grasses but receives little financial support.

We modeled various scenarios of NUE improvement and found that achieving an ambitious global average NUE of 71 percent by 2050 would reduce emissions by 600 million tons, although that would only keep nitrogen emissions close to their 2010 levels. The scope of the nitrogen challenge requires governments to focus on innovative policy approaches:

- Implement flexible regulatory targets to push fertilizer companies to develop improved fertilizers. India provides the closest example to date with its New Urea Policy adopted in 2015.
- Shift subsidies from fertilizers to support for higher NUE, where nitrogen use is excessive.
- Support critical research, particularly into biological nitrification inhibition.
- Fund demonstration projects involving researchers and high nitrogen-using farmers to pursue higher NUE using inhibitors and other innovative technologies.

Figure 19 | **The percentage of applied nitrogen that is absorbed by crops varies widely across the world**



Source: Zhang et al. (2015).

MENU ITEM: Adopt Emissions-Reducing Rice Management and Varieties

The production of flooded or "paddy" rice contributed at least 10 percent of all global agricultural production GHG emissions in 2010, primarily in the form of methane.[86] Available research suggests high technical potential to mitigate rice emissions, and most mitigation options also offer some prospect of economic gains through higher yields and reduced water consumption. We focus on four main options:

- **Increase rice yields.** Because methane emissions are tied more to the area than to the quantity of production, exceeding FAO's forecast rate of yield growth would allow paddy area to remain constant or decrease, reducing emissions.
- **Remove rice straw from paddies before reflooding to reduce methane production.** Straw may be used for other productive purposes such as growing mushrooms or bioenergy.
- **Reduce duration of flooding to reduce growth of methane-producing bacteria.** Farmers can draw down water levels for a few days during the middle of the growing seasons, or plant rice initially into dry rather than flooded land.
- **Breed lower-methane rice.** A few existing varieties emit less methane than others and researchers have shown promising experimental potential,[87] but these traits have not been bred into the most commercial varieties.[88]

A single drawdown reduces emissions, and multiple drawdowns or dry planting plus one drawdown can reduce methane emissions by up to 90 percent.[89] In China and Japan, farmers practice at least one drawdown because it increases yields,[90] though researchers do not find those yield benefits in the United States. Reducing water levels also saves irrigation water, at least at the farm scale.

Yet there are obstacles. Dry planting increases weed growth. Farmers usually will not draw down water unless they are sure they can replace the water and fields are flat enough to ensure no part dries out too much. Another concern is that while drawdowns decrease methane emissions, they tend to increase emissions of nitrous oxide, another powerful greenhouse gas, which encourages joint efforts to use nitrification inhibitors. We propose the following strategies:

- Engineering analyses to determine which farmers have irrigation systems that would allow them to employ drawdowns, followed by programs to reward farmers who practice drawdowns where feasible.
- A major breeding effort to shift to lower-methane varieties.
- Greater efforts to boost rice yields through breeding and management.

MENU ITEM: Increase Agricultural Energy Efficiency and Shift to Nonfossil Energy Sources

Emissions from fossil energy use in agriculture will remain at about 1.6 Gt CO_2e/year in 2050 in our baseline. Our assumption, based on past trends, is that a 25 percent increase in energy efficiency is cancelled out by a 25 percent increase in energy use. Mitigation options mirror those for reducing energy emissions in other sectors: they rely on increasing efficiency and switching to renewable energy sources.

Although studies of potential energy efficiency improvements in agriculture are limited, a small number of country-level studies have found large potential for efficiency gains, for example, in alternative water pumps in India[91] or cassava-drying methods in Africa.[92]

Sixty-five percent of expected agricultural energy emissions in 2050 will result from on-farm energy use. Heating and electrical power can often be provided by solar and wind energy sources, although replacing on-farm coal will require innovative, small-scale solar heating systems. Mitigating the use of diesel fuel by tractors and other heavy equipment will be more difficult and may need to rely on transitions to fuel cells using hydrogen power generated with solar or wind power. Battery-powered equipment and synthetic carbon-based fuels made from renewable electricity may provide alternative technologies.

Renewable sources of hydrogen could also mitigate 85 percent of the emissions from the synthesis of nitrogen fertilizer, currently a highly energy-intensive process. Fortunately, because of the needs of other sectors, substantial research is occurring into production of hydrogen using electricity from solar energy, and costs of solar electricity have been declining rapidly.[93]

The efficiency gains built into our baseline already require significant effort. We estimate that reducing emissions per unit of energy used by 75 percent, rather than the 25 percent in our baseline, would reduce the GHG mitigation gap by 8 percent. To achieve this goal:

- Governments, aid agencies, and large food purchasers should integrate low-carbon energy sources and efficiency programs into all development efforts and supplier relationships with farmers.
- Research agencies and private investors should continue to fund research into production of nitrogen from renewable electricity and support design of demonstration nitrogen fertilizer plants using renewable electricity. Such research could be linked to ongoing work on developing solar-based production of hydrogen.
- Governments should commit to regulating the emissions from fertilizer manufacturing once viable, low-carbon technologies are available.

MENU ITEM: Focus on Realistic Options to Sequester Carbon in Soils

Because reducing agricultural production emissions is challenging, much academic and policy attention has focused on strategies to sequester carbon in agricultural soils to offset those emissions. There are only two ways to boost soil carbon: add more or lose less. But recent scholarship and experience indicate that soil carbon sequestration is harder to achieve than previously thought.[94]

Changes in plowing practices, such as no-till, which once appeared to avoid soil carbon losses, now appear to provide only small carbon benefits or no benefits when measured at deeper soil depths than previously measured. No-till strategies must also contend with adverse effects on yields on some lands and the fact that many farmers who practice no-till still plow up soils every few years, probably releasing much of any carbon gain.[95]

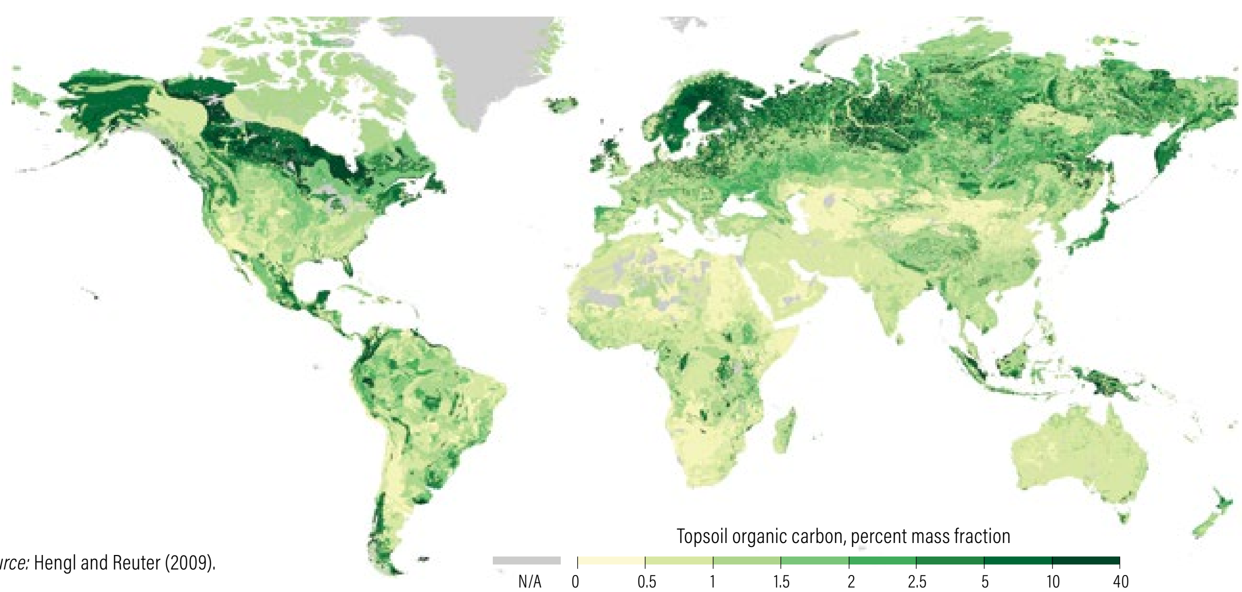
Adding mulch or manure are proposed strategies to add carbon to soils but, in effect, double-count their carbon which would have contributed to carbon storage elsewhere. Leaving crop residues otherwise used for animal feed to become soil carbon requires that the animals' feed comes from other sources, which has some carbon cost because it would often require more agricultural land to grow that feed.

Building soil carbon also generally requires large quantities of nitrogen, which is needed by the microorganisms that convert decaying organic matter to soil organic carbon. Low nitrogen surely limits soil carbon buildup in Africa (Figure 20), where nitrogen additions are insufficient even for crop needs, and probably limits soil carbon buildup elsewhere.[96]

Scientists have come to realize that they do not well understand the factors that lead carbon to remain stored longer in soils rather than being consumed and returned to the air by microorganisms. There is some evidence that croplands are actually losing soil carbon overall in ways neither we nor other researchers count. For these reasons, we do not include additional soil carbon sequestration as a mitigation strategy. We believe efforts are best directed toward stabilizing soil carbon, that is, avoiding further losses, and focusing on no-regrets strategies that provide additional benefits:

- Avoid conversion of carbon-rich ecosystems (e.g., forests).
- Increase productivity of grasslands and croplands, which adds carbon in roots and residues.
- Increase use of agroforestry, which builds above-ground carbon.
- Pursue efforts to build soil carbon, despite the challenges, in areas where soil fertility is critical for food security.

Figure 20 | **Soils in Africa are relatively low in organic carbon**



Source: Hengl and Reuter (2009).

The Need for Flexible Technology-Forcing Regulations

Although many opportunities exist for developing cost-effective, or even cost-neutral, GHG mitigation techniques to curb agricultural emissions, the size of the GHG mitigation gap strongly suggests that voluntary approaches will not be sufficient. We recommend a few forms of flexible regulations that should be designed to spur technological development.

In the case of fertilizer, we recommend that countries develop regulatory systems similar to those developed in the United States that require auto manufacturers to increase the fuel efficiency of their fleets over time. Fertilizer manufacturers would be required to sell increasing percentages of their product in a form with "enhanced efficiency," such as fertilizers incorporating nitrification inhibitors. India has set an example by requiring that fertilizers be coated with neem, which slows nitrogen release.[97] Phased regulation would provide incentives for manufacturers to develop better products, identify the ideal uses, and market them appropriately to farmers who can most benefit from them. Regulating fertilizer is also consistent with historical regulation of agricultural inputs, such as pesticides.

Manure management is typically subject to weak regulation. Governments should phase in requirements for pollution controls that tighten and reach more sources over time, initially covering new and large existing facilities and extending gradually to medium-sized and smaller farms.

In areas where technologies are underdeveloped, such as enteric methane inhibitors, governments should commit in advance to requiring the use of appropriate drugs or feed supplements if a company develops a system that achieves a certain level of cost-effectiveness in mitigation—for example, \$25 per ton of CO_2e. Greater market certainty would provide incentives for the private sector to develop needed innovations.

Many of these options may, at least initially, involve additional costs, but they appear cost-effective when compared to climate change mitigation strategies in other sectors. Many options would have large cobenefits, such as reducing water and air pollution, and controlling disease-bearing organisms from poorly controlled livestock waste. Many might eventually more than pay for themselves as technologies evolve, which is likely true of nitrification inhibitors and could be true of additives to curb enteric methane. Yet these technologies do not seem likely to evolve without either strong incentives or some form of regulation designed to advance their development and deployment.

THE COMPLETE MENU: CREATING A SUSTAINABLE FOOD FUTURE

The individual menu items presented in Courses 1–5 can each contribute to meeting global targets for increasing food production, minimizing expansion of agricultural land area, and reducing GHG emissions. In this section, we use the GlobAgri-WRR model to examine some plausible (or at least possible) combinations of menu items and analyze how they could close the three gaps and achieve a sustainable food future.

To assess the potential of the full menu to close the food, land, and GHG mitigation gaps, we constructed three combination scenarios that reflect ascending levels of ambition (Table 3). They are guided by the following criteria:

- **Coordinated Effort Scenario.** Menu items involve measures we are confident the world could achieve with a strong, coordinated, global commitment to action. The economic costs would be limited or even positive. No fundamental breakthroughs in technology would be required.
- **Highly Ambitious Scenario.** Menu items involve measures at the outer range of what might be technically achieved either with existing technology or with realistic improvements to existing technology. Costs would likely be higher.
- **Breakthrough Technologies Scenario.** Measures from the Highly Ambitious scenario plus those that could be achieved with technological breakthroughs in fields where science has shown significant progress.

The size of the gap closure contributed by each menu item does not necessarily reflect the return per unit of effort. It is more a measure of the definitional scope of each menu item. For example, large reductions in food loss and waste (affecting 24 percent of global calorie production) will, by definition, contribute more than improving productivity of aquaculture, which only affects 1 percent of global calorie consumption.

Table 3 | **The GlobAgri-WRR 2050 baseline projection and three combination scenarios**

MENU ITEM	2050 BASELINE	COORDINATED EFFORT	HIGHLY AMBITIOUS	BREAKTHROUGH TECHNOLOGIES
DEMAND-SIDE SOLUTIONS				
Course 1: Reduce growth in demand for food and other agricultural products				
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
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
Avoid competition from bioenergy for food crops and land	Crop-based biofuels maintained at 2010 share of global transportation fuel (2.5 percent)	Both food and energy crop-based biofuels phased out	Same as Coordinated Effort	Same as Coordinated Effort
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

Table 3 | **The GlobAgri-WRR 2050 baseline scenario and three combined scenarios (continued)**

MENU ITEM	2050 BASELINE	COORDINATED EFFORT	HIGHLY AMBITIOUS	BREAKTHROUGH TECHNOLOGIES
SUPPLY-SIDE SOLUTIONS				
Course 2. Increase food production without expanding 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
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
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)
Course 3. Protect and restore natural ecosystems and limit agricultural land-shifting				
Link productivity gains with protection of natural ecosystems	Linkage prevents most agricultural land-shifting due to yield gains	Same as Baseline	Same as Baseline	Same as Baseline
Limit inevitable cropland expansion to lands with low environmental opportunity costs	Inevitable land expansion is limited such that carbon effects are offset by the menu item below	Same as Baseline	Same as Baseline	Same as Baseline
Reforest abandoned, unproductive, and liberated agricultural lands	Reforestation of lands with little agricultural potential offsets carbon effects of inevitable land shifting	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
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

Table 3 | **The GlobAgri-WRR 2050 baseline scenario and three combined scenarios (continued)**

MENU ITEM	2050 BASELINE	COORDINATED EFFORT	HIGHLY AMBITIOUS	BREAKTHROUGH TECHNOLOGIES
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
Improve productivity and environmental performance of aquaculture	10% increase in aquaculture production efficiencies between 2010 and 2050 across the board	50% switch of extensive pond production to semi-intensive production, and 50% switch of semi-intensive to intensive	Same as Coordinated Effort, plus 20% increase in aquaculture production efficiencies between 2010 and 2050 across the board	Same as Highly Ambitious
Course 5: Reduce greenhouse gas 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 cows—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)
Reduce emissions through improved manure management	Managed manure emissions of 770 Mt CO_2e in 2050 (31% above 2010 level)	40% reduction in methane emissions from wet manure plus 20% reduction in nitrous oxide emissions from all manure (14% growth above 2010 level)	80% reduction in wet manure emissions plus 20% reduction of all nitrous oxide emissions (17% reduction below 2010 level)	Same as Highly Ambitious
Reduce emissions from manure left on pasture	Unmanaged manure emissions from pasture of 653 Mt CO_2e in 2050 (46% above 2010 level)	Same as Baseline	20% reduction of nitrogen left on pastures for non-arid systems (31% growth above 2010 level)	40% reduction in nitrogen left on pastures for nonarid systems (15% growth above 2010 level)
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 improved management plus new technologies
Adopt emissions-reducing rice management and varieties	Rice methane of 1.3 Gt CO_2e in 2050 (13% above 2010 level)	10% reduction in rice methane emissions (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)
Increase agricultural energy efficiency and shift to non-fossil energy sources	25% decrease in energy emissions per unit of output for agriculture 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
Focus on realistic options to sequester carbon in 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

Quantitative results of the three combination scenarios are presented in Table 4. The contributions of specific menu items are shown in Figures 21–23 for the Breakthrough Technologies scenario only. For each menu item, its contribution in the combined scenarios is smaller than its "standalone" contribution due to interaction between menu items (e.g., land "savings" attributed to food waste reductions are smaller if those reductions happen simultaneously with additional crop yield growth).

All three scenarios substantially reduce the food gap by reducing the rate of growth in demand for food. The challenge of increasing crop production by 56 percent between 2010 and 2050 (baseline) is reduced to 43 percent, 35 percent, and 29 percent in the three scenarios, respectively.

The Coordinated Effort scenario reduces agricultural land expansion between 2010 and 2050 by 78 percent. The Highly Ambitious and Breakthrough Technologies scenarios completely close the land gap and create the opportunity for significant reforestation on liberated agricultural land.

The hardest gap to close is the GHG mitigation gap because it is difficult to reduce annual agricultural production emissions to the 4 Gt CO_2e target while feeding everyone in 2050. Annual production emissions remain at 4.4 Gt even in our Breakthrough Technologies scenario (Figure 23). Reaching the 4 Gt goal would require major technological advances as well as full reforestation on at least 80 Mha of liberated agricultural land.

Furthermore, other analyses have suggested that to meet the more ambitious 1.5°C warming target in the Paris Agreement,[98] the world will need to use large quantities of land to offset other sources of emissions. In our Breakthrough Technologies scenario, it might be possible to liberate 585 Mha of agricultural land—after accounting for some expansion of timber plantations and human settlements—which, if fully reforested, could offset around 4 Gt of emissions per year for many years.

Plausible pathways toward a sustainable food future exist, but they will require strong and almost universal political and social effort. Achieving even our Coordinated Effort scenario requires reversing a wide range of current trends. Truly realizing the environmental benefits from food demand reductions and crop and livestock yield gains also depends on policies that greatly reduce agricultural land-shifting and protect forests and other natural areas.

Table 4 | **Global effects of 2050 combination scenarios on the three gaps, agricultural land use, and greenhouse gas emissions**

		SCENARIO				
		NO PRODUCTIVITY GAINS AFTER 2010	2050 (BASELINE)	COORDINATED EFFORT	HIGHLY AMBITIOUS	BREAKTHROUGH TECHNOLOGIES
Food Gap (2010–50)		62%	56%	43%	35%	29%
Change in agricultural area, 2010–50 (Mha)	Pastureland	2,199	401	128	-390	-446
	Cropland	1,066	192	4	-180	-355
	Total	**3,265**	**593**	**132**	**-570**	**-801**
Annual GHG Emissions, 2050 (Gt CO_2e)	Agricultural production	11.3	9.0	7.4	5.5	4.4
	Land-use change	26.9	6.0	1.7	0.3	0.3
	Total	**38.2**	**15.1**	**9.1**	**5.8**	**4.6**
GHG Mitigation Gap (Gt CO_2e)		34.2	11.1	5.1	1.8	0.6

Notes: Numbers may not sum correctly due to rounding. Under the Highly Ambitious and Breakthrough Technologies scenarios, 0.3 Gt CO_2e of ongoing peatland emissions remain, but total agricultural area declines between 2010 and 2050. We discuss the need to reforest "liberated" agricultural lands to offset agricultural production emissions on page 59.
Source: GlobAgri-WRR model.

We conclude that three categories of menu items are particularly important at the global level:

Boosting productivity. The Coordinated Effort scenario requires faster rates of crop yield growth than historical rates since the 1960s. Recent yield trend lines (since the 1980s) are actually slower than those in our baseline, and far from the additional yield gains required. Ruminant meat and milk yield gains in the Coordinated Effort scenario require massive increases in output per hectare of pastureland—far greater than the output gains projected by extending a linear trend from the 1960s.

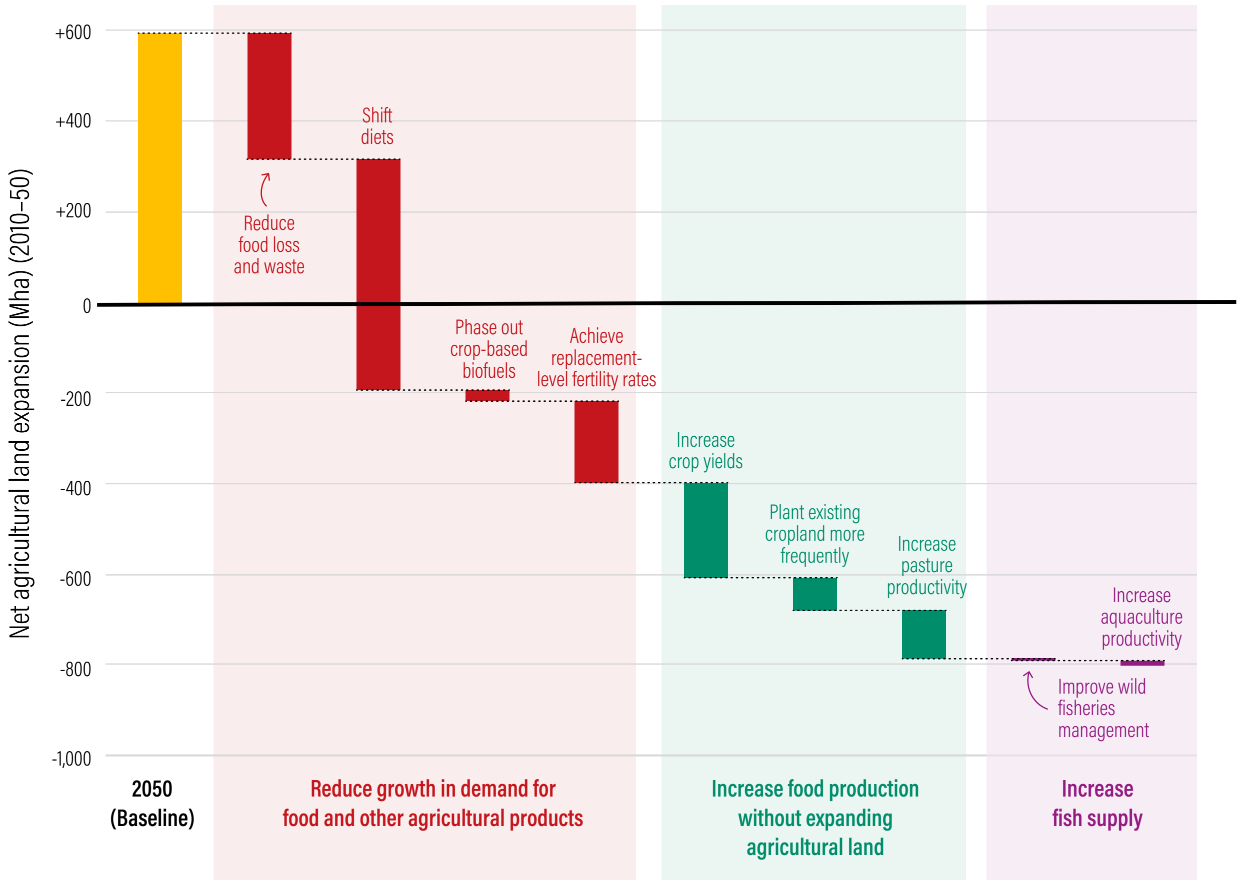
Shifting diets to reduce demand for ruminant meat. A reduction in ruminant meat consumption by 30 percent relative to our 2050 baseline—which still results in a 32 percent increase above 2010 levels—plays a major role in closing the land and GHG mitigation gaps. We consider it eminently practicable, but the cultural and behavioral changes required will be challenging.

Reducing food loss and waste. Globally reducing the rate of food loss and waste by 10, 25, or 50 percent would significantly close all three gaps. However, there is little precedent for achieving such large-scale reductions—particularly because as countries' economies develop, food waste near the consumption side of the food supply chain tends to grow even as food loss near the production side decreases.

Figure 21 | **Under the Breakthrough Technologies scenario, the amount of additional food needed to feed the world in 2050 could be cut by half**

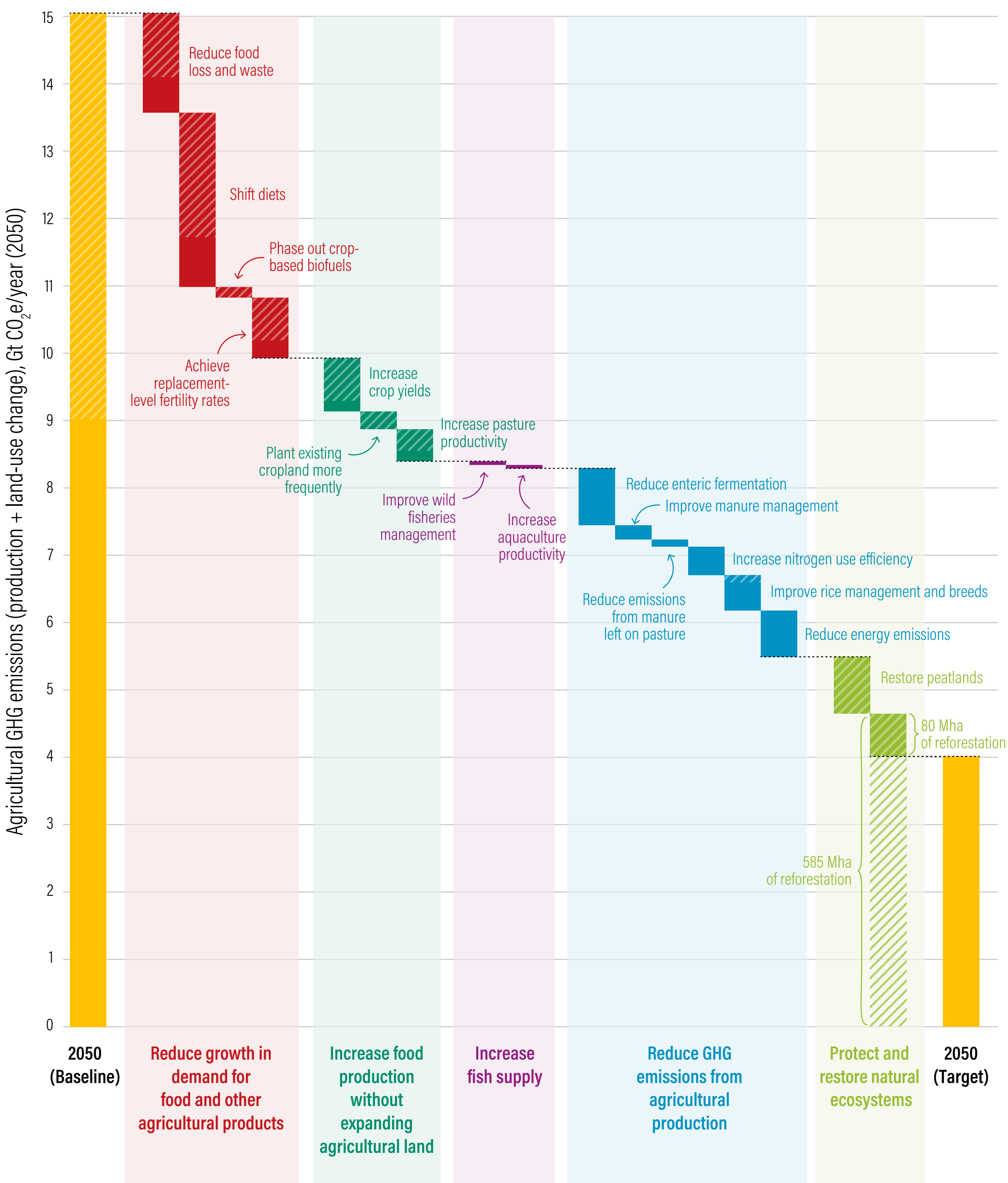
Note: Includes all crops intended for direct human consumption, animal feed, industrial uses, seeds, and biofuels.
Source: GlobAgri-WRR model.

Figure 22 | **Under the Breakthrough Technologies scenario, the area of land needed for agriculture could shrink by 800 million hectares, which would be liberated for reforestation**



Source: GlobAgri-WRR model.

Figure 23 | **Under the Breakthrough Technologies scenario, agricultural greenhouse gas emissions would fall dramatically but reforestation and peatland restoration would be necessary to meet the target of 4 gigatons per year**



Note: Solid areas represent agricultural production emissions. Hatched areas represent emissions from land-use change.
Source: GlobAgri-WRR model.

CROSS-CUTTING POLICIES FOR A SUSTAINABLE FOOD FUTURE

The menu items for a sustainable food future, described and analyzed in our five courses, focus heavily on technical opportunities. However, menu items cannot be implemented in isolation, and they are all subject to a variety of cross-cutting public and private policies. In addition to reducing demand growth and boosting productivity, policies must reduce rural poverty by helping smallholder farmers become more market-oriented, even as many of them inevitably shift toward alternative employment.

Boost Productivity and Reduce Rural Poverty

Higher rural incomes will depend on raising the productivity of smallholder farmers and linking them to more lucrative markets. Progress will require giving farmers greater security to invest in producing marketable products where they have a comparative advantage, securing their land rights, and rectifying historical disadvantages confronting women farmers.

Allow farms to grow based on market and social forces, but avoid large or government-facilitated acquisitions unless they involve existing large farms

About 80 percent of the world's farms are small (less than 2 hectares), but they occupy only about 12 percent of the world's agricultural land.[99] The number of small farms is growing, as families subdivide their land and some farms become too small to supply a full-time livelihood. Small farmers face real obstacles in the form of limited access to capital for productivity improvements, difficulties in meeting the tight sanitary and quality standards required by supermarket chains, and poverty traps that force farmers to sell critical assets in tough times. Yet in Africa and Asia, studies have consistently found small farms to be more productive per hectare than larger farms[100] (though sometimes not the largest farms).[101] More successful small farms tend to have market access and opportunities for off-farm employment to supplement income generated by the farm. Overall, government policies should not force small farms to consolidate or encourage large farms to take over small farms, but neither should they fight the autonomous growth of farms.

This less interventionist policy should also apply to large land acquisitions, which some governments have encouraged in recent years. The size and number of such deals is hard to track, and some early estimates were too high. The best information is that international investors acquired ownership or long-term leases for 44 Mha of land between 2000 and 2016 and are in some stage of agreement to acquire another 18 Mha.[102] Major domestic investors are also acquiring large tracts of land. Although some acquisitions claim to be focused on supplying food for domestic markets, bioenergy production and to a lesser extent producing food destined for foreign markets motivated many transactions.

Acquisitions of preexisting large farms, including abandoned large farms in much of the former Soviet Union, raise few social or environmental concerns. In other parts of the world where small farms predominate, careful analyses have shown mostly adverse consequences for local people despite a variety of claimed social protections.[103] Large acquisitions often involve land that is not intensively cropped but is used by local people for grazing, fishing, and long-rotation cropping. Many acquisitions of forested or other wooded land and wetlands are, in effect, forms of environmentally harmful agricultural expansion.

Move toward more equitable and secure property rights, and facilitate cash crop production through cooperative and contract farming

In much of the world, farmers and forest dwellers lack the secure, registered titles to property that are common in Europe and North America. Many researchers, international aid agencies, and nonprofit organizations have long advocated for stronger recognition of property rights to protect farmer interests and sometimes increase access to credit. However, as the World Bank found in 2008, efforts to shift to Western-style property rights "were often adopted less to increase efficiency than to further interests of dominant groups" and resulted in greater land consolidation and inequality.[104] Many scholars also found that shifting to more official land titling in Africa often did not result in productivity increases, in part because customary rights are more secure than previously thought.

Recent efforts have emphasized recognition of customary rights, including shared rights to use land and trees, and the need for formalization of rights to correct historical inequities, such as the exclusion of women from ownership of or decision-making about land. Information technology has reduced the physical difficulties of mapping and registering land but governments need to reduce the bureaucracy and legal obstacles that still block the award of community rights in many countries.[105]

Governments also should establish legal frameworks and basic social security systems that make it easier for small farmers to raise high-value cash crops through contract or cooperative farming.[106] Farmers can overcome the challenges of small size by linking, in various forms, to larger organizations through contracts or farmer associations. Such arrangements offer potential advantages of branding, access to expertise, shared or lower costs for inputs, and access to more specialized markets. But the costs can sometimes include lower prices imposed by a local monopoly, unfair or inefficient cooperative management, and potential cheating by either party to the contract as prices fluctuate. As a result, these systems tend to focus on high-value food or other cash crops, where high quality or reliability is rewarded by the market.[107] Developing country climates often favor such crops, but, while they are potentially more profitable, specialization can also increase risk due to disease, changing market conditions, or dishonest purchasers. Legal frameworks that fairly enforce contract farming and support basic incomes for rural workers can help small farmers focus on growing more lucrative products, raise incomes, and possibly help reduce global land demands.

Climate Policy and Agriculture

Because no government can know the relative feasibility of all actions to reduce GHG emissions, sound, cost-effective climate policies typically mandate outcomes rather than technologies or practices.

The role of carbon pricing, emissions caps, and carbon offsets

Many governments and economists favor putting a price on emissions via a carbon tax or cap-and-trade system. Each emitting source then has an incentive to reduce emissions as cheaply as possible. Unfortunately, applying this approach to land-use and agriculture faces practical problems. Monitoring emissions from diverse and diffuse sources is not feasible (unlike tracking the quantity of coal or oil burned). Also, it is often not feasible to determine which changes in soil or forest carbon are caused by the landowner, the weather, or the actions of others.

Creative pricing programs therefore have to be designed for features of the agricultural system that can be measured. For example, governments could impose a tax on fertilizers that do not incorporate a nitrification inhibitor or time-release mechanism (assuming these alternative fertilizers are available to farmers). The tax level would be based on the difference in emissions expected from use of conventional versus improved fertilizer. Different forms of manure management could also be taxed differentially. Retail food taxes on high-emissions foods would also help internalize climate costs and could be offset with subsidies for low-emissions foods.

For many years, climate mitigation policies for agriculture focused on their potential to provide offsets to mitigate fossil energy emissions. The hope was that energy users could pay farmers to reduce emissions more cheaply than they could themselves, and that these practices would, in turn, help farmers boost productivity and resilience. The Clean Development Mechanism recognizes a small number of agricultural practices as offsets,[108] and the Canadian province of Alberta recognizes many more in a local program.[109]

Unfortunately, agricultural offsets mean that reductions in the agricultural sector are credited to the energy sector and allow more emissions there, so they cannot count as agricultural mitigation. However, stringent climate goals require sharp reductions of emissions in both sectors. Agricultural offsets also present large administrative challenges. By definition, an offset must require "additional" reductions in agricultural emissions, but additionality is subject to uncertainty. The more cost-effective the mitigation, the greater the likelihood that it would occur anyway and therefore not be additional. Leakage and monitoring requirements are significant, and small farmers often cannot afford to invest money to reduce emissions up-front while waiting to be paid only after they have reduced emissions or sequestered carbon. As discussed above, soil carbon sequestration turns out to be harder and more uncertain than expected. In the short term, some offsets could stimulate progress in the land sector but, at best, offsets have a limited and temporary role to play in achieving a sustainable food future.

Redirect government farm support and attract climate funding

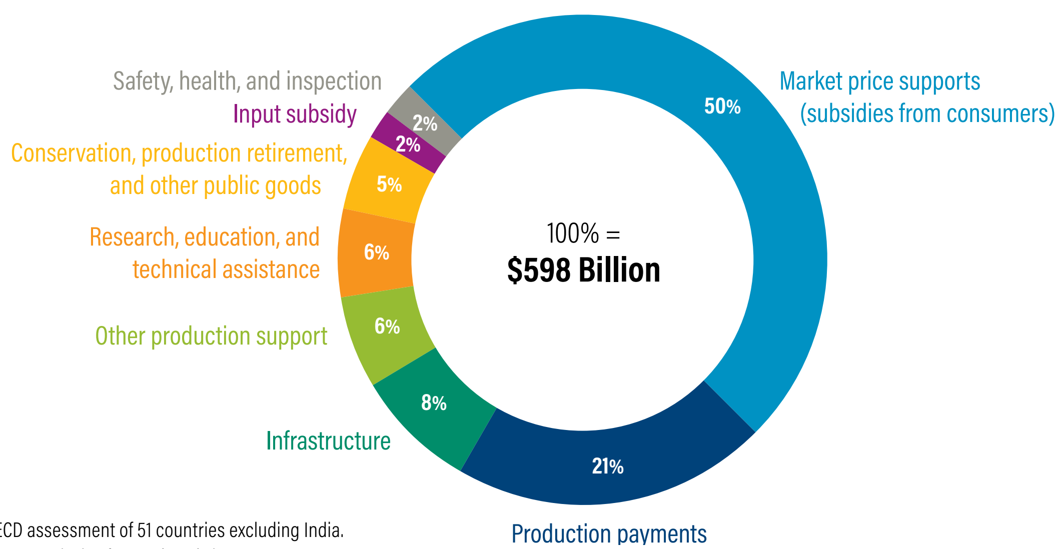
Farming, like any other large industry, requires major investments. The direct investments made by farmers with their own funds or by other domestic private investors account for the overwhelming share of agricultural investment.[110] Policies that facilitate and guide this private investment are therefore more important than direct public funding.

Yet public funding is still important. In 2014–16, public support for agriculture averaged $600 billion per year in countries assessed by the OECD (Figure 24). Half of this total takes the form of market interventions that raise prices to consumers, such as import barriers, tariffs, or systems that limit production by farmers to increase prices. Because these supports are more prevalent in higher-income countries, they offer little market protection for the world's poor. Few of these funds support the menu items identified in this report. From a global perspective, reducing or redirecting the costs of these market interventions would reduce prices and benefit consumers. Many farmers in lower-income countries do, however, benefit from large fertilizer subsidies. The environmental benefits of reducing overapplication of cheap fertilizers are clear in countries where fertilizers are heavily overused. In much of Africa, where soils are nutrient-poor, subsidized fertilizers have achieved only modest yield gains or helped to reduce poverty, though at significant cost to government budgets.

Over the years, countries have reduced some market barriers and linked subsidies to very modest conservation requirements, but funding could do much more to support the interventions needed for a sustainable food future. The most promising examples involve government support for multi-partner research projects to promote new farming practices.

Developed countries have promised to provide $100 billion per year by 2020 to developing countries for climate mitigation and adaptation. To date, they are not on track to meet this goal.[111] For example, as of September 2017, only $10 billion had been committed to the Green Climate Fund.[112] The money is for all climate-related work. If agriculture is to earn its fair share of climate funding, countries are going to need to demonstrate they are implementing detailed, scientifically based plans to mitigate emissions, identify the specific farming changes that will be implemented on specific types of farms, and the likely gains that will result.

Figure 24 | **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: WRI analysis of OECD (2016) data.

Boost Research and Development

Total public and private spending on agricultural research and development (R&D) in 2007–8 (the latest year for which we found global data) was roughly $50 billion.[113] Today, the world probably devotes only around 1.4–1.7 percent of agricultural GDP to agricultural R&D.[114] For a sector that is so sensitive to constantly changing environmental conditions and in which massive growth is required, we consider this amount to be inadequate. We identify two key research and development themes.

Development: The world needs to commit far more resources to the D in R&D for agricultural emissions reduction. "Development" involves the critical technical analyses concerning how to apply research breakthroughs. Researchers know how to draw down water in rice farms and can roughly estimate the emissions reductions, but they do not know which specific irrigation districts have sufficiently reliable water supplies to make drawdowns feasible. Researchers know that improved feeds and health care will increase the productivity of ruminant livestock, but, outside of developed countries, they have only the roughest proxy estimates for how livestock systems work and how they can be improved. Countries have not developed scientifically based land-use plans for targeting agricultural expansion where it is inevitable. Governments and international institutions should fund this kind of development.

Indispensable innovations: We identify multiple examples of technological progress or breakthroughs that are either indispensable or would be enormously helpful in achieving a sustainable food future (Table 5). A few, such as the pursuit of plant-based meat substitutes appetizing to meat eaters, can probably be left mostly to the private sector, but others will require public investment. Governments can also spur innovation by funding pilot projects—particularly large-scale pilots—to use innovative technologies, and by enacting laws to require the use of innovations if they prove effective and cost-efficient.

Table 5 | **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. For example, Apeel Sciences, a small California start-up, has an array of extremely thin 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 using heme that appears to bleed like real meat, and synthetic milk generated from proteins produced by yeasts.

Table 5 | **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 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 initial breeds of rapeseed containing oils nutritionally equivalent to fish oils and promising seaweed varieties. Work is also proceeding on producing algae more economically.
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 reductions for a cheap compound that does not appear to have significant 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 to turn it into energy, but costs and leakage rates reduce viability and greenhouse gas 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 which precise conditions. Moreover, researchers have now identified traits to inhibit nitrification 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 some common rice varieties emit less methane than others and have bred one experimental rice that reduces methane 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.

Avoid Double Counting of Land and Biomass

Some of our menu items differ from other researchers' recommendations where we believe those recommendations are based on analyses that inappropriately count the same land or plant material (biomass) twice. In other words, some other analyses assume that the same land or biomass required to meet one set of needs is simultaneously available to meet another.

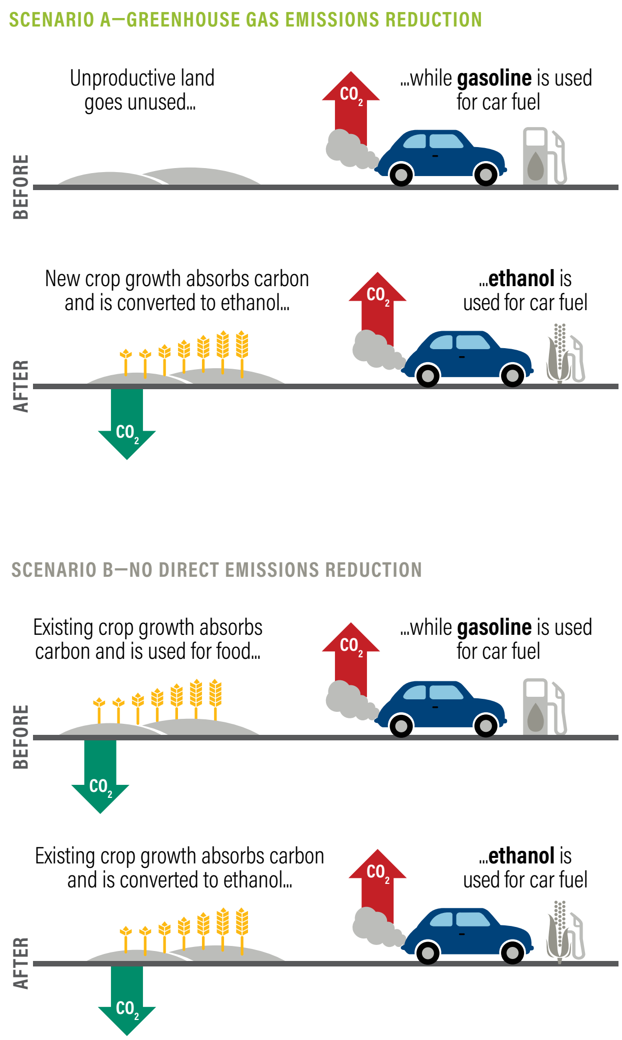
Prominent examples include bioenergy from food or energy crops grown on dedicated land. Many analyses assume that "potential cropland" or "marginal cropland" can be used to produce bioenergy without recognizing their current carbon storage and biodiversity values as forest or savannas, or their current food production function as grazing land. Modelers who estimate large potential climate benefits from "bioenergy with carbon capture and storage" (BECCS) rely on the same estimates of biomass potential that are based on double counting.[115] Other analyses assume yield gains could be used to free up land for bioenergy without clearing more forests and savannas—even as those same yield gains are needed just to meet rising food demand. In claiming GHG savings from bioenergy, analyses often attribute the carbon absorbed by plant growth as an offset for burning biomass even when this plant growth would otherwise have occurred and removed carbon from the atmosphere anyway (Figure 25).

Large estimates of reforestation potential often make similar mistakes in treating grazing land as available to reforest without cost to food production, or regarding potential increases in crop and pasture productivity as automatically liberating land for reforestation without recognizing that this potential must first be exploited just to meet growing food needs. Although important restoration opportunities exist on peatlands and unimprovable grazing land, large-scale reforestation will require significant reductions in demand growth and historically unprecedented increases in yields.

Some soil carbon sequestration estimates also double-count by assuming that biomass (as manure, crop residues, or mulches) can be used as a soil amendment when it is already in use—even if only to store carbon—somewhere else. Other estimates count the benefits of reducing grazing pressure without counting the costs of replacing the forgone meat and milk.

A common theme appears to be a failure to recognize that land is a fixed and therefore limited resource. The only ways to meet growing human demands for both food and carbon storage are to use land more efficiently and to consume agricultural products more efficiently.

Figure 25 | **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.
Source: Searchinger and Heimlich (2015).

CONCLUSIONS

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 report offers several insights that differ in direction or emphasis from much prior work.

Productivity gains are critical. Productivity gains in land, animals, and chemical inputs 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 absent productivity gains after 2010. When adding in the various additional productivity gains required to meet our 4 Gt CO_2e/year emissions target by 2050, the role of productivity gains grows even larger. Productivity gains also provide the most important potential synergy between income, food security, and environmental goals. Thus, new molecular crop-breeding methods will need to be exploited. Moreover, every hectare of global pasture that is capable of and appropriate for sustainable intensification must fully exploit its potential to increase milk or meat output severalfold.

Slowing demand growth is critical too. Despite the major contribution that productivity gains can make to closing our three gaps, they will not be enough. The largest diet-related opportunity lies in limiting the global growth in demand for beef, as well as sheep and goat meat. A 30 percent global shift from ruminant meat to other foods—achieved by the world's highest consumers reducing their consumption by roughly 40 percent relative to 2010 levels—would, by itself, nearly close the land gap and halve the GHG mitigation gap. A 10 percent shift from all animal-based foods by the world's wealthy would benefit human health and open up space for the great majority of poorer consumers to modestly increase their consumption. Moving more rapidly toward replacement-level fertility rates in sub-Saharan Africa would greatly reduce the risks of hunger in the region, provide multiple social and economic benefits, and reduce environmental challenges. Global plans to greatly increase the use of modern bioenergy derived from energy or food crops grown on land dedicated to that purpose, however, would make a sustainable food future unachievable.

Innovation in farm management will also be necessary to mitigate emissions. To implement management measures known to reduce emissions, governments need to develop systems to analyze mitigation potential and track progress across their agriculture sectors, increase incentives, and phase in mandatory performance standards. To stimulate promising management innovations, governments need to boost R&D, and encourage the private sector by requiring that farms use innovative technologies when those technologies demonstrate cost-effective mitigation.

Productivity gains must be linked to protection of carbon-rich ecosystems. Shifting of agricultural land both among and within regions presents a major carbon and biodiversity challenge. Governments therefore must make efforts to avoid such shifts and place more emphasis on reforesting abandoned agricultural land to natural forests when shifts do occur. Because productivity gains can sometimes encourage land-shifting, ensuring that yield gains protect forests and other carbon-rich and biodiverse ecosystems requires that governments and private parties explicitly link efforts to boost yields with protection for those ecosystems through financing, lending conditions, supply chain commitments, and public policies. The forest frontier should be closed to agriculture wherever feasible. New roads must also be located in ways that minimize the incentives to convert natural areas 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. Marginal agricultural lands that cannot realistically be intensified are appropriate for reforestation right now. However, the scale of reforestation necessary to fully achieve climate goals requires that much 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.

Regulation and technological innovation will be essential to achieve the most ambitious levels of our menu items. Regulations must be crafted to spur innovation while allowing flexibility to develop cost-effective solutions. They should apply mostly to manufacturers of agricultural inputs and to managers of concentrated livestock facilities. Many categories of technological innovations are needed but promising options have emerged for menu items in all our courses. Governments will need to give far more weight to R&D and encourage the private sector with a range of policy instruments.

We believe that the challenge of sustainably feeding nearly 10 billion people by 2050 is greater than commonly appreciated. Growth in food demand is high due to population growth and the rapid rise of a global middle class. The strength of competition for land, particularly pastureland, has often been underestimated. Proposed land-use solutions often involve double counting, and the climate implications of land-shifting are not fully recognized. Sub-Saharan Africa presents unique and formidable challenges because of the region's high population growth and low agricultural yields.

Despite the challenges, we believe that a sustainable food future is achievable. Our menu proposed in this synthesis 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.

ENDNOTES

1. We calculate the food gap measured in crop calories at 56%. The growth in demand for animal-based foods is calculated differently (i.e., growth in demand for all food calories, including animal- and plant-based foods) and estimated at 68%. Overall, we estimate the total food gap at 55%. Because the "crop calorie gap" and the "food gap" are so similar, we use the terms interchangeably in this report.

2. 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).

3. 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 (Alexandratos and Bruinsma [2012]). FAO based its projections on economic growth and income trends and culture in different countries. We adjust these FAO projections 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. More specifically, 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. "Food availability" is food available to consumers excluding 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 reach this level of food availability, they have low levels of food insecurity. 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 in 2012, so we further adjust 2050 food demands upward to reflect the new estimate of 9.8 billion people.

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

5. Figures exclude Antarctica. FAO (2011a).

6. Alexandratos and Bruinsma (2012), Table 4.8. FAO data estimate an increase in arable land in use of 220 Mha from 1962 to 2006. According to FAO (2017a), pasture area has increased by 270 Mha since 1962.

7. 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.

8. This estimate is based on the GlobAgri-WRR model.

9. See Figure 18 for a more detailed breakdown of production emissions estimated by GlobAgri-WRR. It excludes downstream emissions from the entire food system in processing, retailing, and cooking, which are overwhelmingly from energy use and must be addressed primarily by a broader transformation of the energy sector.

10. 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, many 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 they occur 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 on the basis of an average from other estimates found in UNEP (2012); FAO (2012a); and Houghton (2008). These estimates included losses from 2000 to 2005, a period for 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) estimate 3.2 Gt CO_2e/year in 2001–10 including deforestation (3.8 Gt CO_2e/year), forest degradation and forest management (-1.8 Gt CO_2e/year), biomass fires including peatland fires (0.3 Gt CO_2e/year), and drained peatlands (0.9 GtCO_2e/year). 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), who based their estimates on FAO's 2015 FRA, calculated 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 CO_2e/year. FAO also estimated peatland emissions separately of 0.9 Gt CO_2e/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 also includes fire. 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. For a summary of the uncertainties and methods, see Searchinger et al. (2013).

11. See Figure 17 for assumptions about changes in baseline emissions from agricultural production, and "The Land Gap" (p. 8) for assumptions about baseline land-use change.

12. 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_2e by 2050, which includes reductions of methane by roughly 50%. Authors' calculations 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°C 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 the likelihood of 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.

    Another useful analysis in our baseline is agriculture's share of 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% chance of meeting the target (Meinshausen et al. 2009). UN Environment uses average estimates of 1,000 Gt for a two-thirds chance of meeting the target (UNEP 2017). 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 (Figueres et al. 2017).

    Given these global maximum allowable emissions, our baseline estimate of cumulative agricultural production 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% of the allowable CO_2 emissions from all human sources. Using the cumulative emissions approach, this scenario would also leave too little room for the bulk of GHG emissions from energy use by other economic sectors to reach acceptable climate goals.

13. FAO (2016); Selman and Greenhalgh (2009).

14. FAO (2011b) estimated this figure at 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. This report's authors estimated the figure of one-quarter as measured by calories by using FAO Food Balance Sheets (FAO 2017a), 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.

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

16. FAO (2015).

17. Lipinski et al. (2013).

18. In 2010, approximately half of the world population consumed at least 75 grams of protein per day (GlobAgri-WRR model based on source data from FAO 2017a and FAO 2011b), whereas the average daily protein requirement for adults is around 50 grams per day, which incorporates a margin of safety to reflect individual differences. 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 grams per kilogram of body weight per day. Since the average adult in the world weighed 62 kilograms in 2005 (Walpole et al. [2012]), applying the rule of 0.8 grams/kilogram/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 grams/kilogram/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 grams per kilogram of body weight per day given in Paul (1989) includes 0.35 grams/kilogram/day as a safety margin.

19. Craig and Mangels (2009).

20. 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.

21. Foley et al. (2011).

22. Scarborough et al. (2014).

23. GlobAgri-WRR model. In 2010, consumption of animal-based foods in Europe was 772 calories per capita per day. In our baseline 2050 scenario, consumption of animal-based foods in sub-Saharan Africa is still projected to be only 201 calories per capita per day. If, instead, consumption in sub-Saharan Africa grew to 386 calories per capita per day (or half of Europe's 2010 per capita consumption, and on par with 2050 baseline consumption projections for the rest of Africa and Asia outside of China and Japan), that additional growth in consumption would completely offset a theoretical 10 percent global reduction in animal-based food consumption (achieved by a 17 percent reduction in Europe, North America, Brazil, China, and other OECD countries). In short: our baseline is arguably conservative in estimating total consumption of animal-based foods in 2050.

24. Using the GlobAgri-WRR model, we estimate U.S. dietary emissions in 2010 (including land-use change) 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. 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.

25. FAO (2017a).

26. Ranganathan et al. (2016).

27. IEA (2016) in REN21 (2017).

28. Searchinger et al. (2017).

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

30. UNDESA (2017).

31. UNDESA (2017).

32. Authors' calculations from FAO, IFAD, UNICEF, et al. (2017); and UNDESA (2017).

33. AnimalChange (2012), Figure 7. This analysis focused on efficiencies based on protein (kg 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.

34. Herrero et al. (2013).

35. 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.

36. Atlin et al. (2017).

37. NAS (2016).

38. Clustered Regularly Interspaced Short Palindromic Repeats and CRISPR-associated.

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

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

41. Arslan et al. (2015).

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

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

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

45. 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 hectares 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 Mha 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.

46. Siebert et al. (2010).

47. Porter et al. (2014).

48. World Bank (2012).

49. Porter et al. (2014).

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

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

52. World Bank (2012); Lobell et al. (2008).

53. FAO (2017a).

54. West et al. (2010).

55. Hirsch et al. (2004).

56. See http://www.bonnchallenge.org/commitments. A variety of scenarios exist to achieve global warming of 1.5°C only but all are uncertain and almost all require substantial "negative emissions," i.e., withdrawals of carbon from the air. We estimate that 585 Mha of reforestation on liberated agricultural land would be needed to fully offset 4 Gt of agricultural emissions. These offsets would persist for 40 years after which other reductions or offsets would be required. This could only be achieved through actions across many menu items in Course 1 (reduce demand), Course 2 (increase productivity), and Course 3 (protect and restore natural ecosystems and limit agricultural land-shifting). The 350 Mha restoration target in the Bonn Challenge includes reforestation, agroforestry, soil enhancement, and other productive forms of restoration. Thus the Bonn Challenge could contribute to the needed 585 Mha.

57. Laurance et al. (2014).

58. Wormington (2016).

59. Jackson (2015); Nepstad et al. (2014); Assunção et al. (2012); Gibbs et al. (2016).

60. Boyd et al. (2018).

61. Estes et al. (2016).

62. In this report, we use the term "restoration" in a relatively narrow sense, meaning to return land to a natural or semi-natural state of vegetation. Other than in the case of peatlands, we usually mean forest restoration. We recognize that the term can be used more broadly, for example, to include agroforestry as a means to restore land to productive use, or more broadly still, to include any measures that restore ecological health to a tract of land, whether or not trees are involved. See, for example, Bessau et al. (eds) (2018); Hanson et al. (2015).

63. See, for example, Stern (2006); Nabuurs et al. (2007); Sathaye et al. (2011); and Sathaye et al. (2005).

64. Siddique et al. (2008).

65. Kolka et al. (2016).

66. Dargie et al. (2017).

67. Wetlands International (2017).

68. Gewin (2018).

69. FAO (2017a).

70. In 2013–15, fish provided about 3.2 billion people with 20% of their animal protein intake (FAO 2018).

71. FAO (2017b).

72. World Bank (2017b).

73. Sumaila et al. (2010); Sumaila et al. (2012); Sumaila and Rachid (2016).

74. FAO (2017b).

75. Hristov et al. (2014) and Gerber et al. (2013) provide good summaries of the research results to date for all these approaches.

76. Hristov et al. (2015); Martínez-Fernández et al. (2014); Reynolds et al. (2014); Romero-Perez et al. (2015).

77. 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/.

78. 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/.

79. 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 manage-

ment 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 systems chosen involve 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.

80. Authors' estimate.

81. USDA/ERS (2015) averages annual prices from 2010 to 2015.

82. Doole and Paragahawewa (2011).

83. Byrnes et al. (2017).

84. Ward et al. (2016); Galbally et al. (2010); Barneze et al. (2014); Mazzetto et al. (2015); Pelster et al. (2016); Sordi et al. (2014).

85. 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]).

86. Authors' estimate.

87. Su et al. (2015).

88. Jiang et al. (2017).

89. Joshi et al. (2013).

90. Itoh et al. (2011).

91. Saini (2013).

92. CGIAR Research Program on Roots, Tubers and Bananas (2016).

93. Goodrich et al. (2012).

94. See, e.g., Powlson et al. (2016); Powlson et al. (2014); van Groenigen et al. (2017).

95. Powlson et al. (2014), summarizing studies.

96. Kirkby et al. (2011).

97. Padhee (2018).

98. UNFCCC (2015).

99. Lowder et al. (2016).

100. Deininger et al. (2011); Ali and Deininger (2014); Larson et al. (2014).

101. Place (2009).

102. Land Matrix database (n.d.).

103. Schönweger et al. (2012); Pearce (2012).

104. World Bank (2008).

105. Notess et al. (2018).

106. Bellemare (2015).

107. Bellemare (2015).

108. 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).

109. 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, wind energy, and energy efficiency. Alberta Agriculture and Forestry (2015).

110. FAO (2012b).

111. Roberts and Welkmans (2016).

112. Green Climate Fund (2017).

113. Beintema et al. (2012); Fuglie et al. (2011).

114. The world devotes 2.23% of total GDP on R&D in all sectors in 2015 (World Bank [2017c]), and a strong case can be made to increase research funding across all sectors generally (Griffith 2000). By contrast, world agricultural GDP was $3.62 trillion in 2014 according to the World Bank (2017d). If agricultural R&D were still $52 billion, the percentage would be roughly 1.4% ($50 / $3,620 = 0.014).

115. 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 carbon mitigation 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.

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Our Challenge
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.

CHANGE IT
We use our research to influence government policies, business strategies, and civil society action. We test projects with communities, companies, and government agencies to build a strong evidence base. Then, we work with partners to deliver change on the ground that alleviates poverty and strengthens society. We hold ourselves accountable to ensure our outcomes will be bold and enduring.

SCALE IT
We don't think small. Once tested, we work with partners to adopt and expand our efforts regionally and globally. We engage with decision-makers to carry out our ideas and elevate our impact. We measure success through government and business actions that improve people's lives and sustain a healthy environment.

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