



COURSE 1

Reduce Growth in Demand for Food and Other Agricultural Products

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

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CHAPTER 5

MENU ITEM: REDUCE FOOD LOSS AND WASTE

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

The Challenge

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

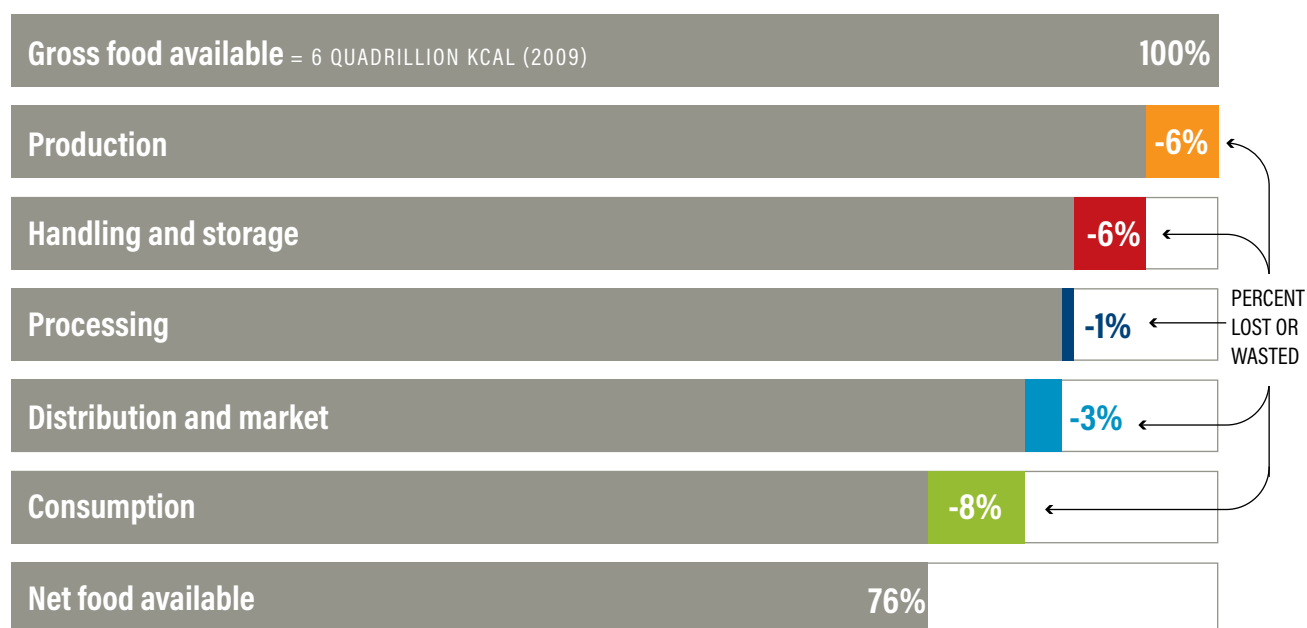
According to the best available estimates by FAO, approximately one-third of all food produced in the world in 2009, measured by weight, was lost or wasted.¹ Food loss and waste refers to food intended to be eaten by people that leaves the food supply chain somewhere between being ready for harvest and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

amount is equivalent to 24 percent of the world's food supply lost somewhere between farm and fork (Figure 5-1).²

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

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

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



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

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

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

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

BOX 5-1 | Defining food loss and waste

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

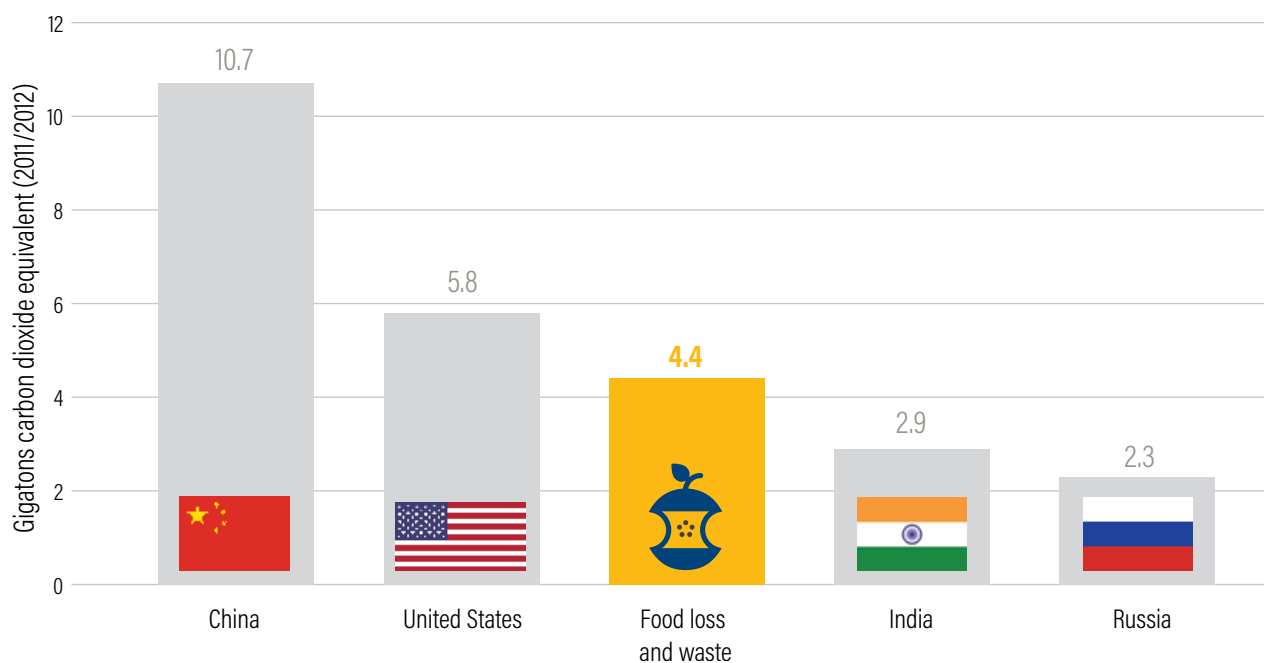
“Food” refers to any substance—whether processed, semiprocessed, or raw—that is intended for human consumption or, more specifically, ingestion. “Inedible parts” refers to components associated with a food that, in a particular food supply chain, are not intended to be consumed by people; inedible parts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

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

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

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

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



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

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

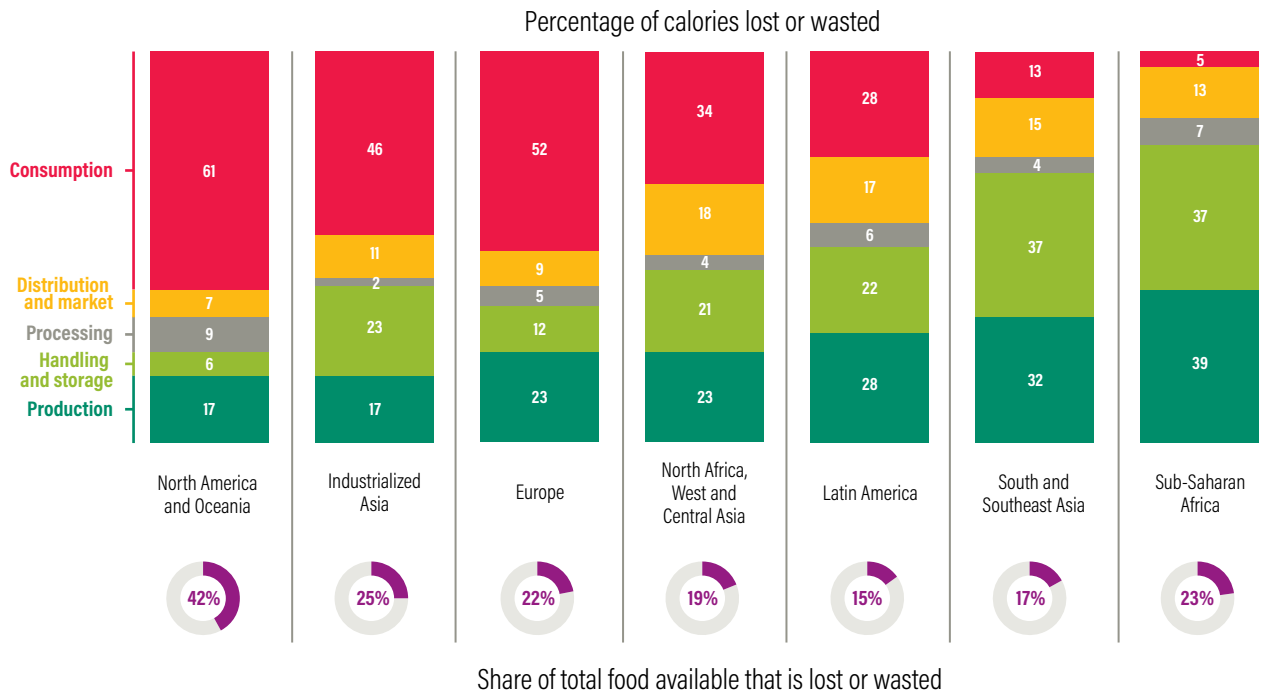
The total share of available food that becomes lost or wasted ranges from 15 percent to 25 percent across most regions. As Figure 5-3 indicates, the outlier is North America and Oceania, where loss and waste is approximately 42 percent of all available food.

On a per capita basis, North America and Oceania¹¹ stand out, with about 1,500 kcal per person per day lost or wasted from farm to fork, while Europe and industrialized Asia hover around 750 kcal per person per day and all other regions lose or waste under 600 kcal per person per day.¹²

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

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

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

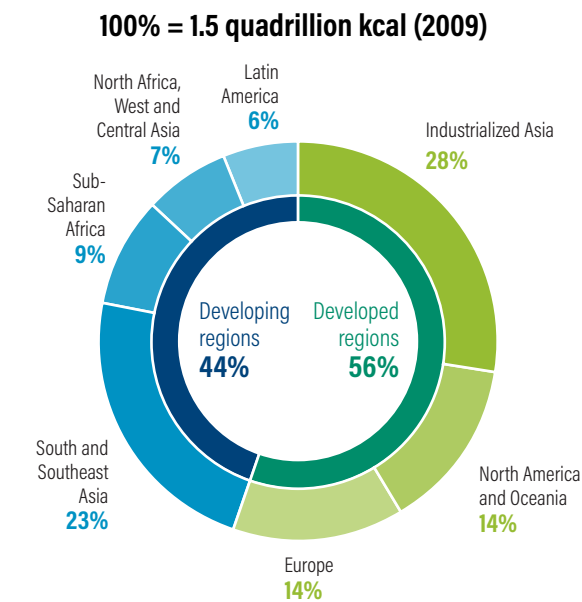


Note: Numbers may not sum to 100 due to rounding. Data are for the year 2009.
Source: WRI analysis based on FAO (2011c).

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

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

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



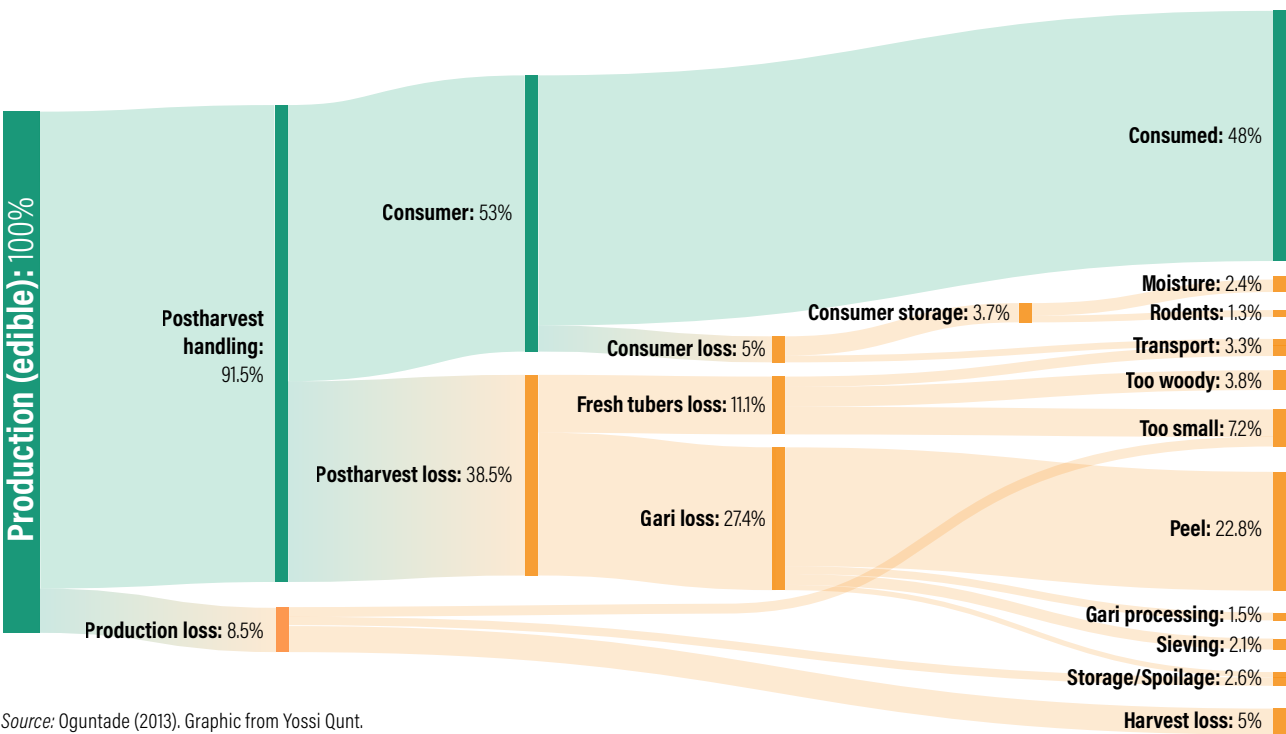
Source: WRI analysis based on FAO (2011c).

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



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

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



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

The Opportunity

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

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

Recent experience

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

Economic savings

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

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

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

Source: Lipinski et al. (2013).

To gain a wider perspective, along with the organization Waste and Resources Action Programme (WRAP), we surveyed efforts to reduce food loss and waste at nearly 1,200 business sites across 17 countries and more than 700 companies. They represented a range of sectors, including food manufacturing, food retail (e.g., grocery stores), hospitality (e.g., hotels, leisure), and food service (e.g., canteens, restaurants). We found that the median benefit-cost ratio was 14 to 1 across all types of companies, while hotels, food manufacturers, and food retailers tended to have ratios between 5 to 1 and 10 to 1.¹⁸

Technical and management approaches to reducing FLW

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

Production stage

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

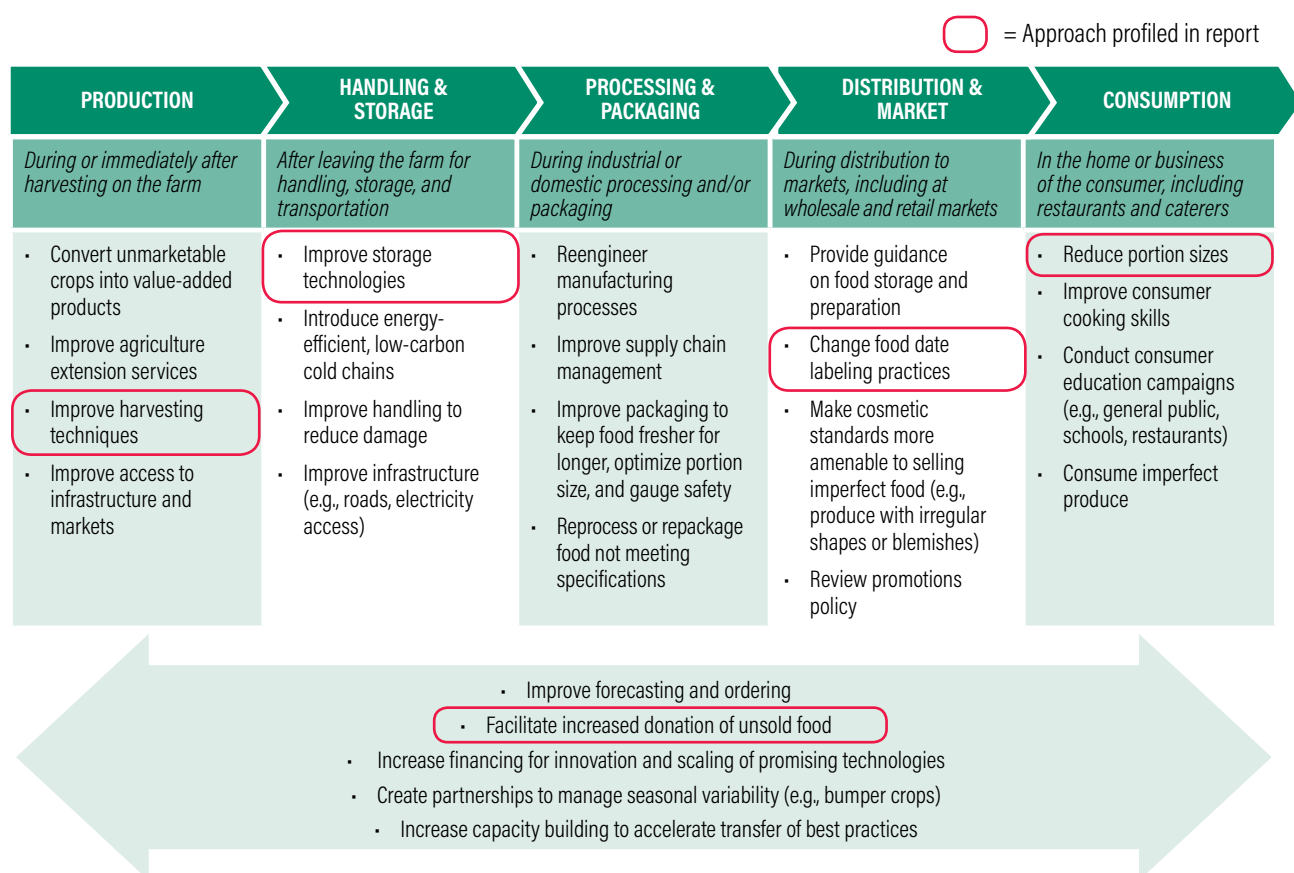
half of rice production in Senegal.²⁰ Similar harvesting technology improvements are needed across a wide array of crops.

Handling and storage stage

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

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

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



Source: Hanson and Mitchell (2017).

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

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

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

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

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

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

overcome through education by extension services, increased support by donors, and reduction of tariffs on key material imports.

Processing and packaging stage

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

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

The Apeel Science company, for example, has illustrated the potential for innovation by developing sprays of thin lipids to coat fruits and vegetables from organic sources. The sprays have extended shelf life by 30 days or more. The lipid, extracted from plant material such as banana leaves and peels, is designed separately for each fruit or vegetable. It helps hold in water, which prevents fruits and vegetable from shriveling. It also controls

the exchange of gases between the interior of the fruit or vegetable and the atmosphere, particularly oxygen and ethylene, to slow decay. Finally, it blocks the ability of bacteria on the surface of foods to sense that they are near a food source, and thus the bacteria multiply much slower.³⁰ Because this method works without refrigeration, it offers great potential benefits in developing countries with limited refrigeration.

Distribution and marketing stage

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

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

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

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

food redistribution, bringing it to the attention of those who might not have considered the practice.³⁶

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

Consumption stage

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

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

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

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

due to labeling, when in fact some of the food is still suitable for human consumption.⁴³

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

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

Model Results

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

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

Recommended Strategies

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

1. Target

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

How much progress has been achieved to date? The United States, the European Union, Australia, Japan, Norway, and the African Union⁴⁶ have now adopted specific FLW reduction targets consistent with Target 12.3. Courtauld 2025, a voluntary commitment on the part of more than 100 businesses and government agencies in the United Kingdom, has set a target for FLW reduction that will put the country on a trajectory to deliver Target 12.3.⁴⁷ Several groups of companies have also set reduction targets, including the Consumer Goods Forum (CGF), the Global Agri-business Alliance, and 2030 Champions (a U.S. business partnership).⁴⁸

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

SCENARIO	FOOD GAP, 2010-50 (%)	CHANGE IN AGRICULTURAL AREA, 2010-50 (MHA)			ANNUAL GHG EMISSIONS, 2050 (GT CO ₂ E)			GHG MITIGATION GAP (GT CO ₂ E)
		Pastureland	Crop-land	Total	Agricultural production	Land-use change	Total	
2050 BASELINE	56	401	192	593	9.0	6.0	15.1	11.1
10% reduction in rate of food loss and waste (<i>Coordinated Effort</i>)	54	367 (-34)	159 (-33)	526 (-67)	8.9	5.5	14.4	10.4 (-0.7)
25% reduction in rate of food loss and waste (<i>Highly Ambitious</i>)	50	318 (-84)	112 (-79)	430 (-163)	8.7	4.7	13.4	9.4 (-1.6)
50% reduction in rate of food loss and waste (<i>Breakthrough Technologies</i>)	44	240 (-162)	39 (-152)	279 (-314)	8.3	3.6	11.9	7.9 (-3.1)

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

Source: GlobAgri-WRR model.

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

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

2. Measure

The adage that "what gets measured gets managed" has particular significance for FLW because data are still relatively weak. For instance, existing globally consistent estimates are at the near-continental scale and rely on extrapolations from a limited set

of target studies. Moreover, different analyses even of one commodity within one country can produce a wide range of estimates. To prioritize reduction strategies and track progress, decision-makers need not just better overall estimates but also estimates of where and why FLW occurs in the food chain.

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

Going forward, more governments at the national and subnational levels and companies need to start quantifying and reporting on their food loss and waste. The release of the Food Loss & Waste Protocol's⁵¹ *Food Loss and Waste Accounting and Reporting Standard* in 2016 can help with this quantification. The *FLW Standard* provides global requirements and guidance for quantifying and reporting on the weight of food and/or associated inedible parts removed from the food supply chain.⁵² The *FLW Standard* empowers countries and companies to create base-year food loss and waste inventories and quantify progress over time toward meeting Target 12.3 or any other goals they may have. Measurement does not need to be a complex and resource-intensive exercise. Quantification and periodic monitoring can be integrated with other resource monitoring programs that governments and companies have in place.

3. Act

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

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

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

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



CHAPTER 6

MENU ITEM: SHIFT TO HEALTHIER AND MORE SUSTAINABLE DIETS

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

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

The Challenge

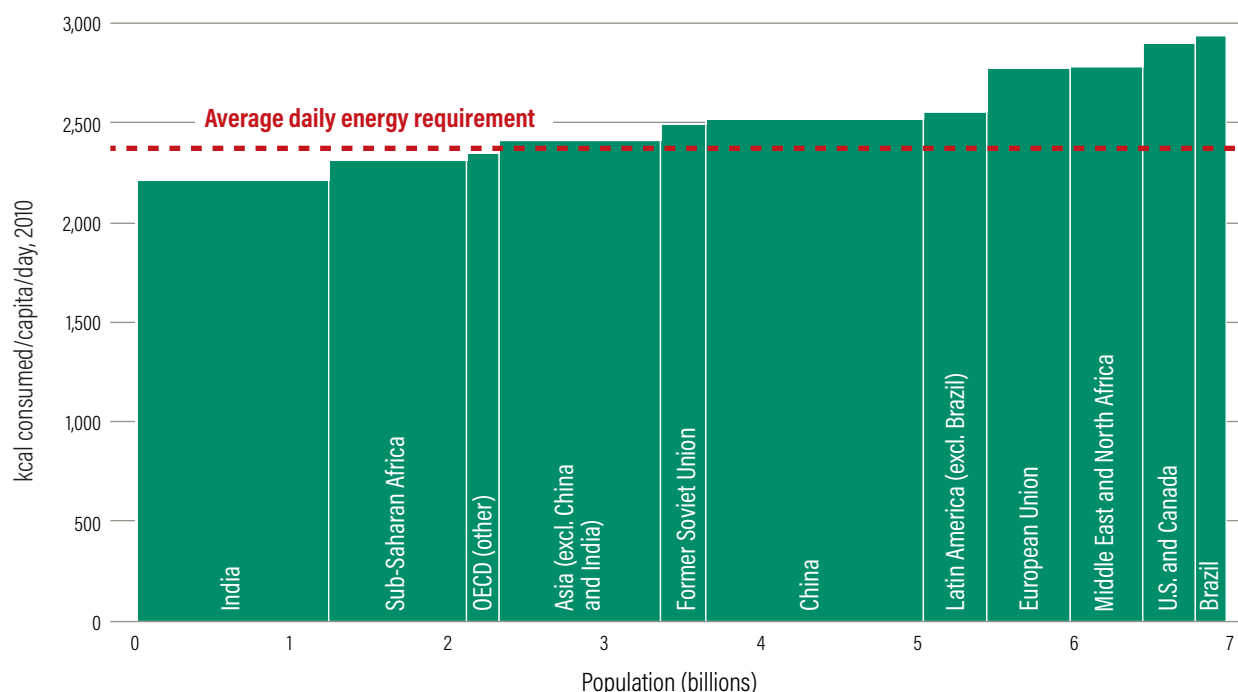
The global convergence toward Western-style diets will make it harder for the world to achieve several of the UN Sustainable Development Goals, including those related to hunger (SDG 2), good health and well-being (SDG 3), water management (SDG 6), climate change (SDG 13), and terrestrial ecosystems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

The great dietary convergence

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

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

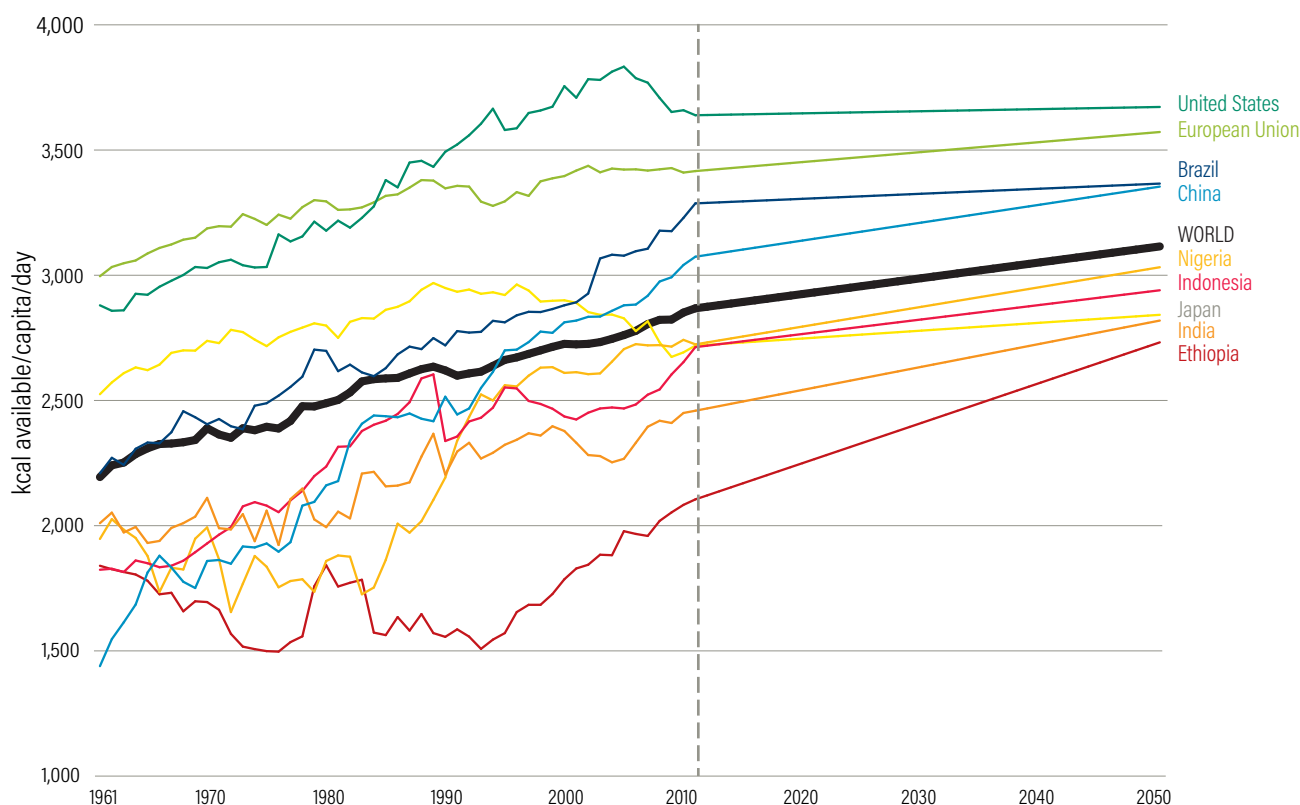
Figure 6-1 | Average per capita calorie consumption exceeds average daily energy requirements in most world regions



Note: Width of bars is proportional to each region's population. Average daily energy requirement of 2,353 kcal/capita/day is given in FAO (2014a). Individuals' energy requirements vary depending on age, sex, height, weight, pregnancy/lactation, and level of physical activity.

Source: GlobAgri-WRR model with source data from FAO (2019a) and FAO (2011c).

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



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

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

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

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

BOX 6-1 | Debunking protein and meat myths

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

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

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

One recent article claimed that vegan diets were inefficient based on a calculation

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

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

Myth: More protein is better.

More protein is not necessarily better, unless an individual is malnourished or undernourished. Although the word “protein” comes from the Greek *proteios*, meaning “of prime importance,” protein is no more important than the other nutrients required for good health, and many people do not need as much protein as they believe. For instance, the average U.S. adult consumed

66 percent more protein per day in 2012 than the average estimated daily requirement, but 21 percent of adults still considered themselves deficient in protein in a 2014 survey.^d The World Health Organization suggests that only 10–15 percent of the daily calorie requirement needs to come from protein.^e A balanced plant-based diet can easily meet this need. Meanwhile, overconsumption of protein is linked to some health problems, including kidney stones and the deterioration of kidney function in patients with renal disease.^f

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

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

Notes:

a. Tessari et al. (2016).

b. Craig and Mangels (2009).

c. Antony (2012).

d. USDA (2014), French (2015).

e. WHO (2003).

f. WHO, FAO, and UNU (2007).

g. Young and Pellett (1994).

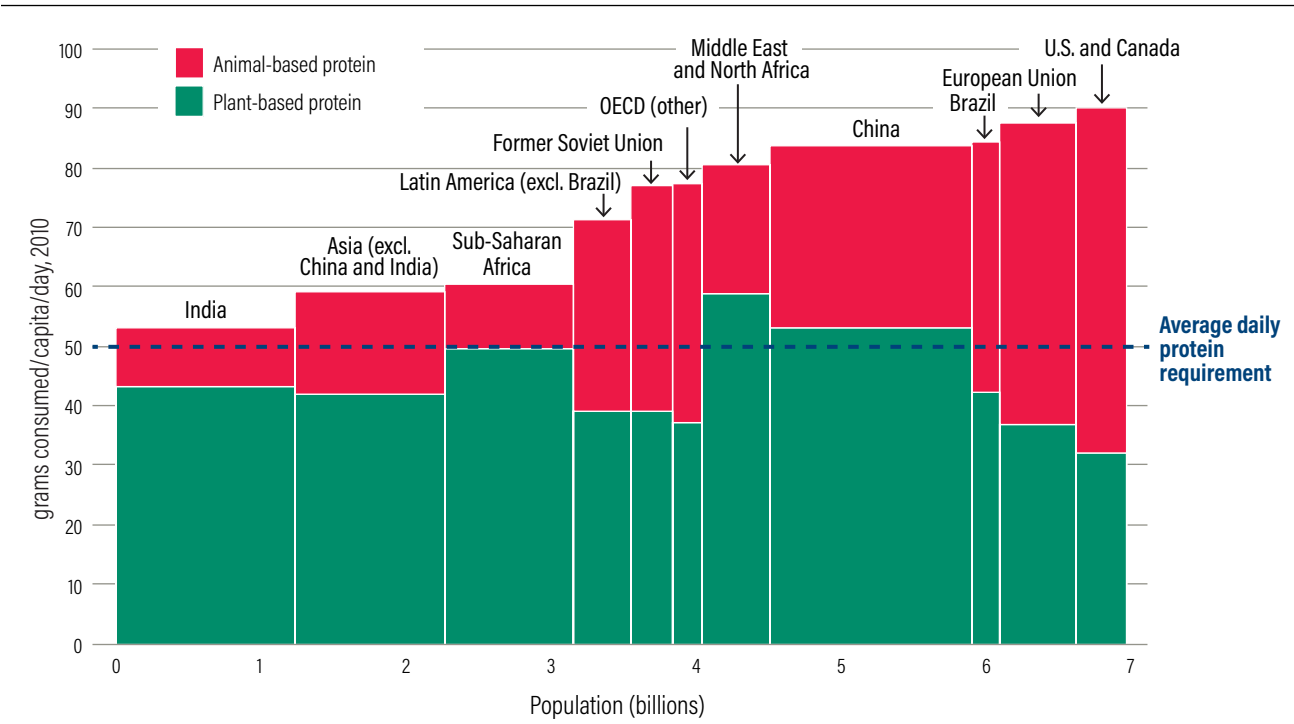
h. Tufts University Health & Nutrition Letter (2012).

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

average just 200 kcal per person per day. If these 6.1 billion people were to consume, on average, even 450 kcal of animal-based foods per day by 2050, the growth in demand for animal-based foods would rise from the 68 percent in our 2050 baseline to 92 percent.⁷⁰

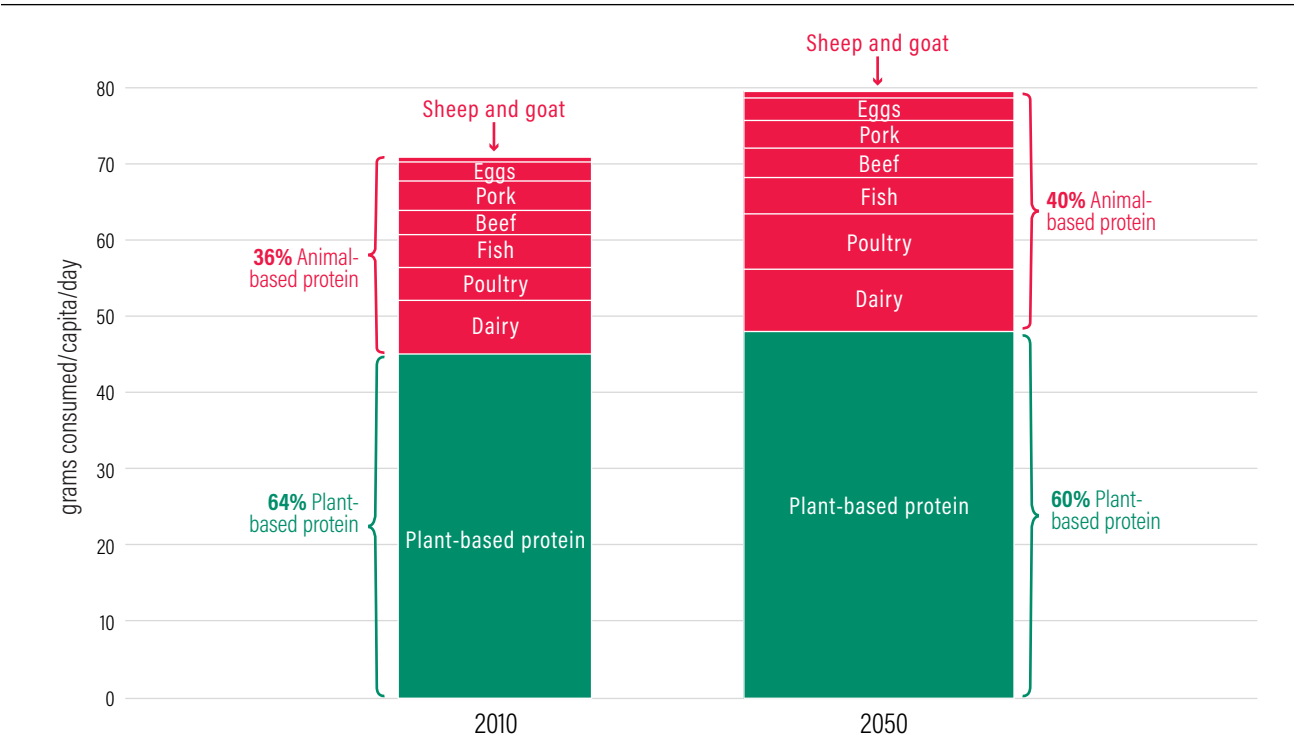
FAO's projection of a continued inequitable distribution of animal-based food consumption has important implications when developing options for a sustainable food future. It means that large *global* reductions in meat and dairy consumption by all would be highly inequitable. Instead, policy should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

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



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

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



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

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

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

Note: Regions are listed in order of projected daily per capita consumption of total animal-based foods in 2050.

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

up “planetary space” for additional consumption of animal-based foods by the world’s poor.

The consequences of the dietary convergence for health and nutrition

When incomes first rise above poverty levels, dietary changes have health benefits, including some additional consumption of meat and dairy. These diet shifts can reduce chronic shortages of calories and many important nutrients, reducing the numbers of stunted and underweight children, and providing a range of health benefits, particularly for children.⁷¹ (The production of modest

levels of livestock products by the rural poor also plays a valuable economic role in reducing poverty and therefore helps avoid hunger through that pathway, too.)⁷²

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

The clearest evidence of diet-related health risks involves obesity, which is linked to all of the illnesses listed above⁷⁵ and to an increased risk of premature death.⁷⁶ Obesity causes large increases in health care costs.⁷⁷ Obesity also adversely affects productivity, with costs estimated in the tens of billions of dollars per year in the United States and Europe.⁷⁸ The McKinsey Global Institute estimated the worldwide economic impact of obesity in 2012 to be around \$2 trillion, or 2.8 percent of global gross domestic product (GDP), roughly equivalent to the global cost of armed conflict or smoking.⁷⁹

The global obesity rate continues to grow. In 2013, 2.1 billion people were overweight or obese⁸⁰—more than two and a half times the number of chronically undernourished people in the world.⁸¹ Once considered a high-income country problem, the number of obese and overweight people is now rising in low- and middle-income countries.⁸² In China, obesity rates tripled between 1991 and 2006.⁸³ Obesity is growing even in countries that have high levels of child stunting from insufficient food, such as Egypt, South Africa, and Mexico.⁸⁴

Globally, there is some evidence that obesity rates may decline at high-income levels,⁸⁵ and may be nearing peaks in developed countries (in the neighborhood of 60% overweight or obese).⁸⁶ Using a variety of trends and association, Ng, Fleming, et al. (2014) suggest a global increase of roughly 10 percent from 2010 to 2050 in the rate of overweight and obesity.⁸⁷ This trend would bring the number of overweight and obese people to 3.1 billion by 2050.⁸⁸

Another major area of health concern with Western-style diets is the link between high consumption of animal-based foods and a variety of diseases. For many years, the primary focus of attention was cholesterol and saturated fats and the linkages between their consumption and heart disease.⁸⁹ Although more recent studies call into question the links between high levels of saturated fats in diets and heart disease,⁹⁰ there still appears to be evidence that switching to other fats—including certain polyunsaturated fats more present in vegetable oils—can have some health benefits related to heart disease and diabetes.⁹¹ Several studies have also linked red meat⁹² consumption directly to type 2

diabetes, cardiovascular disease, and colorectal cancer.⁹³ The exact causal connections remain debated, with some research focusing the concern more on processed meats such as bacon and sausages.⁹⁴ The International Agency for Research on Cancer has classified processed meat as “carcinogenic to humans,” while listing red meat as “probably carcinogenic.”⁹⁵

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

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

The low feed and natural resource efficiency of meat and dairy

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

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

the Council for Agricultural Science and Technology (CAST) in 1999.¹⁰⁰ How inefficient, then, are animal-based foods and how do they differ from each other?

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

- **Overestimates: Failure to compare the effects of meat consumption with realistic alternative diets.** Studies that fail to compare meat-heavy diets with realistic alternative diets can *overestimate* the possible environmental benefits of eating less meat. Many crops used for animal feeds—such as maize, wheat, alfalfa, and soybeans—have higher caloric and protein yields per hectare than many crops that people consume as alternatives to meat, such as beans, chickpeas, lentils, and vegetables. For example, global maize yields per hectare are

roughly five times those of pulses. Some papers have incorrectly assumed that, if people ate less meat, they would instead consume these high-yielding animal feeds, rather than lower-yielding alternative foods that, in practice, they are more likely to eat.¹⁰¹

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

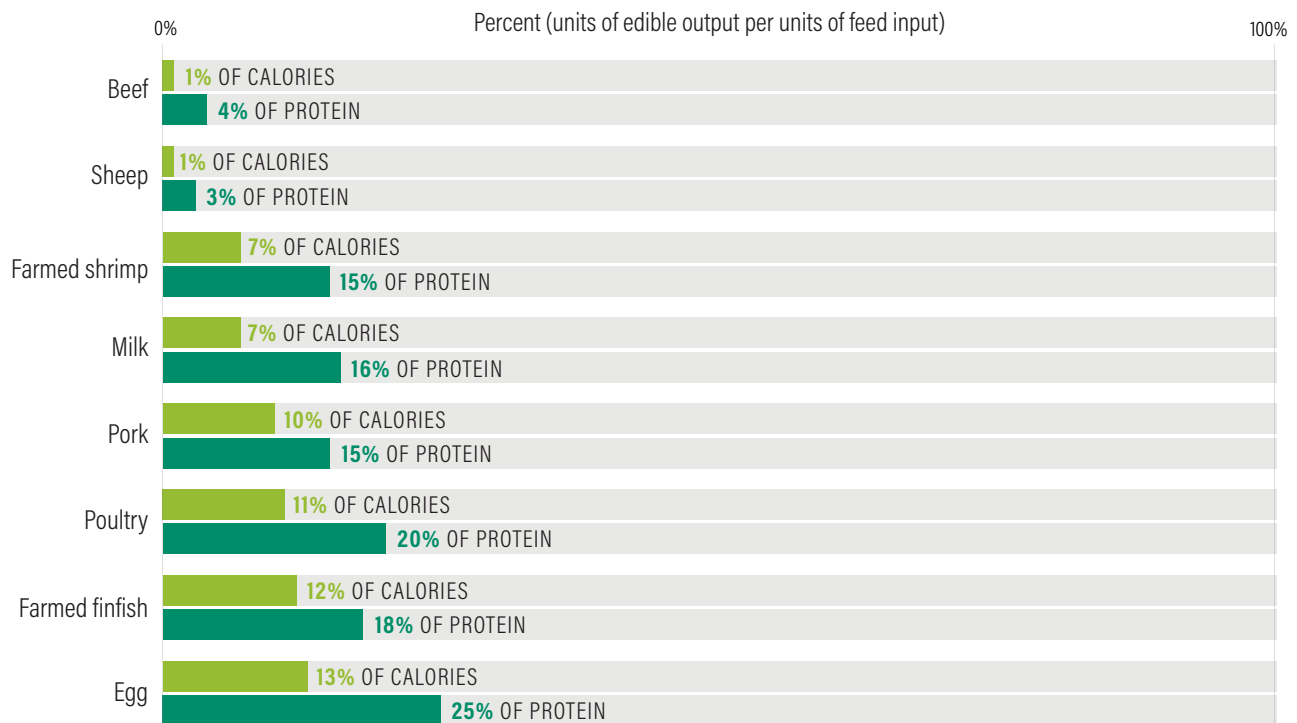


■ **Underestimates: Failure to fully account for all animal feeds.** The most significant underestimate results from methods that count the environmental consequences of only “human-edible” animal feeds.¹⁰⁴ This approach excludes animal feed provided by crop residues and food processing wastes, which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

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

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

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



Notes: “Edible output” refers to the calorie and protein content of bone-free carcass. “Feed input” includes both human-edible feeds (e.g., grains) and human-inedible feeds (e.g., grasses, crop residues).

Sources: Terrestrial animal products: Wirsenius et al. (2010); Wirsenius (2000). Finfish and shrimp: WRI analysis based on USDA (2013a); NRC (2011); Tacon and Metian (2008); Wirsenius (2000); and FAO (1989).

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

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

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

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

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

As a result, if a European pork producer in Europe switched from using Brazilian to U.S. soybeans, that would be counted as eliminating its emissions from land-use change.

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

3. Land-use-change emissions are attributed to marginal (additional) agricultural production. This approach—which is what GlobAgri uses—focuses on the additional emissions from the additional land required to produce any additional amount of a crop or other food. For example, if consuming one ton of soybeans requires one-third of a hectare of additional cropland, each ton of soybeans is responsible for one-third of a hectare of cropland. Under this

approach, land-use-change emissions per unit of food produced are much higher than in approach 2 and are never zero.

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

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

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

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

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

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

Another way of viewing the problem with system 2 is that it does not assign any carbon cost to continued consumption of food produced on existing agricultural land—this land has no opportunity cost in lost carbon storage. Yet continuing to use existing agricultural land each year to meet even long-existing demand has costs. If not used to meet that preexisting demand,

it could be used to meet new demand, avoiding land-use change. For this reason, reducing even preexisting demand enough to reduce agricultural area by one hectare still saves a hectare of expansion.

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

Although GlobAgri-WRR focuses on the incremental effects of each person's consumption, it does not factor in economic feedback effects, which could alter those incremental effects. As prices change as a result of any one person's consumption, that might affect how farmers farm or the amount of consumption by others. But when GlobAgri-WRR evaluates the consequences of any one person's change in diet, it holds other people's consumption constant and keeps yields and other production systems the same. The reasons, which we explain more thoroughly in Chapter 2,

Box 2-1, include the large uncertainties in those estimates.^a But a more fundamental reason is the need to analyze separately the effects of each menu item. For example, if increased food consumption were credited with increased yields, then we could not separately evaluate the effects of increased yields alone.

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

Note:

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

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

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

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

Comparing land-use and greenhouse gas consequences of different foods

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

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

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

We reach the following conclusions:

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

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

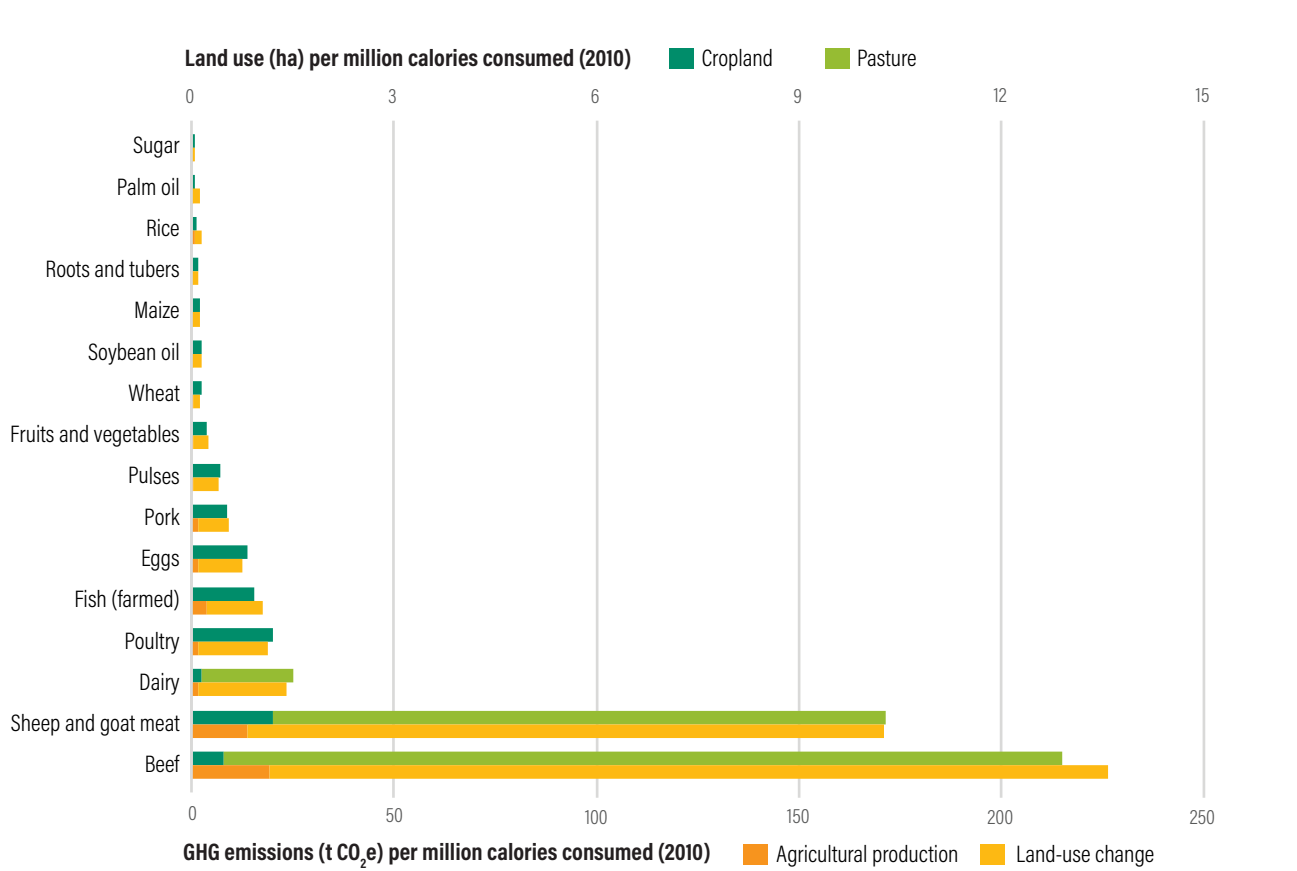


Figure 6-6b | Foods differ vastly in land-use and greenhouse gas impacts

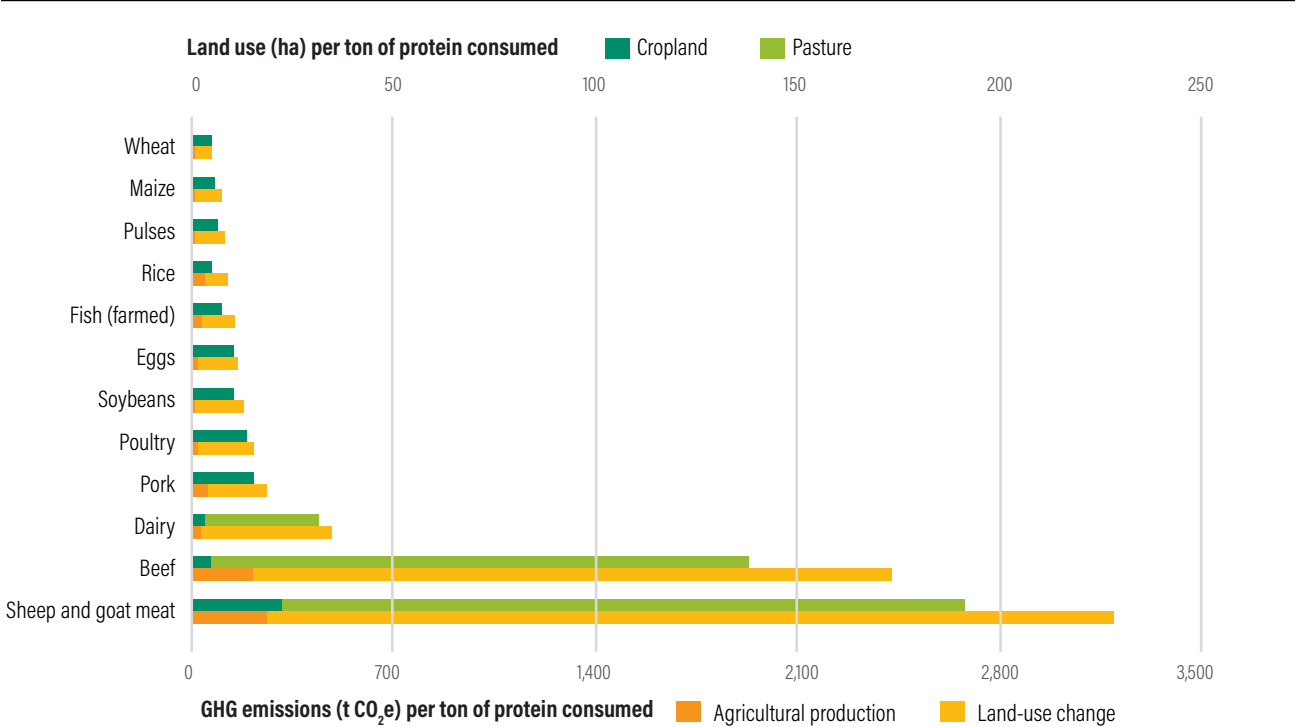


Figure 6-6c | Foods differ vastly in greenhouse gas impacts

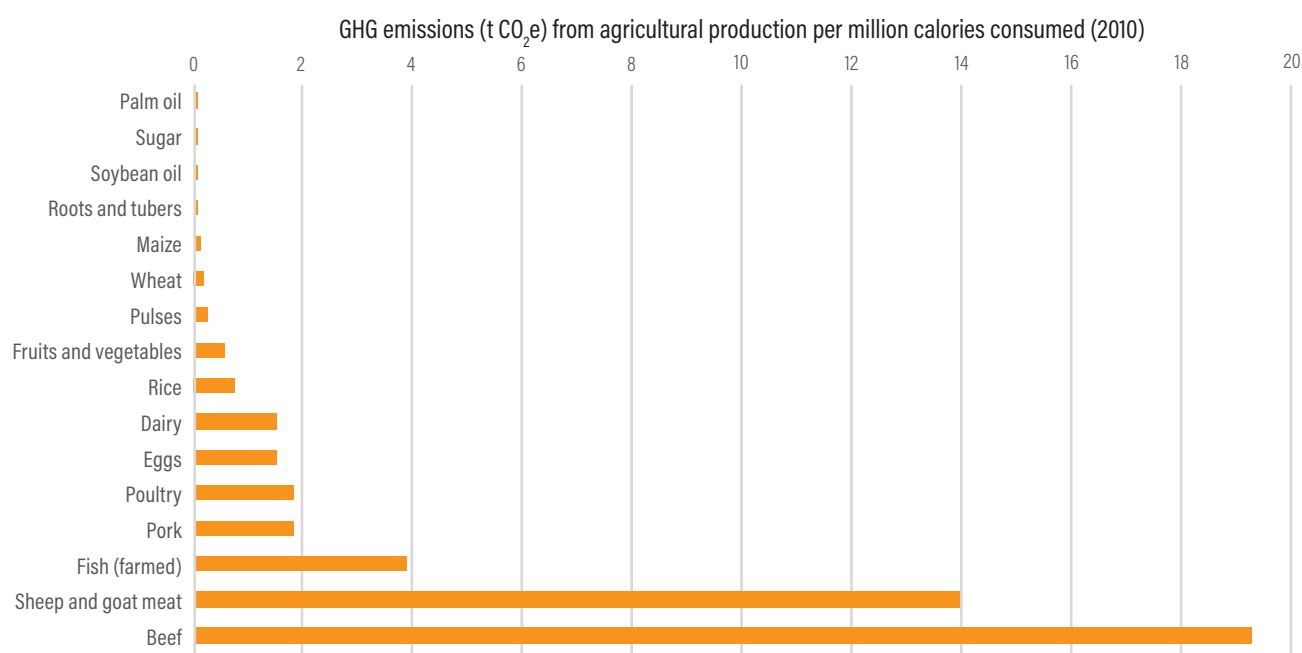
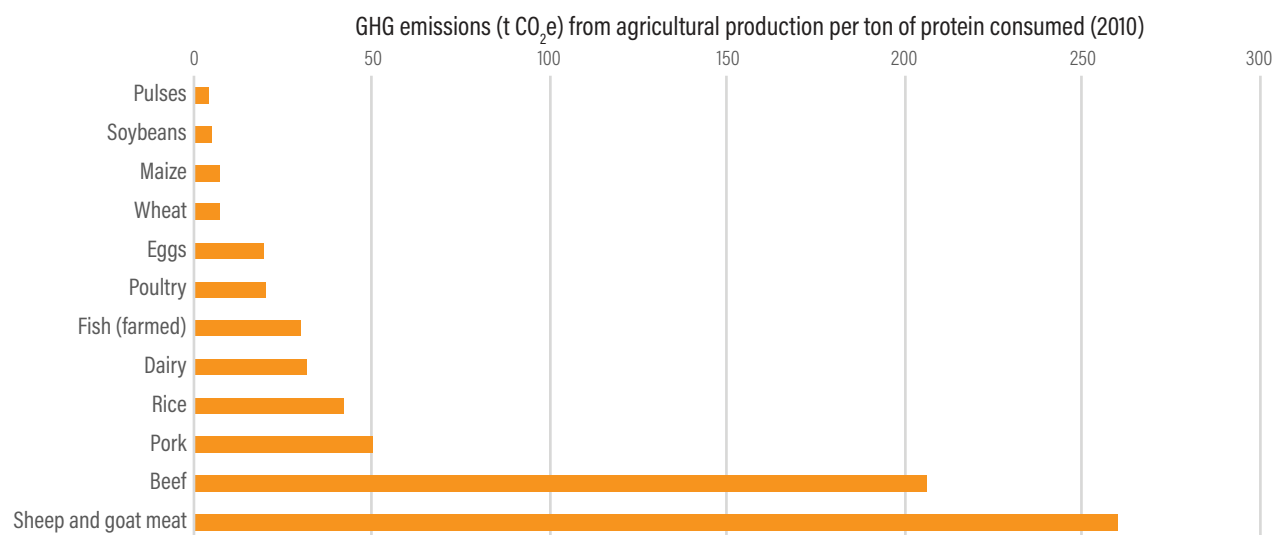


Figure 6-6d | Foods differ vastly in greenhouse gas impacts



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

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

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

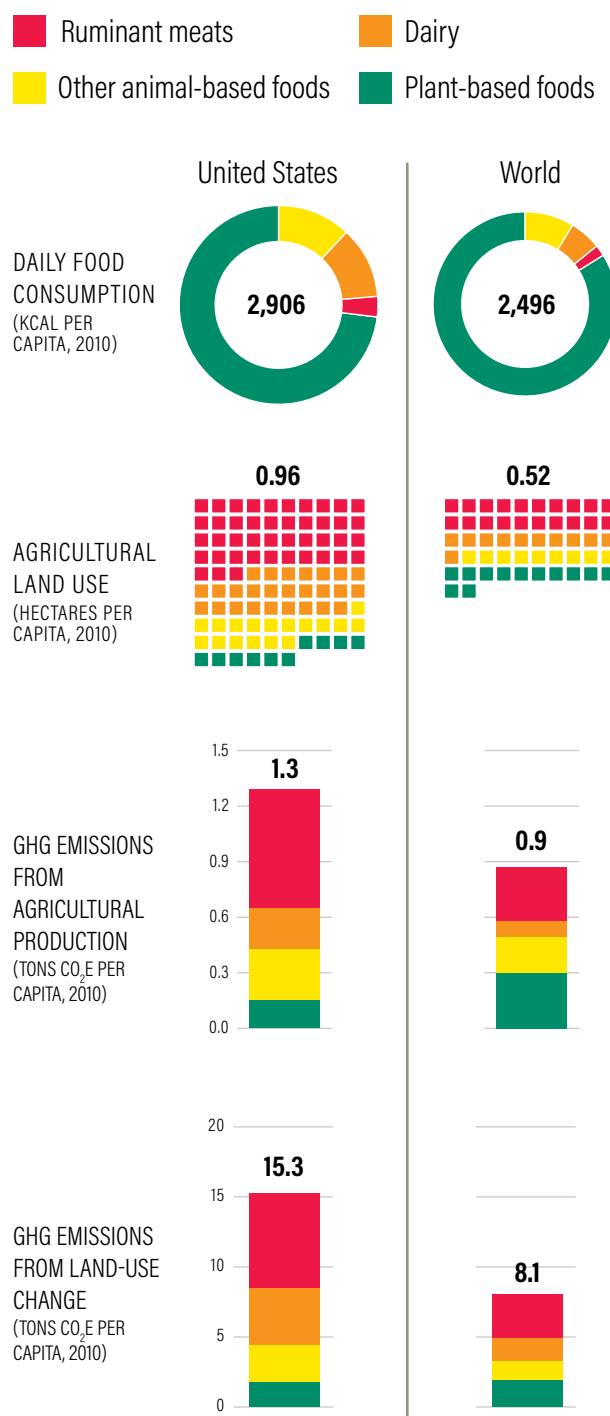
The large differences in land-use and GHG consequences of different foods explain why the global convergence toward Western-style diets has important implications for the resource needs and environmental impacts of agriculture. The average diet of the United States provides a good illustration because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

Animal-based foods accounted for nearly 90 percent of the production-related GHG emissions and agricultural land use associated with the average U.S. diet in 2010.¹¹² Beef had a disproportionately large impact relative to other food types. While beef contributed only around 3 percent of the calories and 12 percent of the protein in the average U.S. diet, it accounted for 43 percent of the annual land use and nearly half of the production emissions associated with the diet.¹¹³

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

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

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



Note: Calculations assume global average efficiencies (calories produced per hectare or per ton of CO₂e emitted) for all food types. Land-use-change emissions are amortized over a period of 20 years and then shown as annual impacts. "Other animal-based foods" includes pork, poultry, eggs, and fish.
Source: GlobAgri-WRR model, based on FAO (2019a).

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

The Opportunity

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

Designing diet shift scenarios

Any realistic answer must recognize that most people in the world eat few animal-based foods and even less ruminant meat. To estimate the potential of shifting diets in a reasonable and fair way, we therefore adopt a principle of equity that assigns reductions first to high consumers until they reach the threshold needed to achieve the percentage reduction in global per capita consumption desired in each scenario. To explore options for diet shifts, we construct and evaluate four categories of alternative diet scenarios in 2050. Figures 6-8 through 6-10¹¹⁶ show the distribution of dietary changes across countries. Table 6-2 shows the full results. All diet scenarios can help to close our gaps, and some by a great deal. But we believe that, given the scope of the changes needed, changes in ruminant meat consumption stands out as the most promising strategy.

Model Results

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

Because even obese people probably consume on average only 500 more calories per person per day, this scenario would reduce caloric consumption by only 2 percent globally¹¹⁸ and would thus close the crop calorie gap by only 2 percent (which is consistent with simpler analyses from earlier reports in this series).¹¹⁹ The contribution to the land target

is more significant, however, as reduced calorie consumption leads to agricultural land area in 2050 growing by 84 Mha less than projected in the baseline scenario, thus achieving 14 percent of the land target.

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

Less Animal-Based Foods Diet (Figure 6-8). By 2050, we project that 3.6 billion people will live in regions where average consumption of animal-based foods (meats, dairy, fish, and eggs) is at or above 600 kcal per day, which is roughly the level of consumption of Brazil in 2010.¹²² We explore scenarios in which we cut back total global consumption of all animal-based foods by 10 percent and 30 percent and shift this consumption to plant-based foods.¹²³

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

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

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

SCENARIO	FOOD GAP, 2010-50 (%)	CHANGE IN AGRICULTURAL AREA, 2010-50 (MHA)			ANNUAL GHG EMISSIONS, 2050 (GT CO ₂ E)			GHG MITIGATION GAP (GT CO ₂ E)
		Pastureland	Cropland	Total	Agricultural production	Land-use change	Total	
2050 BASELINE	56	401	192	593	9.0	6.0	15.1	11.1
SKINNY DIET								
Obesity/overweight reduced by 50%	54	350 (-52)	159 (-32)	509 (-84)	8.9	5.4	14.3	10.3 (-0.8)
LESS ANIMAL-BASED FOODS DIET								
10% shift to plant-based foods	52	195 (-207)	36 (-56)	330 (-263)	8.5	4.1	12.6	8.6 (-2.5)
30% shift to plant-based foods	44	-289 (-690)	18 (-173)	-271 (-864)	7.5	1.1 ^a	8.6	4.6 (-6.5)
LESS MEAT DIET								
10% shift to legumes	55	276 (-126)	181 (-11)	456 (-137)	8.8	5.0	13.7	9.7 (-1.3)
30% shift to legumes	48	-16 (-418)	123 (-69)	106 (-487)	8.1	2.2	10.3	6.3 (-4.8)
10% shift to U.K. vegetarian diet	55	368 (-33)	179 (-14)	547 (-46)	8.8	5.7	14.5	10.5 (-0.6)
30% shift to U.K. vegetarian diet	49	248 (-154)	137 (-54)	385 (-208)	8.3	4.3	12.6	8.6 (-2.5)
LESS RUMINANT MEAT DIET								
10% shift to legumes (<i>Coordinated Effort</i>)	56	220 (-181)	188 (-4)	408 (-185)	8.7	4.4	13.2	9.2 (-1.9)
30% shift to legumes (<i>Highly Ambitious, Breakthrough Technologies</i>)	55	-154 (-555)	171 (-21)	18 (-576)	8.1	1.4	9.4	5.4 (-5.6)
50% shift to legumes	53	-573 (-974)	154 (-38)	-418 (-1,012)	7.4	1.1 ^a	8.5	4.5 (-6.6)
10% shift to poultry/pork	57	221 (-181)	206 (14)	426 (-167)	8.8	4.6	13.3	9.3 (-1.7)
30% shift to poultry/pork	58	-153 (-555)	225 (33)	71 (-522)	8.2	1.7	9.9	5.9 (-5.1)
50% shift to poultry/pork	59	-573 (-975)	237 (45)	-336 (-930)	7.6	1.1 ^a	8.7	4.7 (-6.4)

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

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

Source: GlobAgri-WRR model.

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

Less Meat Diet (Figure 6-9). We explore scenarios in which people cut back their consumption of all meats (but not other animal-based foods), by 10 or 30 percent (to a maximum of 372 or 238 kcal/person/day, respectively). In one variation for each level of cut, people substitute their meat with a 50/50 combination of pulses and soy. In the other variation, they switch to a combination of more plant-based foods, dairy, and eggs that reflects the experience of self-reported vegetarians¹²⁶ as observed in the United Kingdom in the 1990s.¹²⁷

The switch from meat to plant-based foods only would achieve roughly half the savings in land and emissions achieved by the reduction in all animal-based foods. For example, the 30 percent meat

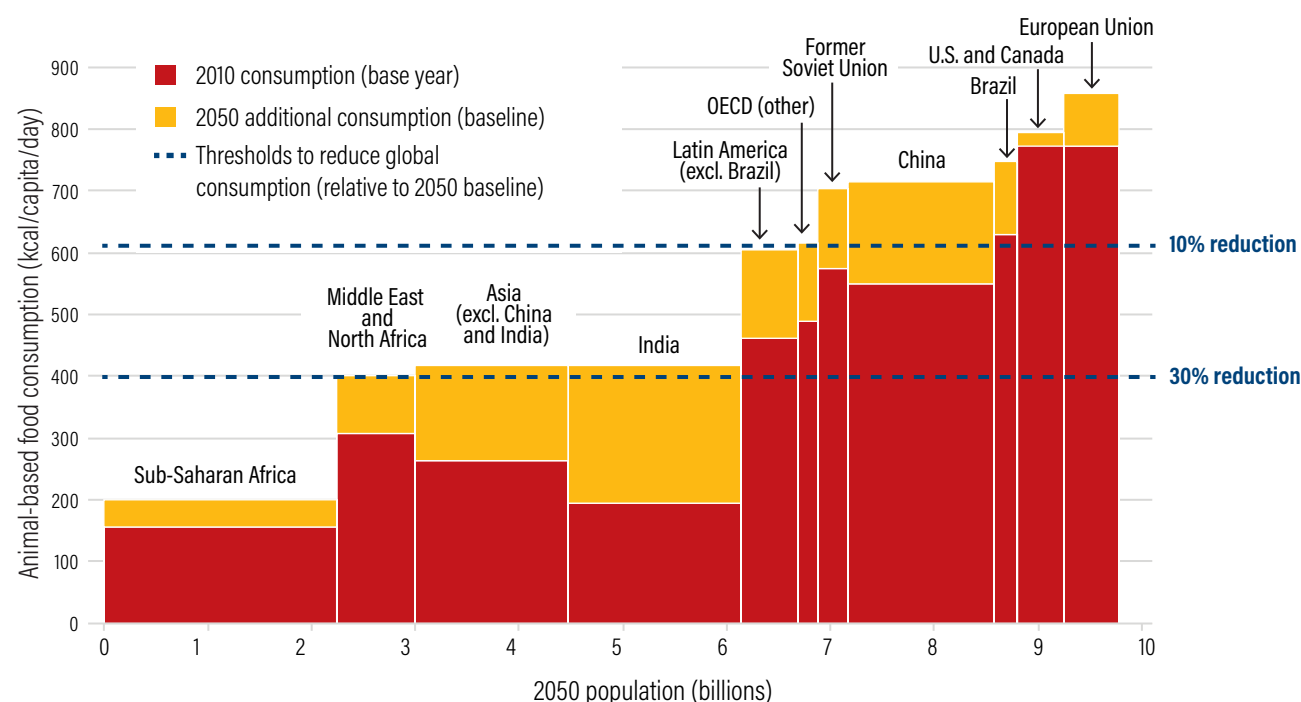
reduction would reduce the food, land, and mitigation gaps by 8 percent, 82 percent, and 43 percent, respectively. If these meat reductions were accomplished by shifting not only to vegetables but also to dairy and eggs, which is what vegetarians typically do, they would produce only half this level of reductions in land and GHG mitigation gaps (Table 6-2).

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

Less Ruminant Meat Diet (Figure 6-10).

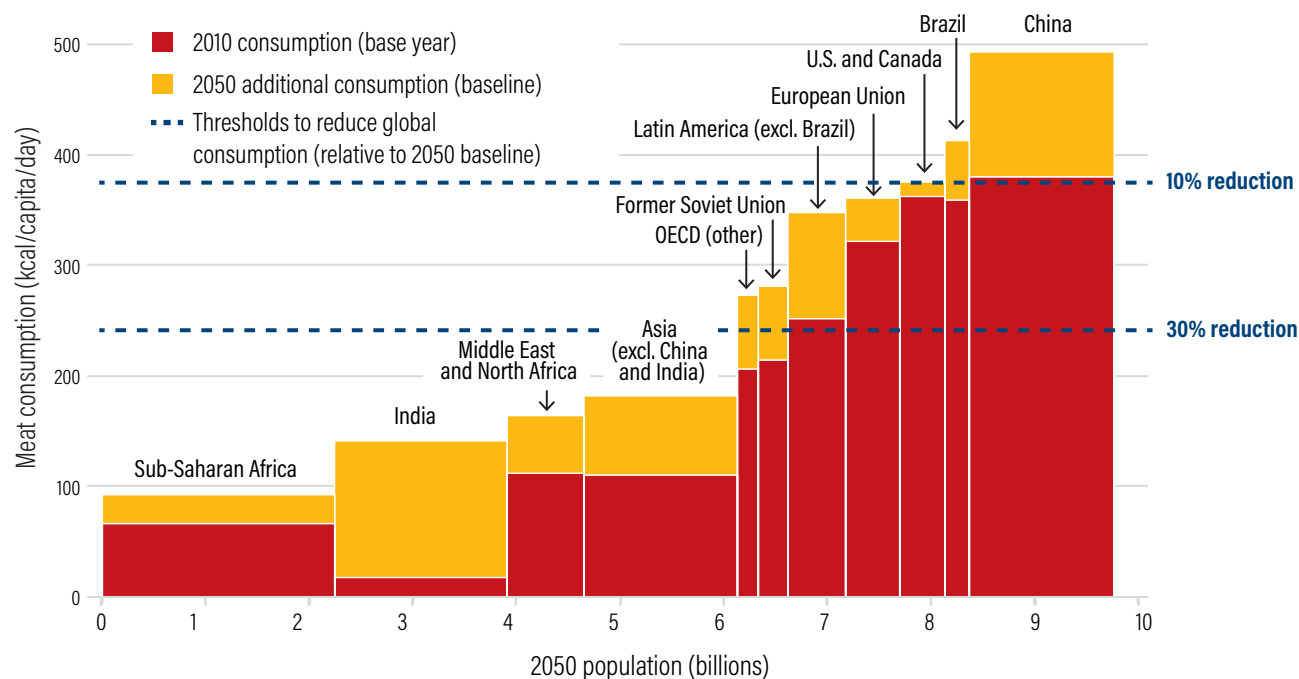
A fourth category of alternative diets focuses on reducing consumption of ruminant meats only (beef, sheep, and goat). These changes require large reductions in consumption but only by people in the United States, Canada, Europe, Latin America, and the former Soviet Union because, in 2010, they consumed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

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



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

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



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

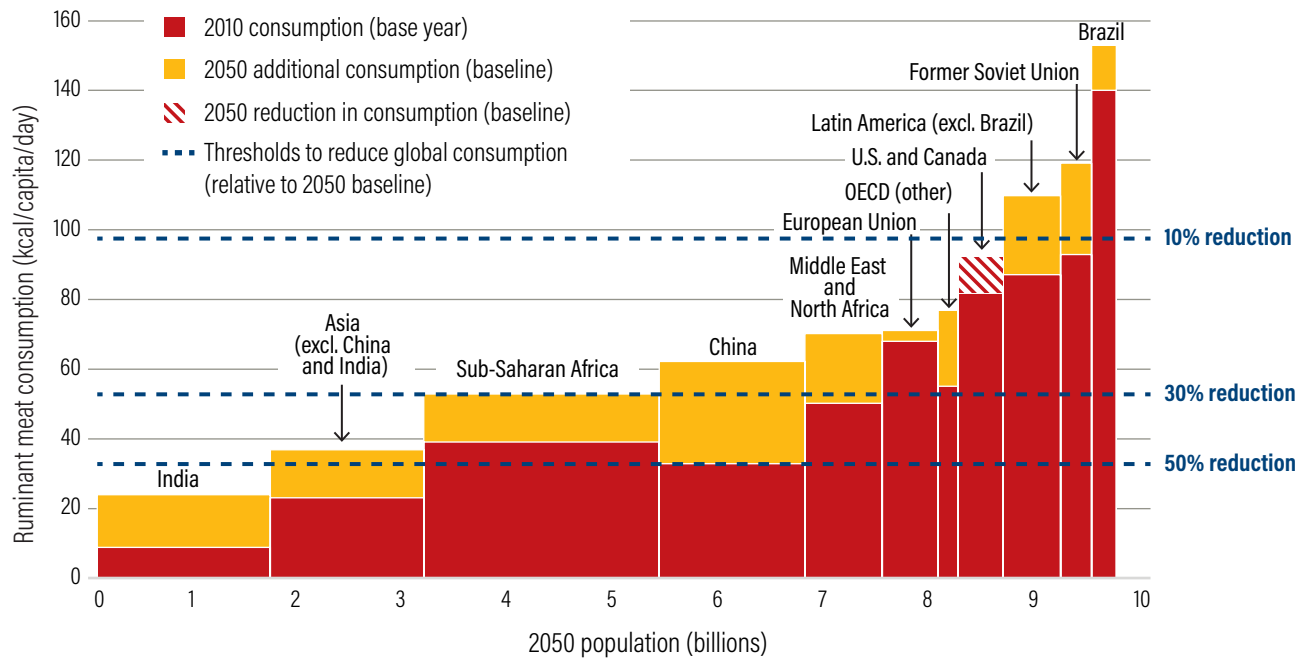
meat, although they comprised just one-quarter of the world's population.¹²⁸ Using our threshold approach, we explore three levels of cuts in global ruminant meat consumption relative to predicted 2050 levels:

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

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

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

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



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

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

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

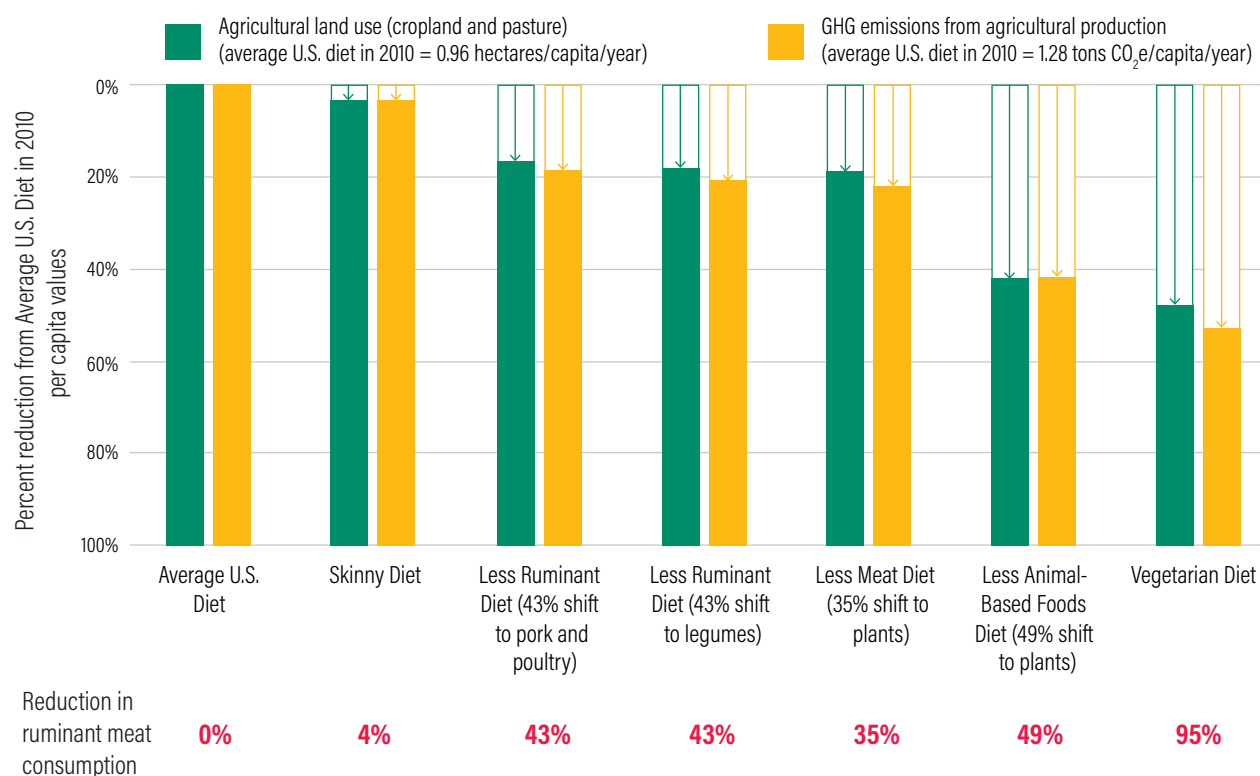
To better understand the feasibility and importance of the various global diet shifts we analyzed, Table 6-3 explains the dietary changes that would be required in the United States (a high meat-consuming country) in 2010, according to our principle of equity, and Figure 6-11 shows the per capita implications of each diet for land use and GHG emissions.¹³³ We also simulated one completely vegetarian diet¹³⁴ as an “upper bound” against which the other diet shifts could be compared.

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

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

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

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



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

Key Lessons from Our Analysis of Potential Diet Shifts

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

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

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

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

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

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

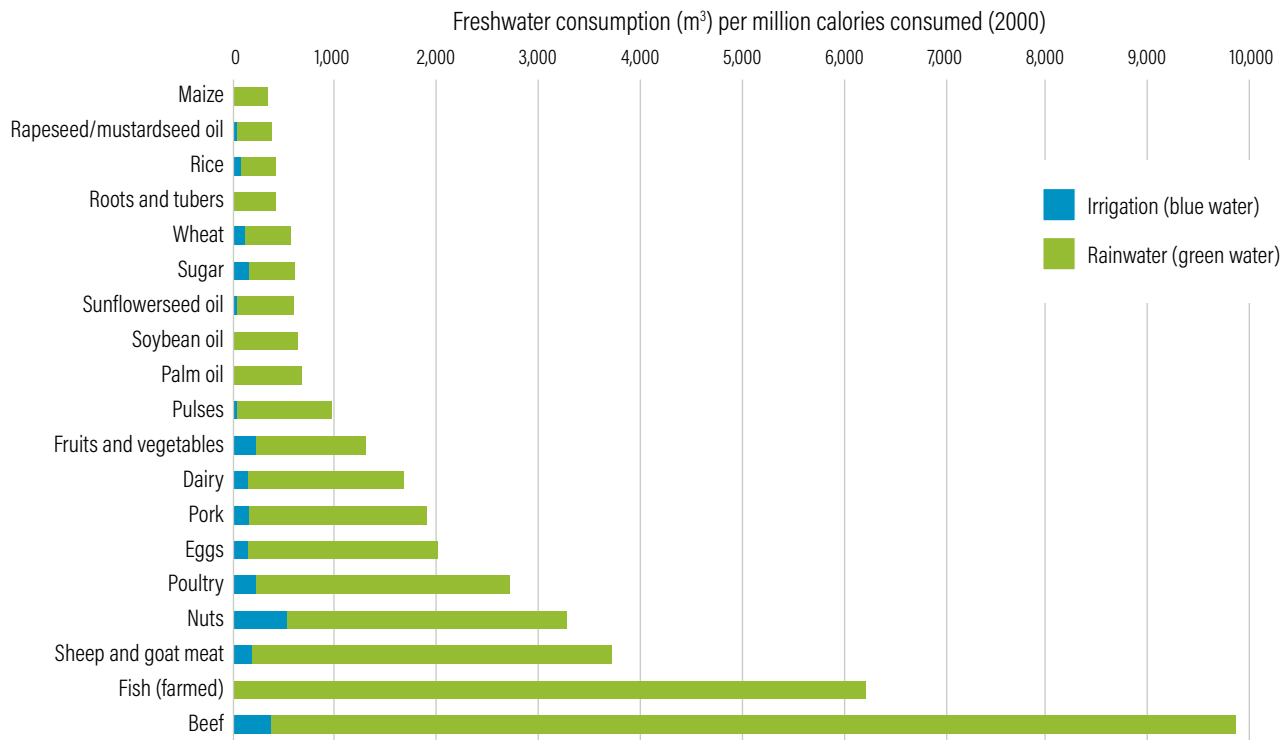
The majority of agricultural water consumption is rainwater or “green” water. A product's “green water footprint” tracks quite closely to GlobAgri-WRR's estimate of land use. Water managers, however, tend to be most concerned with irrigation water or a food's “blue water footprint,” which represents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

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

Sources:

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

Figure 6-12 | Foods differ vastly in freshwater requirements



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

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

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

Recommended Strategies

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

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

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

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

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

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

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

Interventions to change food consumption behavior, therefore, need to affect not only consumers' rational, informed decisions but also their automatic or unconscious decisions. This insight suggests that interventions must go beyond information and education campaigns and attempt to alter consumers' choices and the ways those choices are presented.¹⁴² For example, fishers, processors, and retailers in the United Kingdom have worked together to rebuild demand for pilchards. The fish

were renamed "Cornish sardines." Sardines are regarded favorably as a Mediterranean dish and preferable to the humble pilchard, traditionally sold in cans. Since this repositioning in the late 1990s, catches of pilchards in Cornwall increased from 6 tons per year in the early 1990s to 2,000 tons in 2008.¹⁴³

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

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

Supermarkets accounted for 70 to 80 percent of food retail sales in the United States and France in 2000,¹⁴⁴ and they are playing an increasingly important role in developing countries. Between 1980 and 2000, supermarkets grew their share of food retail sales from an estimated 5–20 percent to 50–60 percent in East Asia, Latin America, urban China, South Africa, and Central Europe.¹⁴⁵ This expansion continued through the first decade of the 2000s; supermarket sales grew at a 40 percent compound annual growth rate in China, India, and Vietnam between 2001 and 2009.¹⁴⁶ New supermarkets typically open in urban areas with concentrations of affluent consumers before diffusing to middle- and lower-income consumers and expanding from urban to rural areas.¹⁴⁷ Supermarkets increase consumers' access to foods more common in developed countries, such as meat, dairy products, temperate fruits and vegetables, and processed foods and drinks.¹⁴⁸

People are also increasingly choosing to dine out—in restaurants, cafeterias, and other food service facilities. In the United States, expenditures on "food away from home" as a share of total food expenditures grew from 25 percent in 1954 to 50 percent in 2013.¹⁴⁹ In China, out-of-home food consumption grew by more than 100-fold between 1978 and 2008, as people increasingly eat food from street stalls, traditional restaurants, and fast-food outlets.¹⁵⁰ This trend is driven by the growing share of women in the workplace, higher incomes, smaller households, more affordable and convenient fast-food outlets, and increases in advertising by large restaurants.¹⁵¹ Given that these drivers are

increasingly relevant worldwide, restaurants and other food service facilities will likely capture a still higher share of global food sales in coming decades.

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

SHIFT WHEEL: A FRAMEWORK FOR SHIFTING CONSUMPTION

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

markets and eating outside the home. We analyzed these shifts by reviewing published literature and market data reports, commissioning sales research, and consulting marketing strategy professionals and academic behavior specialists.

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

Minimize disruption

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

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

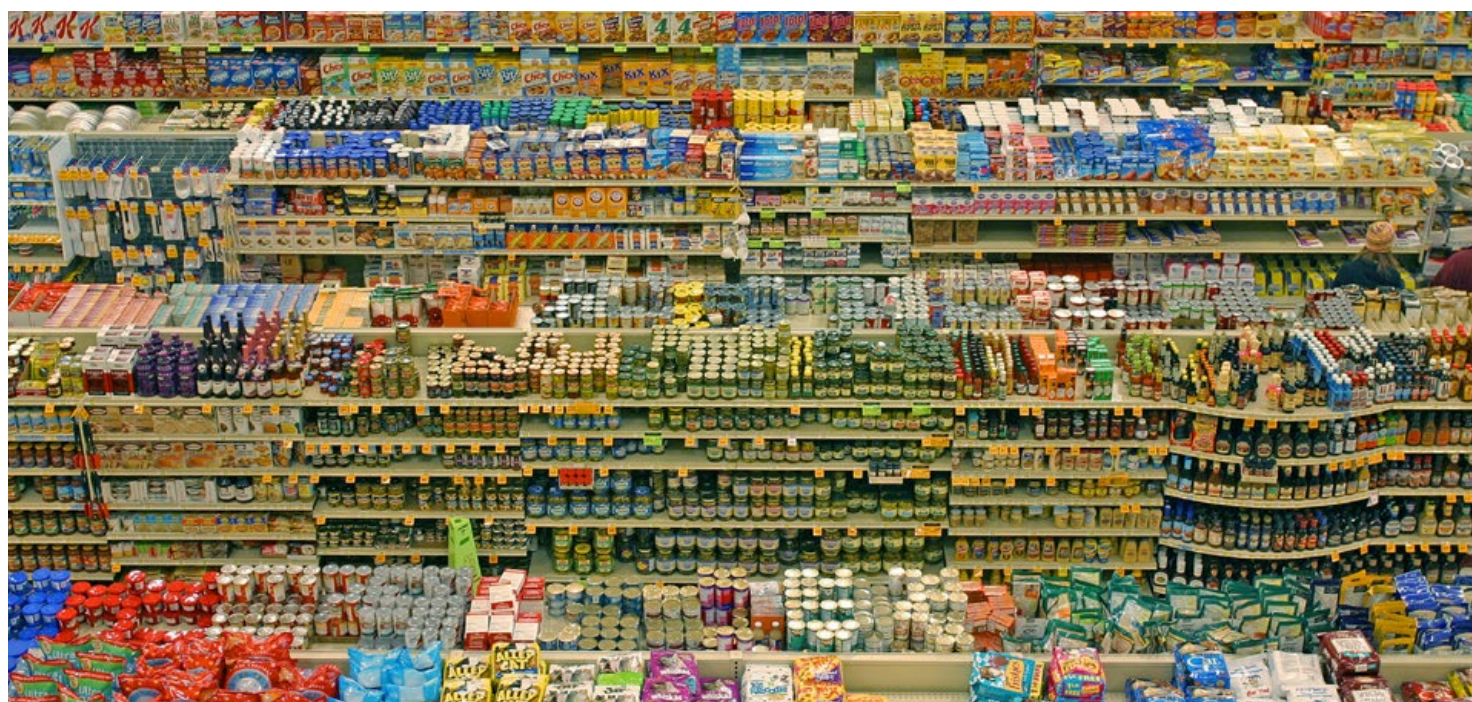
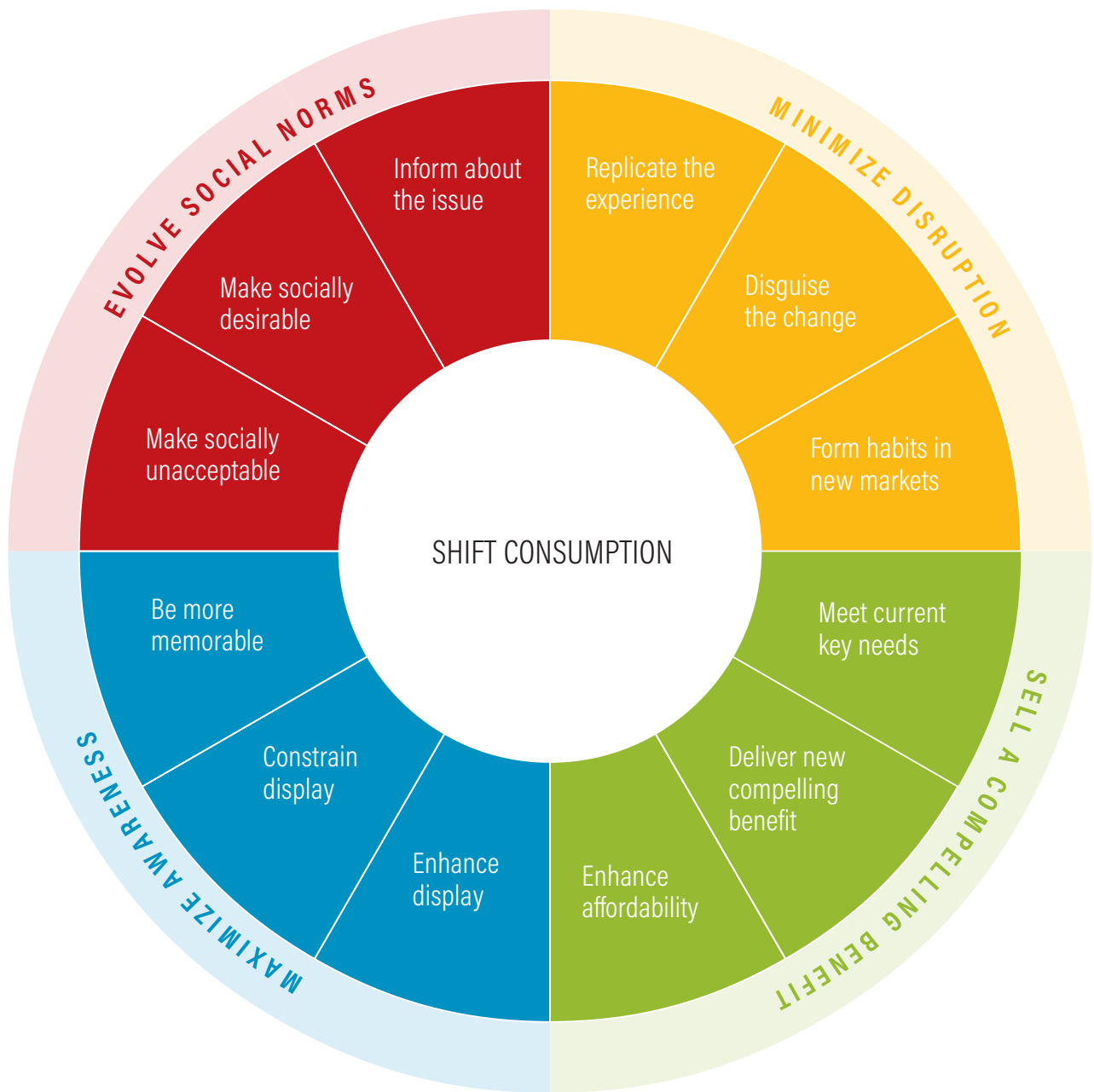


Figure 6-13 | The Shift Wheel comprises four strategies to shift consumption



Source: Ranganathan et al. (2016).

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

- **Disguise the change.** A number of products have blended in new ingredients within current formats to help disguise the shift toward plant-based ingredients. For example, the “Lurpak” Danish brand of butter has released a number of variants, such as “Lurpak Lighter,” which has around 30 percent vegetable fat blended into the butter. These inclusions are listed in the ingredients label, but the marketing leads with messaging about its buttery taste and spreadability, a result of the vegetable fat. Change can also be disguised through small, imperceptible steps (sometimes referred to as “stealth changes”). This approach has been used by food companies to steadily cut sodium and sugar levels in food. For example, manufacturers have reduced salt levels in UK bread by an average of 20 percent over the past decade.
- **Form habits in new markets.** Getting consumers to purchase healthy and more sustainable products is less disruptive if they have yet to form buying habits. This approach is especially relevant to countries where consumption of animal-based protein and beef is rapidly rising or is projected to do so by 2050. Introducing programs that limit consumers' shift toward buying more animal-based food products in geographies or social groups without a prior history or unformed buying norms can be an effective strategy.

Sell a compelling benefit

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

- **Meet current key needs.** The UK egg industry has built upon and reinforced the consumer perception that eggs from free-range chickens taste better than those from cage-reared chickens. Brands such as “Happy Eggs,” with their tagline “happy hens lay tasty eggs,” demonstrate this approach. Although free-range eggs are 30–50 percent more expensive than conventional eggs, this quality association has helped capture around 45 percent of the UK market.¹⁵²
- **Deliver new compelling benefit.** Although much current messaging around the benefits of plant-based foods relates to health and nutrition—which can be effective in certain circumstances—health-related messaging can be a double-edged sword. Studies have found that calling plant-based dishes “healthy” can actually create negative connotations for consumers, with many experiencing “healthy” dishes as less enjoyable, less tasty or less filling.¹⁵³ Rather than leading with a health message, certain food service outlets emphasize the unique taste sensations of plant-based food. For example, restaurants such as Dirt Candy in New York champion the natural sweetness of plant-based foods in their description of main dishes (e.g., Tomato Cake). And Stanford University found that giving vegetable-based dishes flavorful, indulgent, or exciting names (e.g., “twisted citrus-glazed carrots”) boosted sales of those dishes in cafeterias by 25 to 41 percent relative to less-appealing names.¹⁵⁴ The converse is also true. Research from the London School of Economics has shown that placing plant-based dishes within a vegetarian box on a menu can reduce the chances a nonvegetarian will order these dishes by more than half because it is not based on offering a compelling benefit except to vegetarians.¹⁵⁵

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

Maximize awareness

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

- **Enhance display.** One study in New York City found that when supermarket checkout lines were stocked with more healthy foods, customers purchased more healthy items and fewer unhealthy ones, relative to standard checkout lines.¹⁵⁹ In a retail environment, food manufacturers can encourage retailers to increase the amount and quality of space given to displaying their products by providing greater margins to retailers or running promotional campaigns, such as offering discounts or engaging celebrity chefs to feature their products. In a food service environment, layout and design of menus, buffets, and cafeteria spaces can all enhance the success of target dishes by increasing their visibility.
- **Constrain display.** In some cases, undesired food choices can be curtailed by limiting product distribution and display. Public food procurement policies in schools, hospitals, prisons, and government offices have been used to influence consumption habits. The complete removal or “choice editing” from stores is possible, but it is sensitive; 46 percent of British shoppers are in favor of more choice editing for ethical reasons but 26 percent object, and 73 percent were against editing for health reasons.¹⁶⁰ Some countries also are experimenting with limiting marketing of undesirable foods.

Chile passed a law in 2012 that limits children’s exposure (through marketing and sales) to foods that are high in calories, salt, sugar, and fat—and began implementing the law in 2016.¹⁶¹

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

Evolve social norms

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

- **Inform about the issue.** Although evidence shows that information and education alone do not lead to sufficient action,¹⁶⁷ they can sometimes contribute to a broader effort, as demonstrated by their role in the past decade in reducing consumption of trans fats in several countries.¹⁶⁸ In many cases, information can

lead to indirect or multiplier effects, by raising the profile of an issue, prompting product reformulation (in the case of labeling), or forming the basis of food and nutrition policy and programs (e.g., national dietary guidelines).¹⁶⁹

- **Make socially desirable.** In 2012, celebrity chef Delia Smith helped increase UK sales of gammon (ham) nearly threefold relative to the previous year after featuring a recipe for gammon on television. The chef's influence over food sales has been called the "Delia effect," a term coined when sales of cranberries quadrupled the day after she used them on television.¹⁷⁰ Plant-based food companies such as Beyond Meat, Silk, and MorningStar Farms have used athlete or male celebrity endorsements, prominent protein claims, and masculine language like "Beast Burger" to create associations with strength and power to avoid feelings of emasculation. Tossed, a UK-based salad chain, attracts men through naming certain products "Muscle Builders" and forming partnerships with local gyms to offer male personal assistants discounts if they eat in their stores.
- **Make socially unacceptable.** A number of campaigns have helped make a specific food socially unacceptable to consumers. For example, in 2008 the celebrity chefs Hugh Fearnley-Whittingstall and Jamie Oliver both launched high-profile TV programs and campaigns to highlight the issues associated with buying non-free-range chicken. During the campaign, sales of free-range poultry reportedly increased by 35 percent relative to the previous year, while sales of caged birds fell by 7 percent.¹⁷¹ In another example, WildAid launched a campaign to draw attention to the devastating impacts of shark fishing, helping to reduce consumption of shark fins in China.¹⁷² It is important to note, however, that the long-term impact of these campaigns is unknown.

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

Improve plant-based or cultured meat substitutes

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

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

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

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

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

In recent years, corporate investment and research in alternative meat products has grown rapidly.¹⁸³ Food critics appear to confirm that substitutes are coming closer to matching the experience of at least some meats.¹⁸⁴ Because of the inefficiency of meat production, these alternatives have a high potential to become cheaper than meat. Even with a high rate of growth, however, the retail market is only projected to grow from \$3.8 billion worldwide in 2015 to \$5.2 billion in 2020.¹⁸⁵ By comparison, the retail market for conventional meat and seafood was \$741 billion in 2014.¹⁸⁶ The industry will need to grow at a vastly greater rate if it is to have a real effect on global meat consumption.

Leverage government policies

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

Procurement

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

Taxes

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

Modeling studies agree that food taxes could have a significant effect on consumption, using a variety of economic methods. These studies generally estimate substantial reductions in specific targeted foods and have emphasized that taxes work best when there are untaxed, appropriate substitutes. Estimated elasticities of consumption for various meats also suggest that a tax on beef, for example, could lead to substantial switching at least to other meats if not vegetable alternatives.¹⁹² In fact,

U.S. consumption of beef declined by 12 percent just from 2007 to 2015 as retail prices rose by 51 percent,¹⁹³ although with the recession over, and beef production rebounding to prerecession levels, consumption has somewhat rebounded.¹⁹⁴

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

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

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

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

Subsidies

Governments should phase out subsidies that favor meat and dairy production and explore subsidies instead for healthy plant-based foods. Bailey et al. (2014) found that livestock subsidies in Organisation for Economic Co-operation and Development (OECD) countries amounted to \$53 billion in 2013, and pork subsidies in China exceeded \$22 billion in 2012. The U.S. Department of Agriculture estimated in 2009 that a subsidy lowering retail prices of fruits and vegetables by 10 percent would encourage low-income households to increase their consumption by 2 to 5 percent,¹⁹⁹ and would cost around \$600 million to implement annually. A more recent U.S. study also estimating the effects of a 10 percent reduction in fruit and vegetable prices came to a more hopeful conclusion that consumption would rise by 14 percent, preventing or postponing more than 150,000 deaths from heart disease in the United States by 2030.²⁰⁰

Stronger policy coherence

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

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



CHAPTER 7

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

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

Bioenergy is any form of energy that is derived from recent (as opposed to fossil) plant or animal tissue. For millions of the world's people who cannot afford fossil fuels, bioenergy has long provided and continues to provide the major source of energy in the form of wood, charcoal from wood, and sometimes dung. Traditionally estimated at roughly one-tenth of the world's energy supply,²⁰¹ these traditional sources of bioenergy will probably continue for many years to serve millions of people who cannot afford modern alternatives. Even so, reducing this traditional bioenergy use has been a major focus of many international efforts both to preserve forests²⁰² and to reduce adverse impacts on human health.²⁰³

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

The Challenge

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

Over the past few decades, however, many governments have made strong pushes to expand “modern” bioenergy that diverts land or plants from alternative uses. These policies encourage liquid biofuels for transportation made from crops. Governments are also encouraging power plants to replace coal, at least in part, with wood pellets or chips generated by additional harvest of trees or diversion of the parts of trees that would otherwise

provide pulp and paper. Governments have created incentives to cultivate fast-growing grasses for biomass energy feedstocks on agricultural land, although this has not yet occurred in meaningful volumes.

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

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

In 2010, our base year, biofuels provided roughly 2.5 percent of the energy in the world's transportation fuel (the fuel used for road vehicles, airplanes, trains, and ships). The source of these biofuels was, overwhelmingly, food crops.²⁰⁵ They include ethanol distilled mainly from maize, sugarcane, sugar beets, or wheat (88.7 billion liters),²⁰⁶ and biodiesel refined from vegetable oils (19.6 billion liters). The United States, Canada, and Brazil accounted for about 90 percent of ethanol production, while Europe accounted for about 55 percent of biodiesel production (Figure 7-1).²⁰⁷ Excluding feed by-products, about 4.7 percent (3.3 exajoules [EJ]²⁰⁸) of the energy content in all crops grown worldwide was used for biofuels in 2010.²⁰⁹

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

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

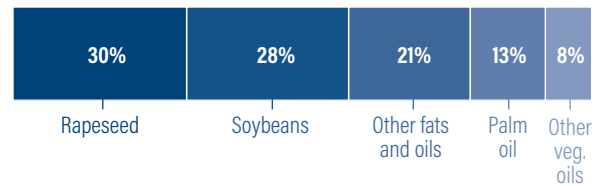
Crops used in **ethanol** (100% = 88.7 BILLION LITERS)



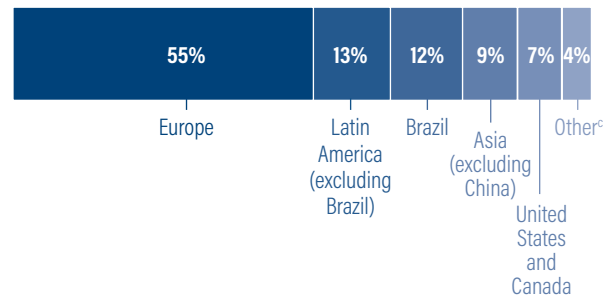
Where **ethanol** is generated



Crops used in **biodiesel** (100% = 19.6 BILLION LITERS)



Where **biodiesel** is generated



Notes:

a. Includes wheat (4%), cassava (1%), and other feedstocks (1%).

b. Includes China (2%) and other regions (3%).

c. Includes China (2%) and other regions (2%).

Source: EIA (2014a).

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

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

to the crop calorie gap.) For 2050, the answer is roughly 30 percent of all the energy in today's (2010) crop production (Figure 7-2).

Because transportation fuel is only one part of the world's energy use, 30 percent of all today's crop energy would provide only around 2 percent of final, net delivered energy in 2050.²¹⁰

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

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

COUNTRY	MANDATE/TARGET
Angola	E10
Argentina	E10, B10
Australia: New South Wales (NSW), Queensland (QL)	NSW: E6, B2; QL: E3 (by 2017), E4 (by 2018), B0.5
Belgium	E4, B4
Brazil	E27 and B8 (by 2017), rising to B10 (by 2019)
Canada	E5, B2 (nationwide), E5–E8.5 (in 5 provinces), B2–B4 (in 5 provinces)
Chile	E5, B5 (target, no mandate)
China	E10 (9 provinces), B1 (Taipei)
Colombia	E8, B10
Costa Rica	E7, B20
Dominican Republic	E15, B2 (target, no mandate)
Ecuador	E10, B5
European Union	10% renewable energy in transport by 2020 with 7% cap on crop-based fuels ^a
Ethiopia	E10
Fiji	E10, B5 (approved target in 2011, mandate expected)
Guatemala	E5
India	E22.5, B15
Indonesia	E3, B20
Italy	0.6% advanced biofuels blend by 2018, 1% by 2022

COUNTRY	MANDATE/TARGET
Jamaica	E10
Kenya	E10 (in Kisumu)
Malawi	E10
Mexico	E5.8
Malaysia	E10, B10
Mozambique	E15 (2016–20), E20 (from 2021)
Norway	B3.5
Panama	E10
Paraguay	E25, B1
Peru	E7.8, B2
Philippines	E10, B2
Republic of Korea	B2.5, B3 (by 2018)
South Africa	E2, B5
Sudan	E5
Thailand	E5, B7
Turkey	E2
Ukraine	E5, E7 (by 2017)
United States	136 billion liters of any biofuel, equivalent to ~12% of total transportation fuel demand in 2020–22 ^b
Uruguay	E5, B5
Vietnam	E5
Zimbabwe	E15

Notes:

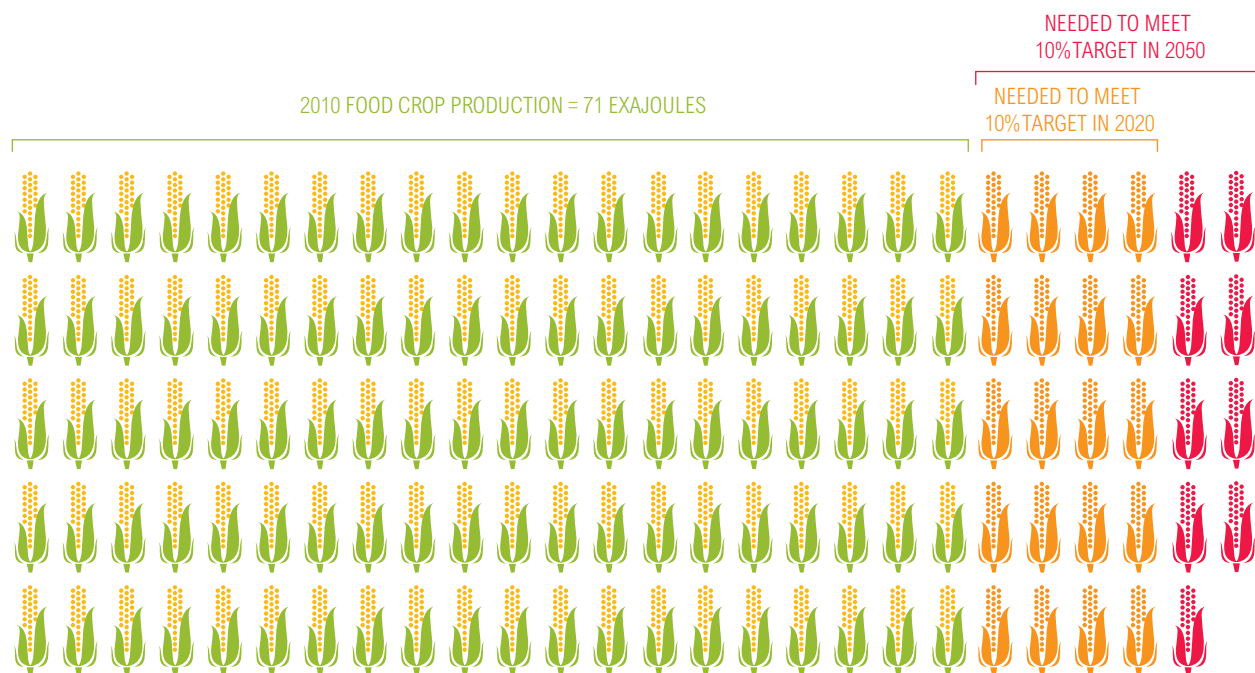
E= ethanol (e.g., "E2" = 2% ethanol blend); B = biodiesel (e.g., "B2" = 2% biodiesel blend)

a. Lignocellulosic biofuels, as well as biofuels made from wastes and residues, count twice and renewable electricity 2.5 times toward the target.

b. The U.S. mandate is for a volume, not a percentage, and this volume may be met either by ethanol or biodiesel, despite their different energy contents. The estimated percentage of U.S. transportation fuel in 2020–22 is based on the assumption of 34 billion gallons of ethanol and 2 billion gallons of biodiesel and a U.S. Energy Information Administration projection of 2020 U.S. transportation energy demand. The U.S. mandate includes a goal that 16 billion gallons of the 36 billion gallons (136 billion liters) come from cellulosic sources, but that requirement can be waived and all 36 billion gallons could come from crops as long as maize-based ethanol does not exceed 15 billion gallons.

Source: IEA (2016a) in REN21 (2017).

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



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

Biofuel from cellulose?

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

Unfortunately, growing trees and grasses well requires fertile land, resulting in potential land competition with food production. In general, growing grasses and trees on cropland generates the highest yields but is unlikely to produce more biofuel per hectare than today's dominant ethanol

food crops. For example, a hectare of maize in the United States currently produces roughly 1,600 gallons (about 6,000 liters) of ethanol after deducting the part of the land that produces feed products.²¹³ For cellulosic ethanol production to match this figure, the grasses or trees must achieve almost double the national cellulosic yields estimated by the U.S. Environmental Protection Agency (EPA),²¹⁴ and two to four times the perennial grass yields farmers actually achieve today.²¹⁵ Although there are optimistic projections for even higher yields, they are unrealistically predicated on small plot trials by scientists—sometimes only a few square meters,²¹⁶ which scientists can tend more attentively than real farmers.

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

The implications of possible bioenergy targets for all forms of energy

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

How much of today’s world biomass harvest would be required to supply 230 EJ? The answer is roughly all of it: all the crops, plant residues, and wood, and all the biomass grazed by livestock around the world, probably amounts to roughly 225 EJ²²³ (Figure 7-3). Yet the world would still need all this biomass for food, livestock, wood, and other uses. To meet this bioenergy demand while also meeting projected food demand, the world would therefore have to approximately double the present total harvest of plant material and produce roughly 50 percent more food at the same time.

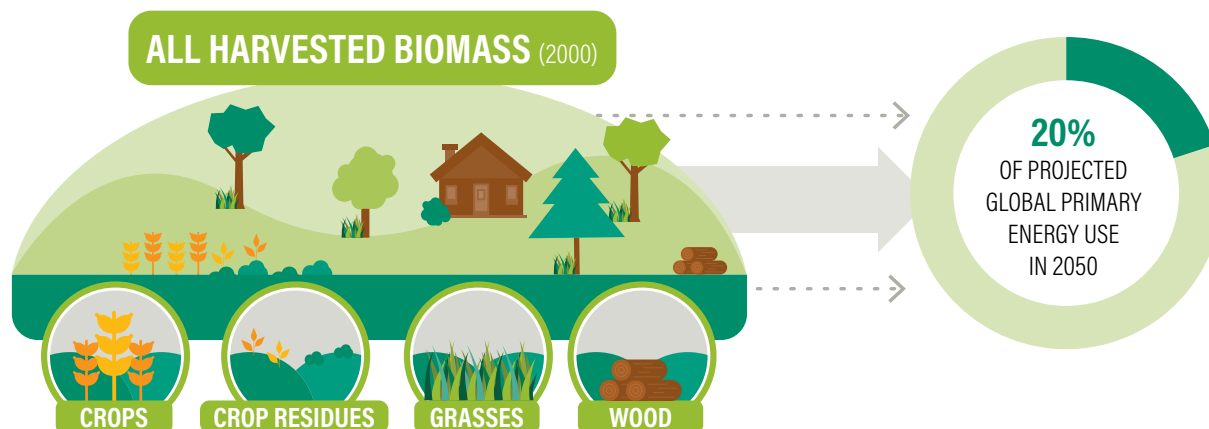
The Opportunity

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

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

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

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



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



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

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

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

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

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

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

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

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

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

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

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

This assumption is erroneous because the first requirement for any offset is that it be additional. For example, if an employer wishes to “offset” a worker’s overtime by providing vacation time, the employer must offer the worker more vacation time and not merely allow the worker to take vacation time already earned. For this reason, if bare land—that would otherwise remain bare—is brought into production to grow biomass for energy, the additional carbon absorbed by these plants offsets the carbon released by burning them. Similarly, if crop residues were going to be burned in the field, the carbon released by collecting and burning them for bioenergy is offset by the emissions avoided by not burning the residues in the field. But if maize is grown for ethanol by clearing forest, there is a large

release of carbon, so that the net effect of growing maize for ethanol production is to release far more carbon than the maize plants will absorb and turn into ethanol for decades. (That point is now broadly accepted.)

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

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

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

“Renewable” and “sustainable” does not make biomass carbon-neutral

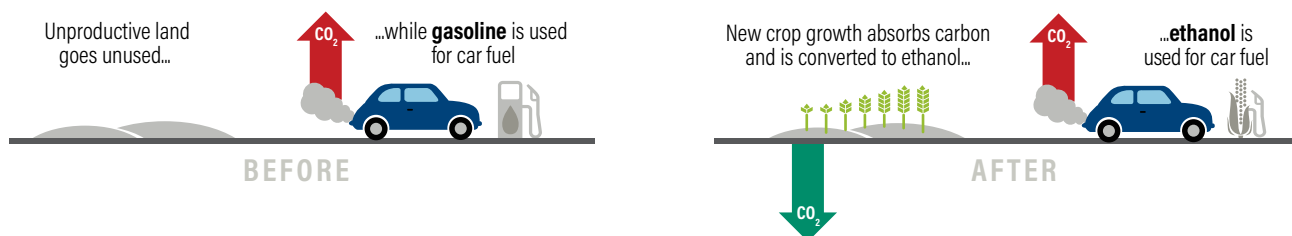
What explains the belief that all bioenergy is carbon-neutral? One explanation is the common but incorrect intuition that anything renewable is carbon-free. That idea is based on thinking like the following: “If the world uses plant growth for energy and the plants grow again, it cannot cost the world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

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

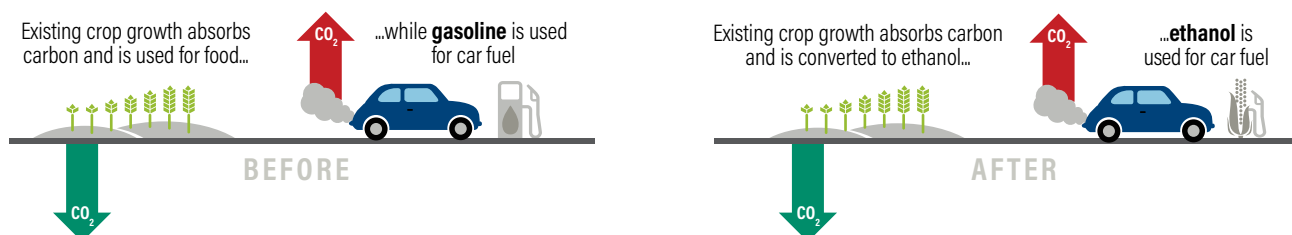
Analogously, people use annual plant growth and the carbon it absorbs for food and forest products, and they leave some of the carbon to be stored in vegetation and soils—thereby limiting climate change. That annual plant growth and carbon is not free for the taking by bioenergy. The cost of using the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

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

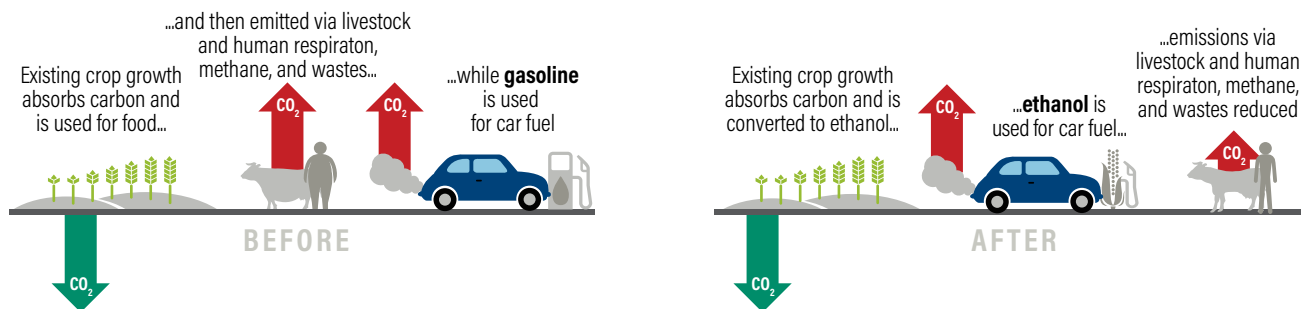
SCENARIO A—ADDITIONAL PLANT GROWTH FOR BIOENERGY REDUCES GREENHOUSE GAS EMISSIONS



SCENARIO B—FOOD CROPS ARE DIVERTED TO BIOFUELS, EMISSIONS REMAIN UNCHANGED



SCENARIO C—FOOD CROPS ARE DIVERTED TO BIOFUELS, FOOD CONSUMPTION DECLINES, EMISSIONS DECLINE



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

Source: Searchinger and Heimlich (2015).

Modeling studies can be misleading

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

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

Food reduction

First, some models estimate that many of the food crops diverted to biofuels are not replaced. When food prices rise because of the additional demand for biofuels, the market responses are not only that other farmers produce more food but also that some consumers consume less. The reduction in consumption reduces GHGs in two ways. First, if people eat less food, farmers do not have to clear as much additional land to replace the forgone food

crops. More directly, when people eat crops, they release that carbon, mostly through respiration (and a little through their wastes). If crops are not replaced, then people or livestock eat fewer crops and physically breathe out less carbon dioxide. Economic models used by the European Commission and the state of California have estimated that this effect is large—that between one-quarter and one-half of the food calories (and therefore roughly that much carbon) diverted to biofuels is not replaced.²³⁷

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

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

Yield gains

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

Yet the evidence for yield responses due to higher prices is weak and limited at best.²⁴⁰ Global yield growth has shown remarkably consistent trends that fluctuate little or not at all in response to annual changes in price.²⁴¹ Unless yield gains rather than expansions of cropland replace nearly all the

crops diverted to biofuels, the GHG reductions from biofuels relative to gasoline and diesel would at best be modest because the emissions from clearing more land would negate them.²⁴²

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

"Marginal" or "degraded" land

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

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

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

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

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

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

Second, there is no benefit to applying carbon capture and storage even to additional biomass to achieve "negative emissions" unless and until that is cheaper than reducing positive emissions,

for example, from the continued use of fossil fuels. Generating one kilowatt hour of low-carbon energy through additional biomass in one location and applying carbon capture and storage to the burning of coal in another location generates precisely the same amount of GHG benefit as applying that CCS to the bioenergy itself, creating BECCS. The only reason to use BECCS would therefore be if it were cheaper, but even in favorable assessments, BECCS costs are estimated in the hundreds of dollars per ton of carbon dioxide mitigation, which is far more expensive than typical costs of mitigating emissions from power plants.²⁴⁷ As some people have pointed out, if ethanol plants are going to continue to use crops, it would be beneficial to capture the carbon released from the fermentation of those crops to energy—just as it would be preferable to apply CCS to any source of carbon dioxide—but doing so only captures one-third of the carbon released by the whole process and therefore does not make the production of ethanol beneficial.²⁴⁸ Only once cost-effective options for eliminating coal and other fossil emissions have been exhausted does the prospect of low-carbon biomass combined with carbon capture and storage perhaps provide an added cost-effective opportunity to mitigate climate change through negative emissions.

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

“Additional biomass” alternatives

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

Estimates of the technical potential to produce energy from these wastes vary. Some are as high as 125 EJ per year, which would be enough to generate almost 25 percent of global primary energy demand today and 14 percent in 2050.²⁴⁹ More appropriate estimates must start by recognizing that most of these residues are already put to valuable use.²⁵⁰

Crop residues

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

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

Wood residues

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

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

INADVISABLE: FEEDSTOCKS THAT REQUIRE DEDICATED USE OF LAND	ADVISABLE: FEEDSTOCKS THAT DO NOT MAKE DEDICATED USE OF LAND
<ul style="list-style-type: none"> ❌ Food crops ❌ Fast-growing trees or grasses purposely grown on land dedicated to bioenergy ❌ Harvests of standing wood from existing forests 	<ul style="list-style-type: none"> ✅ Some forest slash left behind after harvest ✅ Black liquor from papermaking ✅ Unused sawdust ✅ Municipal organic waste ✅ Landfill methane ✅ Urban wood waste ✅ Crop residues that are otherwise not used, are not needed to replenish soil fertility, and do not add substantial carbon to the soil or the soil functions of which are replaced by additional cover crops ✅ Cover crops that would not otherwise be grown ✅ Unused manure ✅ Wood from agroforestry systems that also boost crop or pasture production ✅ Intercropped grasses or shrubs for bioenergy between trees in timber plantations in ways that maintain timber yields ✅ Tree growth or bioenergy crop production that has higher yields and is more efficiently burned than traditional fuelwood and charcoal and that replaces these traditional fuels in societies that continue to rely on them

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

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

Cover crops

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

Algae

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

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

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

Replacing traditional fuelwood

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

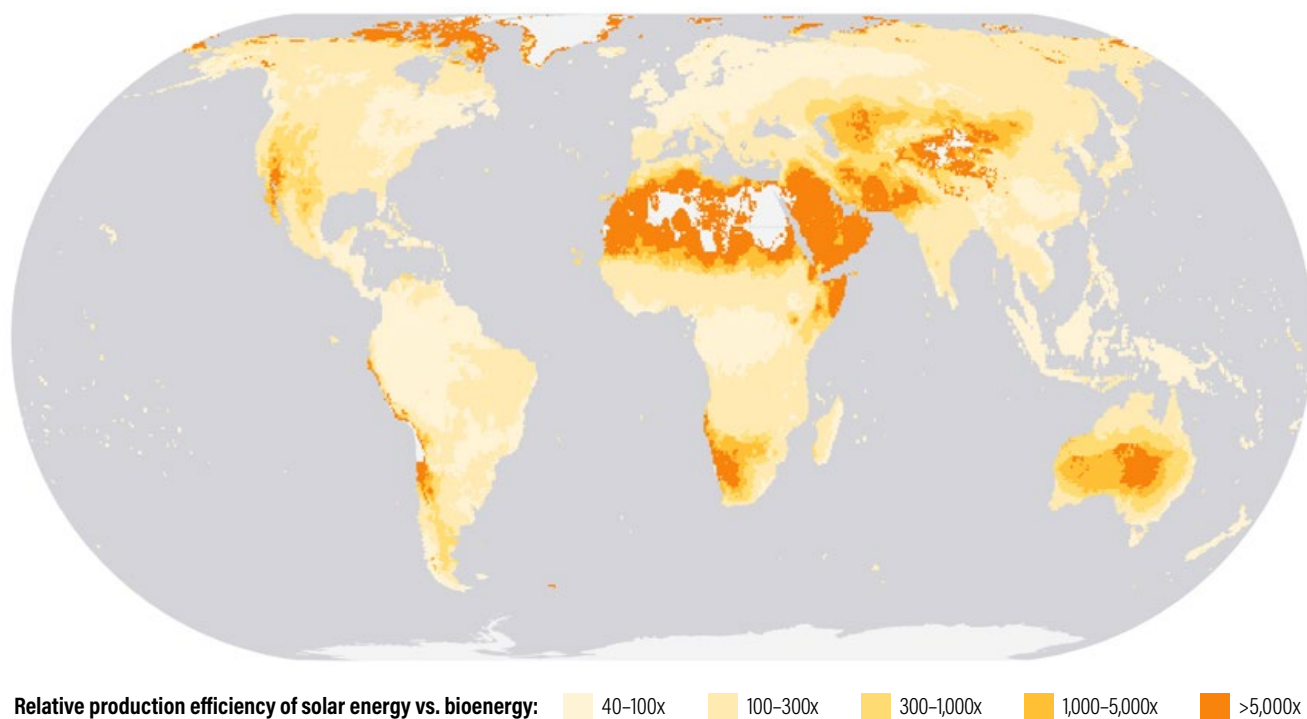
Solar alternatives to bioenergy

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

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

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

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



Source: Searchinger et al. (2017).

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

Even this comparison underestimates the advantages of solar energy because solar installations can use drylands and rooftops, while bioenergy requires

productive land that could produce food or store carbon if not used for bioenergy.²⁷⁶ For example, as shown in Figure 7-5, some of the “best” land for bioenergy is the world’s dense, tropical forests, but clearing this land to plant bioenergy crops obviously would come with high carbon costs. According to this analysis, on one-quarter of the world’s land, which is less productive but excluding desert and ice-covered areas, the ratio is a minimum of 5,000 to 1 in favor of solar.

Biomass is more easily stored than solar energy. But because electric vehicles provide their own storage and could, if required or given incentives, mostly be powered during the day, the storage advantage for bioenergy as a vehicle fuel is less significant. Phasing in solar-electric cars will take time, so biofuels might be a legitimate short-term alternative if they could reduce emissions today and do so cost-effectively but, for the reasons given in this chapter, we believe they cannot. Fortunately, with solar power providing less than 2 percent of

global energy supply and the potential to supply solar without storage likely in the range of at least 20 percent,²⁷⁷ there is abundant room to expand solar to displace use of fossil fuels. Unless and until that reasonable potential is exhausted, there is no need to direct climate change effort toward shifting transportation fuels. And by the time solar energy has saturated the capacity of both transportation and other end uses to use it without storage, the large research and development investments in storage may have made continued displacement of fossil fuels by solar both practical and economic.

Model Results

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

A complete phase-out would reduce agricultural land demand in 2050 by 28 Mha, and reduce agricultural GHG emissions from both production and land-use change by 330 million tons CO₂e per year, closing the GHG mitigation gap by 3 percent (Table 7-3).

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

Recommended Strategies

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

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

SCENARIO	FOOD GAP, 2010-50 (%)	CHANGE IN AGRICULTURAL AREA, 2010-50 (MHA)			ANNUAL GHG EMISSIONS, 2050 (GT CO ₂ E)			GHG MITIGATION GAP (GT CO ₂ E)
		Pasture land	Cropland	Total	Agricultural production	Land-use change	total	
2050 BASELINE	56	401	192	593	9.0	6.0	15.1	11.1
Phase out use of crops for biofuels (compared to maintaining 2.5% transportation fuel in baseline) (<i>Coordinated Effort, Highly Ambitious, Breakthrough Technologies</i>)	49	401 (0)	164 (-28)	566 (-28)	9.0	5.8	14.7	10.7 (-0.3)
Meet a 10% transportation fuel target from crop-based biofuels	78	401 (0)	298 (106)	699 (106)	9.3	7.1	16.4	12.4 (1.3)

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

Source: GlobAgri-WRR model.



Phase out mandates and subsidies

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

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

Countries should not allow biofuels made from food crops or from land dedicated to biofuel production to qualify for low-carbon fuel standards. These laws—in California, British Columbia, and the European Union—require that the carbon-intensity of all the transportation fuels sold by a company decline by a small percentage relative to gasoline and diesel, typically by 10 percent.²⁸⁰ Proponents originally hoped that these laws would provide incentives to

incorporate environmentally preferable biofuels, particularly those from cellulose. The policy reflects a time when thinking about the GHG consequences of biofuels ignored the land-use implications. California regulators later recognized the importance of land use and made efforts to incorporate emissions from land-use change into their analyses of crop-based biofuels. But we believe that, as with similar efforts, California's analysis incorporated forms of double counting discussed earlier in this chapter. For example, the state credited biofuels for the GHG reductions that its model estimated would result from reduced food consumption.²⁸¹

Exclude bioenergy produced on dedicated land from renewable energy standards

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

States and Canada for manufacturing and shipping wood pellets to Europe.²⁸³ As many papers have now shown, burning whole trees or wood pellets increases GHG emissions for decades.²⁸⁴ These standards also threaten to create a significant increase in the global harvest and degradation of forests for relatively little energy impact: Doubling the world's commercial timber harvest and using that additional harvest for energy would supply at most an additional 2 percent of global electricity supply by 2035.²⁸⁵

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

Reform accounting of bioenergy

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

Maintain blend wall limitations

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

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

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



CHAPTER 8

MENU ITEM: ACHIEVE REPLACEMENT-LEVEL FERTILITY RATES

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

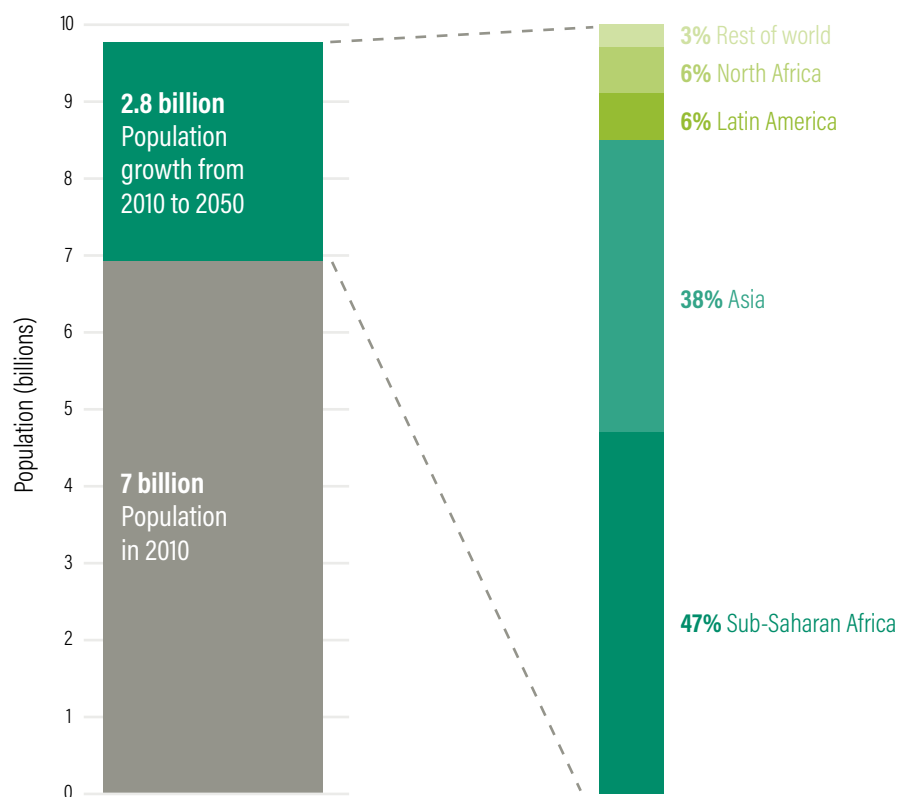
Achieving replacement fertility levels worldwide would bring enormous social benefits and could make a meaningful contribution to the food, land, and GHG mitigation gaps. But such an achievement would bring the greatest benefits to sub-Saharan Africa, whose population is facing the most formidable challenges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

The Challenge

According to the medium-fertility scenario in the UN population growth projections, global population will rise from 7 billion in 2010 to 9.8 billion by 2050.²⁹⁰ Roughly half of this 2.8 billion increase will occur in Africa, and one-third will occur in Asia (Figure 8-1). The reasons for population growth differ by region. Asia's growth will come from a demographic bulge of people of childbearing age that results from high fertility rates in the past, while Africa's growth will result in large part from continuing high birth rates.

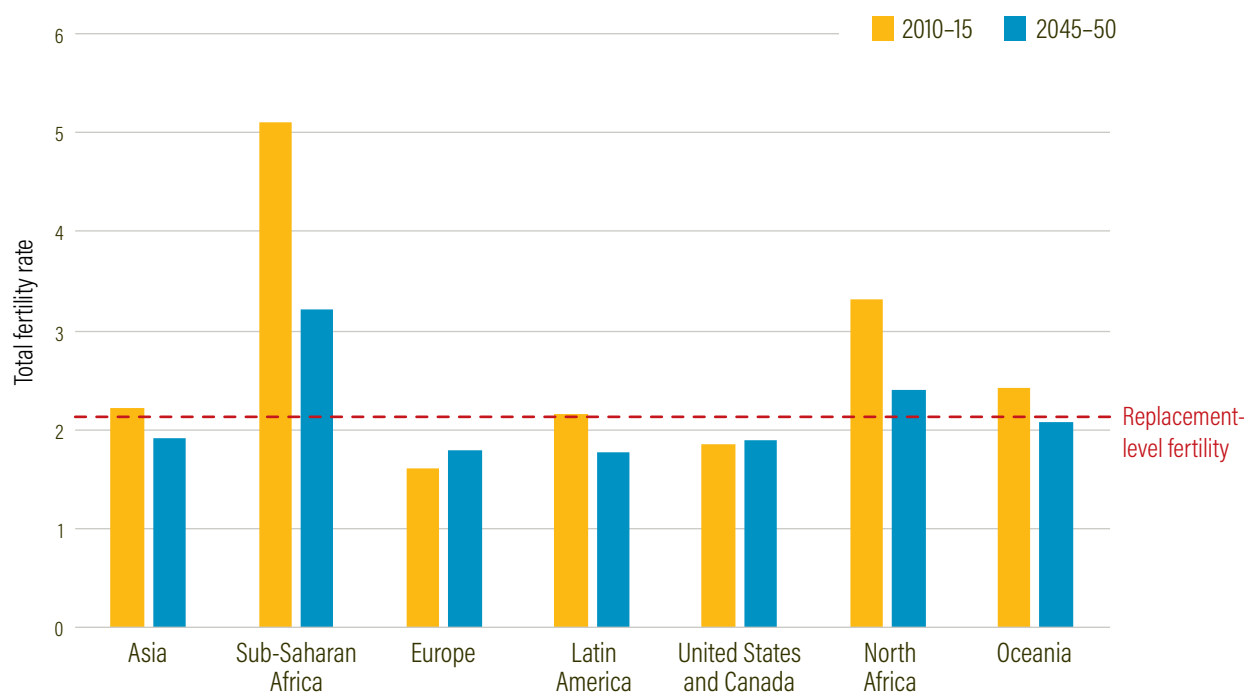
Overall, most of the world's regions are close to achieving replacement-level fertility rates and will achieve or even dip below replacement level by 2050 (Figure 8-2). The "replacement-level" rate is the total fertility rate²⁹¹ at which a population exactly replaces itself from one generation to the next (excluding migration) and is typically around 2.1 children per woman.²⁹² North America and Europe are already below replacement level and are projected to remain there through 2050. Asia, Latin America, and Oceania had fertility rates just above replacement level in 2010–15, and these rates are likely to fall below replacement levels by 2050. North Africa's average total fertility rate is projected to decline from 3.3 in 2010–15 to 2.4 in 2050, which is close to the replacement level.

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



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

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



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

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

This projected increase in sub-Saharan Africa’s population poses substantial economic, social, and food security challenges. The region must spend enormous resources on infrastructure just to maintain present transportation, housing, and living standards. As described in Chapter 2, Box

2-4 of this report, the region is already the planet’s hungriest, has the lowest crop yields, and has low average income levels. In many parts of the region, soils are depleted of organic matter and nutrients, and rainfall levels can be quite variable. Climate change threatens to exacerbate the difficulty in growing crops, putting downward pressure on crop yields. As a result, the region is at the center of the sustainable food challenge.

The Opportunity

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

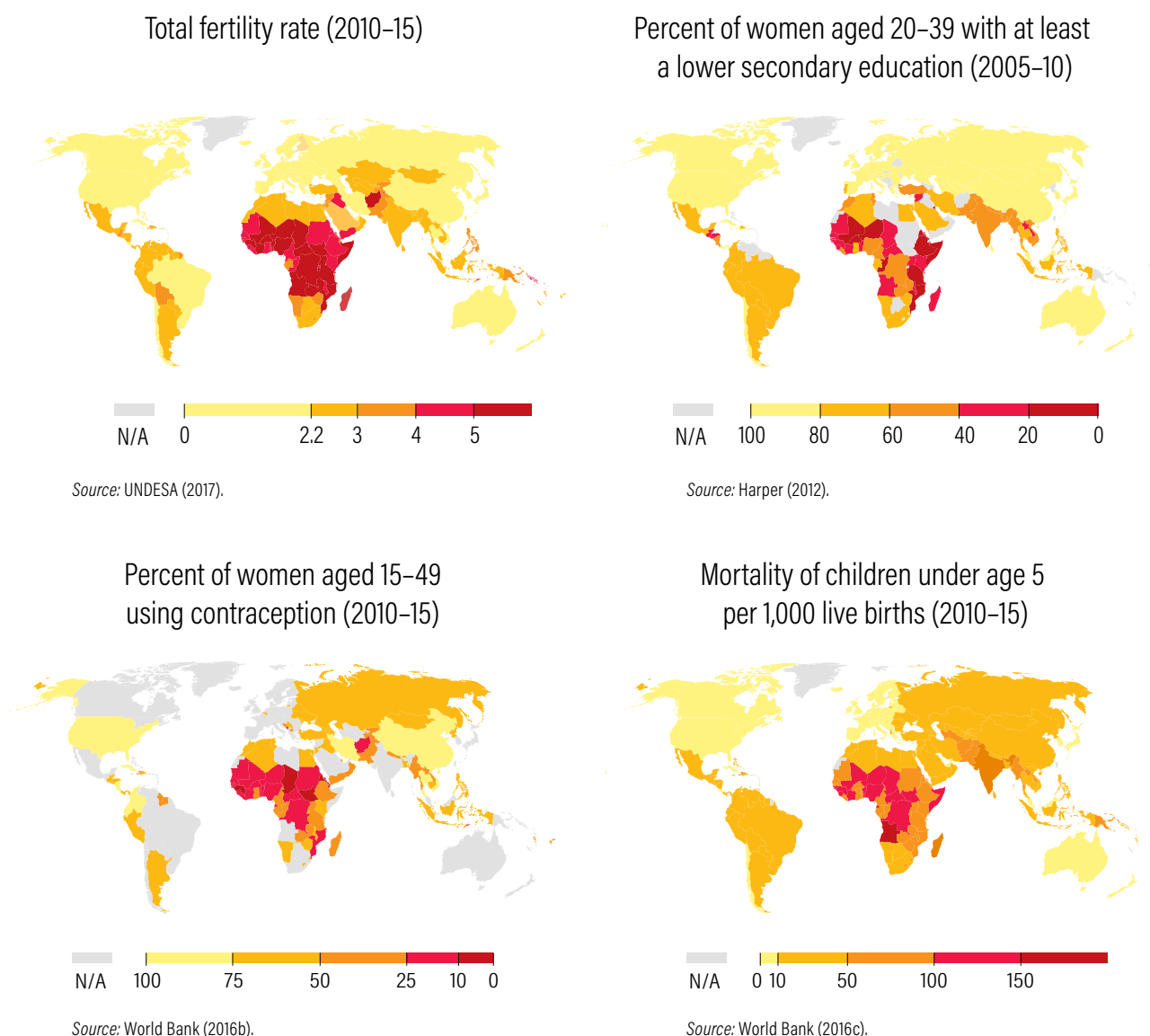
Female education

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

tion of girls attaining lower secondary education and the highest fertility rates in the world.

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

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



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

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

Reproductive health services

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

Infant and child mortality

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

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

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



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

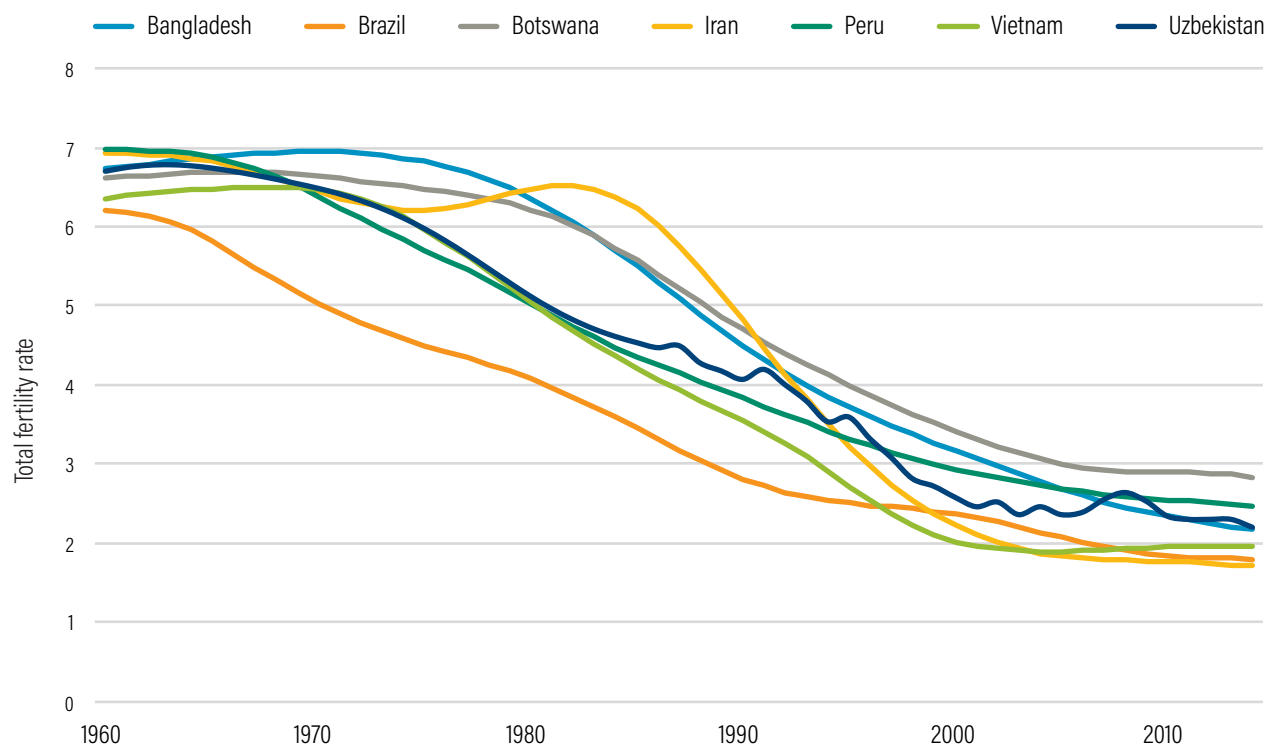
Could sub-Saharan Africa achieve replacement-level fertility by 2050? History from other regions suggests it could. Although some researchers once believed that only developed countries could dramatically lower their birth rates,^a a number of less-developed countries have done so as well. For example,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

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

Sources:

- a. Coale (1973).
- b. World Bank (2016a).
- c. World Bank (2016b).

Figure 8-4 | Total fertility rates can decline rapidly



Source: World Bank (2017c).

its population in the most economically productive age bracket. Researchers have estimated that this demographic dividend was responsible for up to one-third of the economic growth of the East Asian “Tigers” between 1965 and 1990.³⁰⁵ With good governance, sub-Saharan African countries should also be able to reap a demographic dividend if fertility levels fall.³⁰⁶

Model Results

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

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

Replacement-level fertility scenario. This more ambitious scenario has the effect of further reducing sub-Saharan Africa’s fertility rate from 2.7 to the replacement level of 2.16.³⁰⁸ According to our analysis, the region’s population is then reduced by 446 million compared to the medium-fertility scenario.³⁰⁹



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

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

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

Recommended Strategies

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

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

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

SCENARIO	FOOD GAP, 2010-50 (%)	CHANGE IN AGRICULTURAL AREA, 2010-50 (MHA)			ANNUAL GHG EMISSIONS, 2050 (GT CO ₂ E)			GHG MITIGATION GAP (GT CO ₂ E)
		Pastureland	Cropland	Total	Agricultural production	Land-use change	Total	
GLOBAL EFFECTS								
2050 BASELINE	56	401	192	593	9.0	6.0	15.1	11.1
UN low-fertility scenario (216M fewer people) <i>(Coordinated Effort)</i>	54	335 (-66)	148 (-44)	483 (-111)	8.9	5.2	14.0	10.0 (-1.0)
Replacement-level fertility scenario (446M fewer people) <i>(Highly Ambitious, Breakthrough Technologies)</i>	51	277 (-125)	113 (-78)	390 (-203)	8.7	4.4	13.2	9.2 (-1.9)
EFFECTS IN SUB-SAHARAN AFRICA								
2050 BASELINE	192	158	104	262	1.1	2.1	3.1	N/A
UN low-fertility scenario (216M fewer people) <i>(Coordinated Effort)</i>	164	110 (-48)	72 (-32)	182 (-80)	1.0	1.4	2.4	N/A
Replacement-level fertility scenario (446M fewer people) <i>(Highly Ambitious, Breakthrough Technologies)</i>	135	59 (-99)	38 (-66)	97 (-164)	0.9	0.8	1.6	N/A

Notes: "Cropland" includes cropland plus aquaculture ponds. Numbers not summed correctly are due to rounding. Numbers shown in parentheses are changes relative to 2050 baseline. Although it is straightforward to define a "food gap" for sub-Saharan Africa (i.e., change in regional crop calorie production between 2010 and 2050 baseline), it is not straightforward to define a GHG mitigation gap for the region because the 4 Gt CO₂e target is global.

Source: GlobAgri-WRR model.

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

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

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

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

BOX 8-2 | Progress in Botswana and Rwanda

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

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

Sources and notes:

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



CHAPTER 9

POVERTY IMPLICATIONS OF RESTRICTING GROWTH IN FOOD DEMAND

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

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

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

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

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

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

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

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

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

- First, the hungriest regions in the world—namely, portions of sub-Saharan Africa and South Asia—import large quantities of food staples on a net basis.³²⁸ Although results will vary by country, poor countries as a whole will therefore have to transfer more money to richer countries when global staple crop prices increase. This fact means they will be poorer. Any economic gains accruing to farmers in net food-importing poor countries can therefore only result from a transfer of wealth from other people in those countries. Some of those other people will be wealthy, but many will be poor or living just above the poverty line.
- Second, although Latin America is a large net food exporter, and will benefit at the gross economic level from higher prices, large farms dominate its production, particularly of staple crops. The benefits to the poor of higher farm prices will therefore be diffuse, while the harm will be direct.
- Third, the basic economic finding that demand for food falls when prices rise suggests that higher food prices harm the poor. When prices rise, demand decreases.³²⁹ Although the effects of global price increases vary greatly from country to country and among groups of poor people, the evidence is strong that poorer consumers reduce their consumption more than richer consumers.³³⁰ The reasons are obvious. Poorer consumers are less able to afford higher prices, so richer consumers outcompete them when supplies are limited. Moreover, poor consumers eat foods with less processing, and thus the food prices they pay more directly reflect the wholesale prices of crops.

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

ENDNOTES

1. FAO (2011c). This figure is one-third as measured by weight. This is a rough estimate given that it extrapolates from individual food loss and waste studies across countries and stages of the food supply chain. Subsequent research papers have found wide variations in food loss and waste estimates. For instance, as reported in Affognon et al. (2015), one study for maize in Benin found postharvested losses of 41% while another found losses of 12%, and one sweet potato study in Tanzania found losses of 67%, while another found losses of 6%. Yet FAO estimates are consistent in a broad way with estimates in the differences between how much food farmers produce and how much people consume. Although the food loss and waste estimates provided by FAO have uncertainties, they are the most comprehensive global numbers currently available.
2. Authors' calculations based on FAO Food Balance Sheets, which convert metric tons into calories per type of food. We convert tons into calories in order to estimate the impact of food loss and waste on the food gap (which we measure in calories) and in order to more closely reflect the nutritional value of food, since a lot of weight in food is water. Measuring by calories avoids the water embedded in food. Kummu et al. (2012) separately found loss and waste on a caloric basis to equal 24% of all food produced.
3. FAO (2015a). The precise FAO figure is \$940 billion.
4. World Bank (2011b).
5. Buzby et al. (2014).
6. WRAP (2015).
7. Kummu et al. (2012).
8. FAO (2015a).
9. FAO (2015a).
10. FAO (2011c); Gunders (2012); Kummu et al. (2012).
11. In FAO (2011c), Oceania includes Australia and New Zealand. The FAO data combine North America and Oceania. One cannot split the data apart.
12. Authors' calculations based on FAO (2011c).
13. Gebhardt and Thomas (2002).
14. Oguntade (2013).
15. WRAP (2013).
16. Hanson and Mitchell (2017). Costs covered in the UK analysis are those associated with a wide range of actions including the "Love Food Hate Waste" campaign, date labeling changes, pack size and format changes, in-store messaging by food retailers, TV and digital media advertising that included "Love Food Hate Waste" messaging, and periodic quantification of food waste to monitor progress. The financial benefits were primarily the savings to households of the food waste that was prevented (measured by retail purchase value) complemented by municipal savings from avoided food waste disposal costs.
17. Hanson and Mitchell (2017). Costs included communication and outreach to resident households, practical tips on managing food, and other awareness-raising expenditures. The benefits reflect the boroughs' avoided waste management and disposal costs. The benefit to borough citizens reflect the avoided purchase value of food that otherwise would have been wasted.
18. Hanson and Mitchell (2017). Although specifics varied between sites, the financial costs incurred by company sites in this analysis included conducting food loss and waste quantification ("inventories") in order to identify how much and where food was being lost and wasted, prioritize hotspots, and monitor progress over time; purchasing or leasing on-site equipment to quantify food loss and waste; training staff on food loss and waste reduction practice; purchasing equipment as part of material flow process redesigns or improved storage; changing food storage, handling, and manufacturing processes; changing packaging to extend shelf-life; changing date labeling on packaging; and pursuing other staff and technology investments to reduce food loss and waste. The financial benefits realized by the company sites included avoiding the costs of buying food (as ingredients or directly for sale) that previously had been lost or wasted without being sold; increasing the share of food purchased or prepared that gets sold onward to customer; introducing new product lines made from food that otherwise would have been lost or wasted; reducing food waste management costs (including labor) and tipping fees; and realizing other modes of reducing input costs or increasing output sales.
19. It is important to note that many technical solutions can be effective only when other parts of the food supply chain are effective. For example, improved on-farm storage will not ultimately lead to reductions in food loss if farmers have no access to a market where they can sell their harvest surplus. Retailers using poor forecasting techniques may place food orders and later cancel them, negating per unit efficiency gains made by food processors. Therefore, progress in reducing food loss and waste will require an integrated supply chain approach. Personal communication, Robert van Otterdijk (team leader, Save Food, FAO), May 17, 2013.

20. Frid-Nielsen et al. (2013).
21. Practical Action (2010).
22. Practical Action (2003).
23. Nenguwo (2013); Kitinoja et al. (2011).
24. Baributsa et al. (2012).
25. Hell et al. (2010).
26. Coulibaly et al. (2012).
27. Moussa et al. (2012).
28. Moussa et al. (2012).
29. Parfitt et al. (2016).
30. Kowitt (2017); Garfield (2017). Short videos of its performance can be seen at <http://www.businessinsider.com/coating-extends-produce-life-apeel-sciences-2017-10#the-coating-is-made-of-discarded-materials-from-organic-produce-everything-from-pear-stems-to-leftover-grape-skins-to-grass-clippings-we-dont-discriminate-rogers-said-7>.
31. Parfitt et al. (2016).
32. Gunders (2012).
33. Lipinski et al. (2016).
34. One such example of this type of law is the Bill Emerson Good Samaritan Act in the United States, enacted in 1996. This law protects food donors from civil and criminal liability if the product they redistributed in good faith to a charitable organization later causes harm to the needy recipient. It also standardizes donor liability exposure: donors no longer have to accommodate 50 different liability laws in 50 different states.
35. Morenoff (2002).
36. Morenoff (2002).
37. Gunders (2012).
38. EPA (2013).
39. Young and Nestle (2002).
40. Bloom (2011), as cited in Gunders (2012).
41. Gunders (2012).
42. Aramark (2008).
43. WRAP (2011).
44. USDA (2011). The only product that is required in the United States to have a "use-by" date is infant formula. More than 20 states have laws regarding food date labeling, but these laws vary greatly.
45. USDA (2011); Gunders (2012).
46. In 2014, the 54 member states of the African Union issued the Malabo Declaration, a set of agriculture goals aimed at achieving shared prosperity and improved livelihoods. Part of the Malabo Declaration is a commitment "to halve the current levels of postharvest losses by the year 2025." Although this target does not match SDG Target 12.3 directly since the numeric target applies to food losses and not to food waste, it is "in the spirit" of SDG Target 12.3 in that it calls for a 50% reduction—and even five years earlier than the SDGs. Moreover, focusing on food loss is arguably justified since, as Figure 1 indicates, food losses during production and storage are currently a larger issue in Africa than food waste at the market or consumption stage.
47. See WRAP (n.d).
48. Lipinski et al. (2016). For information about 2030 Champions, see USDA (2017).
49. Republic of Rwanda (2015).
50. Lipinski et al. (2016).
51. The Food Loss & Waste Protocol (FLW Protocol) is a partnership that has developed the global *FLW Standard* for quantifying and reporting on food and/or associated inedible parts removed from the food supply chain. FLW Protocol partners are the Consumer Goods Forum, EU FUSIONS, FAO, UN Environment, World Business Council for Sustainable Development, and WRAP. WRI serves as the FLW Protocol's secretariat.
52. The FLW Protocol website, <http://www.flwprotocol.org>, provides access to the *FLW Standard*, supporting tools, case examples, and training material.
53. Recognizing the need for collaborative action, actors in the food service industry created the International Food Waste Coalition to reduce food loss and waste all along the value chain. Members include Sodexo, which is working to prevent and reduce food waste in schools, hospitals, and workplace restaurants.
54. For more on these examples, see Lipinski et al. (2016).
55. It is important to note that many technical solutions can be effective only when other parts of the food supply chain are effective. For example, improved on-farm storage will not ultimately lead to reductions in food loss if farmers have no access to a market where they can sell their harvest surplus. Retailers using poor forecasting techniques may place food orders and later cancel them, negating per unit efficiency gains made by food processors. Therefore, progress in reducing food loss and waste will require an integrated supply chain approach. Personal communication, Robert van Otterdijk (team leader, Save Food, FAO), May 17, 2013.

56. However, the environmental and economic implications of these solutions can vary greatly based on where the roads are built and the type of fuel used to generate the electricity.
57. Pulses are annual leguminous crops harvested for dry grain, including beans, peas, and lentils.
58. Keats and Wiggins (2014); Khoury et al. (2014); Tilman and Clark (2014); Popkin et al. (2012).
59. Strong correlations between per capita gross domestic product and consumption of both total calories and meat are demonstrated in Tilman and Clark (2014), (Figure 2); Khoury et al. (2014); and Pingali (2007).
60. Anand et al. (2015); Reardon et al. (2014).
61. Popkin et al. (2012); Delgado et al. (1999).
62. In this report, we use the term "per capita [calorie or protein] availability" to mean the quantity of food *reaching the consumer*, as defined in the FAO Food Balance Sheets (FAO 2019a). We use the term "per capita consumption" to mean the quantity of food *actually consumed*, when accounting for food waste at the consumption stage of the value chain. "Consumption" quantities (which exclude all food loss and waste) are therefore lower than "availability" quantities. Data on "per capita consumption" are from the GlobAgri-WRR model, using source data from FAO (2019a) on "per capita availability" and FAO (2011c) on food loss and waste. Because historical rates of food loss and waste are unknown, graphs showing trends from 1961 display "availability" instead of "consumption."

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

63. Protein requirements differ by individual based on age, sex, height, weight, level of physical activity, pregnancy and lactation (FAO, WHO, and UNU 1985). Similar to other developed countries, the U.S. government (CDC 2015) lists the estimated daily requirement for protein as 56 grams per day for an adult man and 46 grams per day for an adult woman, or an average of 51 grams of protein per day. Paul (1989) estimates the average protein requirement at 0.8 g per kg of body weight per day. Since the average adult in the world weighed 62 kg in 2005 (Walpole et al. 2012), applying the rule of 0.8 g/kg/day would yield an estimated global average protein requirement of 49.6 grams per day.

Other international estimates are lower still. For instance, FAO, WHO, and UNU (1985) estimate an average requirement of 0.75 g/kg/day. Furthermore, these estimates are conservative to ensure that they cover individual variations within a population group. For example, the estimated protein requirement of 0.8 g per kg of body weight per day given in Paul (1989) includes 0.35 g/kg/day as a safety margin.

64. GlobAgri-WRR model with source data from FAO (2019a) and FAO (2011c). Of course, countries exceeding the threshold of consumption of 50 grams of protein per capita per day will likely have a percentage of their populations below the threshold. See the discussion around Figure 6-1. A true comparison of protein intakes to dietary requirements would involve an analysis of the distribution of usual intakes across a population, rather than simply comparing to mean intakes. For example, the U.S. Department of Agriculture used the 2001–02 national dietary survey in the United States to find that protein consumption fell under the estimated dietary requirement in only 3% of the population (Moshfegh et al. 2005).
65. GlobAgri-WRR model, based on projections from Alexandratos and Bruinsma (2012).
66. FAO (2019a).
67. GlobAgri-WRR model.
68. As summarized in Valin et al. (2014), the average demand increase for calories among other models was actually 37% higher than the FAO projection, with the lowest other model projection 15% higher. Nearly all model projections of increases in ruminant meat are also higher than FAO projections, and most are higher for pig and poultry meat, eggs, and dairy products (Valin et al. 2014, Figure 2). Tilman et al. (2011) also projects much greater consumption of animal products due to historical relationships across societies between income and their consumption. Bijl et al. (2017) also developed a statistical model to project future consumption of animal products, which results in higher projections for consumption in 2050 under business-as-usual.
69. Authors' calculations using Alexandratos and Bruinsma (2012), updated population projections from UNDESA (2017), and postconsumer waste figures incorporated into GlobAgri-WRR.
70. Authors' calculations based on GlobAgri-WRR model.
71. A basic summary of the literature showing the reductions in stunting provided by improved total nutrition, some meat consumption among the poor, and general dietary diversity is provided in Godfray et al. (2010); Neumann, Demment, et al. (2010); and Dror and Allen (2011).
72. One survey of 13 low-income countries in Asia, Latin America, and Africa found that livestock provided 10–20% of the average income of rural households in each of the lowest three out of five income categories. Pica-Ciamarra et al. (2011).

73. Popkin and Gordon-Larsen (2004).
74. USDA and HHS (2015); WHO (2012); Popkin and Gordon-Larsen (2004); Micha et al. (2017).
75. USDA and HHS (2015); WHO (2012).
76. USDA and HHS (2015).
77. According to various studies, obesity accounted for 12% of the growth in health spending between 1987 and 2001 in the United States (American Diabetes Association 2008), accounted for 13% of health care costs in China in 2010 (*Economist* 2014), and caused \$144 billion in excess health care spending in 2008 (Finkelstein et al. 2009). Another study found that obesity leads to 25% higher health care costs on average for an obese person than a person of normal weight across different countries (OECD 2010).
78. Fry and Finley (2005); Finkelstein et al. (2010).
79. Dobbs et al. (2014).
80. The World Health Organization defines "overweight" as having a body mass index (BMI) greater than or equal to 25 and "obese" as having a BMI greater than or equal to 30. BMI is an index of weight-for-height that is commonly used to classify overweight and obesity in adults. It is defined as a person's weight in kilograms divided by the square of his or her height in meters (kg/m²) (WHO 2012a).
81. Ng, Fleming, et al. (2014).
82. Popkin et al. (2012).
83. Cecchini et al. (2010).
84. FAO, WFP, and IFAD (2012), Figure 16.
85. Greco and Rothhoff (2015).
86. Within a population, the degree to which calorie availability has peaked varies based on a number of factors, such as socioeconomic status and race or ethnicity. See Ng, Slining, et al. (2014) for a discussion relevant to the United States.
87. These are rough extrapolations of growth between 1980 and 2013 that translates into linear growth rates of more than 0.2% per year, which would generate growth of around 10% by 2050. Because our analysis, which follows, shows modest land and greenhouse gas savings even from drastic declines in rates of obesity and overweight, we do not bother to try to tease out more precise statistical relationships.
88. Authors' calculations. Of these 3.1 billion people, 2.1 billion would be overweight and 1 billion obese.
89. WHO (2012); Campbell et al. (2006).
90. Papers finding limited health consequences of saturated fats include Chowdhury et al. (2014) and de Souza (2015).
91. After the Chowdhury (2014) paper was published, the authors found some errors and published corrections, but the errors had the effect of reducing the findings of the benefits of certain other types of fats, such as fish oils, rather than underestimating the consequences of saturated fats (Kupferschmidt 2014). Two more recent meta-analyses (Wang et al. 2016; Imamura et al. 2016) also find benefits to switching from saturated to polyunsaturated fats, particularly ones with higher omega-3 to omega-6 ratios.
92. Nutritionists define "red meat" as meat from mammals, which includes beef and other ruminant meats (sheep and goat), as well as pork.
93. Dwyer and Hetzel (1980); Armstrong and Doll (1975); Sinha et al. (2009); Larsson and Orsini (2013); Micha et al. (2017).
94. Binnie et al. (2014); Micha et al. (2012).
95. Bouvard et al. (2015). "Processed meat" refers to meat that has been transformed through salting, curing, fermentation, smoking, or other processes to enhance flavor or improve preservation. Most processed meats contain pork or beef but might also contain other red meats, poultry, offal (e.g., liver), or meat by-products such as blood.
96. WCRF and AICR (2007). Konde et al. (2015); Netherlands Nutrition Centre (2017).
97. Micha et al. (2017), Table 1.
98. GlobAgri-WRR model, using FAO (2019a) source data.
99. Lappé (1971). However, this book also popularized the myth that plant-based foods needed to be combined in single meals to meet protein nutritional needs (see Box 6-1 debunking this myth).
100. CAST (1999).
101. Foley et al. (2011).
102. Ripple et al. (2014).
103. Brown (2009).
104. Numbers cited in Brown (2009), a critic of meat efficiencies, are based only on human-edible feeds, while the Council for Agricultural Science and Technology (CAST 1999) generally defends the efficiency of meat production in significant part by arguing that only human-inedible feeds should count. Similarly, Fry et al. (2018) found that aquaculture and beef conversion efficiencies were similar, because their analysis did not take calories and protein from grasses into account. The aquaculture conversion efficiencies estimated in Fry et al. (2018), however, are similar to those calculated here.
105. See Figure 2.4 from Wirsén et al. (2010).

106. FAO (2011e). Similarly, Mottet et al. (2017) state this case for protein: "Ruminant systems, together with backyard pig and poultry systems, produce close to 41 Mt of animal protein per year while consuming about 37 Mt of human-edible-feed protein."
107. With the help of the lead author in Wirseniens et al. (2010), Figure 6-5 adjusts the numbers of the original study by excluding bones from edible food in order to provide reasonable comparisons between meat, milk, and fish and also to provide figures that match how the FAO counts "edible" food calories. Excluding bones from the measures of "food out" modestly lowers the efficiencies as typically presented, and as shown in Wirseniens et al. (2010). "Edible output" refers to the calorie and protein content of bone-free carcass. Sources for terrestrial animal-based foods (adjusted from carcass weight values to bone-free carcass weight values through personal communication with S. Wirseniens): Wirseniens et al. (2010) (extra unpublished tables), Wirseniens (2000). Sources for finfish and shrimp: Authors' calculations based on USDA (2013a); NRC (2011); Tacon and Metian (2008); Wirseniens (2000); and FAO (1989).
108. The authors of a global FAO livestock analysis, Gerber et al. (2013), provided background information on protein efficiencies for poultry of 19% and pig meat of 12%. They are lower than the global estimates of protein efficiencies by Wirseniens (2010, 2000) (when bones are counted as in other analyses) of 26% for poultry and 18% for pork. CAST (1999) generally argued for focusing only on human-edible feeds but provided estimates for efficiencies using total feeds. However, it did so only in a few countries, primarily relatively developed agriculturally and not including India or China. But CAST's estimate of the energy efficiency of beef in Kenya, its one agriculturally low productivity country, was 1%. CAST's estimates of protein efficiency were similar where comparable. For example, CAST estimated identical protein efficiencies for poultry in the United States of 31%, and Wirseniens estimated 31% for poultry efficiencies in North America and Oceania. Using the same regional comparisons, CAST estimated protein efficiency for pork at 19%, compared to 23% for Wirseniens, and identical beef protein conversion efficiencies in these regions of 8%. The biggest difference in comparable areas was the energy efficiency of beef, at 7% for CAST versus 2.5% for Wirseniens. We are skeptical of this particular CAST estimate. The differences between energy and protein efficiencies are almost always large for all livestock in all regions, and CAST's estimated energy and protein efficiencies for U.S. beef are close.
109. The principal adjustment is that we assume that all new grazing land must come from woody savannas or forests because native grasslands capable of being grazed are already used. We are aware of no significant areas of truly native grasslands that are not in use. There are areas of woody savanna, particularly in Africa, where grazing use is limited, mainly because of tsetse flies, and these areas have grasses that could be consumed, but converting them to cattle production involves significant clearing of the woody vegetation. When we evaluate diets in a particular country, we assume that food used in that country is generated according to 2010 trade patterns (e.g., that if 80% of a food is generated domestically and 20% is imported, the same will be true of new production).
110. In other words, we divide the one-time loss of emissions from land conversion by 20 to obtain land-use-change emissions and then add them to annual agricultural production emissions. This follows the European approach to evaluating land-use change for biofuels and provides one rough way of evaluating the costs of emissions over time to reflect the added value of earlier emissions mitigation.
111. GlobAgri-WRR model. More precisely, the per person land use and greenhouse gas effects of each diet, as modeled in GlobAgri and shown in Figures 7-7 and 7-12, are the marginal effects of adding one additional person to the world population in 2010. This is why the per person land-use change emissions are higher than the agricultural production emissions; because yields and trade patterns are held constant, GlobAgri estimates the annual emissions that would result from converting the additional land (roughly 0.5 hectares for the average world diet and roughly 1 hectare for the average U.S. diet) from natural ecosystems to agricultural production.
112. GlobAgri-WRR model.
113. In the United States, nearly all ruminant meat consumption is beef consumption; very little sheep and goat meat was consumed in the United States in 2010 (FAO 2019a).
114. World Bank (2016a) estimated emissions from energy use per person per year at 4.7 tons CO₂e.
115. We estimate U.S. dietary emissions in 2010 at 16.6 tons CO₂e per person per year. Total U.S. energy-related emissions of 5,582 million tons CO₂ (EIA 2015), when divided by a U.S. population of 309.3 million, equal per capita emissions of 18 tons CO₂e in 2010. Land-use-change emissions of 332 tons CO₂e are therefore equal to 18.4 times average U.S. per capita energy-related CO₂ emissions in 2010.

Energy-related CO₂ 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 CO₂ emissions (defined as the amount of emissions associated with the consumption of goods and services in a country, after accounting for imports and exports) were 22 tons per capita per year in 2004.
116. This chart differs from similar charts in earlier reports in this series because it shows our estimates of consumption, after deductions of waste in households in restaurants, rather than "food availability." Food availability is a category produced by FAO that is intended to reflect food reaching households and retailers.
117. The numbers of obese are based on data in Ng, Fleming, et al. (2014). Our analysis factors in estimated numbers of overweight and obese people in each region, assumes that obese people consume on average 500 more calories per person per day than a person of healthy weight, and that overweight people consume only half these additional calories (250 more calories per person per day). This estimate of extra calorie consumption is based on the best estimate of

- the excess calorie consumption for U.S. obese adults (BMI over 35) of roughly 500 kcal/day (Hall et al. 2011a). That represents the increased calorie consumption to maintain obese conditions for U.S. adults, and is actually more than double the increased calorie consumption necessary to become obese. This estimate represents a revised view upward compared to the traditional view of only around 200 kcal/day, which did not account for the greater calorie intake required to maintain the larger body size of the overweight or obese. The 500 kcal/day assumes that all obese children have a similar overconsumption. Similarly, FAO has estimated that consumption of 2,700 to 3,000 kcal per person per day will lead to obesity by people with sedentary lifestyles (FAO 2004). Using the midpoint of 2,850 kcal, and assuming that an acceptable diet would consist of 2,350 kcal per person, we estimate that the elimination of obesity would reduce consumption by 500 kcal per person per day.
118. Authors' calculations from Ng, Fleming, et al. (2014). Regionally, the smallest caloric reductions occur in lower-income regions (e.g., 1% in sub-Saharan Africa) with the largest reductions in higher-income regions (e.g., 4% in the United States and Canada).
 119. Searchinger, Hanson, Ranganathan, et al. (2013); Ranganathan et al. (2016).
 120. Ng, Fleming, et al. (2014).
 121. Skinner et al. (2018).
 122. As discussed further in Course 4, the 2050 baseline projection assumes a 10% decrease in wild fish catch relative to 2010, and it assumes that all increases in global fish demand are met by aquaculture (thus farmed fish make up a larger proportion of total fish consumption by 2050).
 123. These reductions set maximum thresholds of animal-based foods of 613 kcal per person per day for the 10% reduction and 399 kcal for the 30% reduction (Figure 6-8). They also reduced the global increase in animal-based food consumption between 2010 and 2050 from 68% (baseline) to 51% (10% reduction) and to 18% (30% reduction).
 124. In order to be conservative, for the diet scenarios explored in this chapter, whenever land use in 2050 was reduced below 2010 levels, we set land-use-change emissions between 2010 and 2050 to zero (rather than assuming perfect restoration of all "liberated" lands back into native vegetation by 2050).
 125. Ranganathan et al. (2016), Figure 10. Using data on UK vegetarian diets from Scarborough et al. (2014), Ranganathan et al. (2016) found that a scenario that halved U.S. meat and dairy consumption reduced the proportion of animal-based food calories to total calories to 14%, whereas the typical UK vegetarian in Scarborough et al. (2014) consumed 18% of their calories in the form of animal-based foods (including dairy and eggs, but not fish or meat).
 126. Scarborough et al. (2014).
 127. A 10% global cut, relative to 2050 baseline, set a threshold level of 373 calories of meat per person per day, slightly above the level of meat consumption in the United States in 2010 (Figure 6-9). A 30% global cut in meat requires a threshold of 238 calories of meat per day, slightly higher than per capita meat consumption in Russia in 2010. These scenarios reduced the global increase in meat consumption between 2010 and 2050 from 71% (baseline) to 54% (10% reduction) and to 20% (30% reduction).
 128. GlobAgri-WRR model using source data from FAO (2019a).
 129. In addition to a "less ruminant meat, shift to poultry and pork" scenario, we could have also modeled shifts to other nonmeat animal proteins, such as fish, dairy, or eggs. Because fish, dairy, and eggs are of a similar level of resource intensity as poultry and pork (more resource-intensive than plant proteins, and much less resource-intensive than ruminant meats), the results in terms of closure of the food, land use, and GHG emissions gaps would have been similar.
 130. Springmann, Godfray, et al. (2016).
 131. Willett et al. (2019), Springmann et al. (2018). These authors, however, did not assess changes in pastureland use under their healthy diet scenario, which would have certainly shown a large decline given the pronounced move away from ruminant meat and, to a lesser extent, away from dairy.
 132. For example, Springmann, Godfray, et al. (2016) estimated that 97 percent of the GHG emissions reductions in their "healthy global diets" scenario were attributable to the reductions in red meat consumption (and we assume the vast majority of those reductions were due to reductions in ruminant meat consumption, since pork is of similar resource intensity to poultry).
 133. For the calculations in this section, we used 2010 global average production efficiencies (shown in Figure 6-6). GlobAgri-WRR can also analyze the addition to the world of a person in the United States alone, which would assign more production to the United States because it would follow existing trade patterns. We followed the global average approach because we wished to analyze the consequences of other people adopting this diet globally.
 134. The Vegetarian Diet scenario, which uses data from Scarborough et al. (2014), actually includes very small amounts of meat, as "vegetarians" were self-reported.
 135. FAO (2019a).
 136. Beattie et al. (2010); Tootelian and Ross (2000).
 137. Larson and Story (2009). However, studies have shown that labeling can provide an incentive to food companies to reformulate products to make them healthier (Vyth et al. 2010; Variyam 2005).
 138. Capacci et al. (2012).
 139. Dumanovsky (2011).

140. Hammer et al. (2009).
141. Winter and Rossiter (1988); McDonald et al. (2002).
142. Thaler and Sunstein (2008); Garnett (2014); Bailey and Harper (2015); Wellesley et al. (2015).
143. Stummer (2003); Cornish Sardine Management Association (2015).
144. Reardon et al. (2003).
145. Reardon et al. (2003); Reardon and Timmer (2012).
146. Reardon and Timmer (2012).
147. Reardon et al. (2007).
148. Pingali (2007).
149. USDA/ERS (2014a).
150. Hawkes (2008) in Garnett and Wilkes (2014).
151. USDA/ERS (2014b).
152. DEFRA (2014).
153. Suher et al. (2016).
154. Turnwald et al. (2017).
155. Bacon and Krpan (2018).
156. Keats and Wiggins (2014).
157. Haley (2001).
158. For example, based on average U.S. retail prices in 2013, the price per gram of protein ranged from 0.9 cents for dried lentils, 1.1 cents for wheat flour, 1.2 cents for dried black beans, and 2.3 cents for dried white rice, to 2.7 cents for eggs, 2.9 cents for milk, 3.1 cents for fresh whole chicken, and 4.4 cents for ground beef. Authors' calculations based on USDA/ERS (2015a); USDA/ERS (2015b); BLS (2015); and USDA (2013a). See also Lusk and Norwood (2016).
159. Adjoian et al. (2017).
160. Arnold and Pickard (2013).
161. Corvalán et al. (2013); Jacobs (2018).
162. Sharp (2010), Chapter 12.
163. Sharp (2010), Chapter 12.
164. Robinson et al. (2014).
165. Ruby and Heine (2011); Rozin et al. (2012); Sobal (2005).
166. Lea et al. (2006).
167. House of Lords (2011); Reisch et al. (2013). Beattie et al. (2010); Toote-
lian and Ross (2000); Capacci et al. (2012); Dumanovsky (2011).
168. Downs et al. (2013).
169. USDA and HHS (2015).
170. Smith (2008).
171. Hickman (2008).
172. Videl (2014).
173. Jha (2013); Hanlon (2012).
174. Maastricht University (2014).
175. Bello (2013).
176. Purdy (2017).
177. Impossible Foods (2017).
178. Oregon State University (2015).
179. Gewin (2017).
180. Henry (2015).
181. Close (2014).
182. Black (2014); Mushroom Council (2016).
183. *Economist* (2015).
184. Nasdaq Global Newswire (2015).
185. Upadhyay (2016).
186. MarketLine (2014).
187. House of Lords (2011).
188. See, e.g., Health Care without Harm (2017); Friends of the Earth (2017).
189. Humane Society International (2013).
190. Ecorys (2014); Thow et al. (2014); Nordström and Thunström (2009);
Hawkes (2012); Thow et al. (2010); Jensen and Smed (2013); Colchero
et al. (2016).
191. Thow and Downs (2014); Nordström and Thunström (2009); Hawkes
(2012).
192. Gallet (2010).
193. USDA/ERS (2015b).
194. Haley (2018).
195. Dumortier et al. (2012).
196. *Economist* (2012).
197. Gallet (2010).

198. Springmann, Mason-D'Croz, et al. (2016).
199. Dong and Lin (2009).
200. Pearson-Stuttard et al. (2017).
201. Although FAO has cited this 10% figure in some publications, its own published estimates of global fuelwood amount to only about 3%. For example, the 2008 fuelwood harvest reported by FAO in its 2011 *State of the World's Forests* report amounted to 1.87 billion cubic feet, which by conventional conversion factors should contain roughly 17.5 EJ, relative to 2010 global energy demand of around 500 EJ.
202. Many papers have estimated that charcoal production is a major source of forest degradation. For example, Sedano et al. (2016) estimated that charcoal production in Mozambique had effects on forest carbon comparable to those of agricultural expansion, and fuelwood and charcoal production are the main components of forest degradation in Africa generally. Hosonuma et al. (2012); Chidumayo and Gumbo (2013). See Vinya et al. (2011), which focuses on Zambia, as an example of REDD+ (Reduced Emissions from Deforestation and Forest Degradation) plans that try to address charcoal production.
203. Nijhuis (2017).
204. For a good graphic display of the recovery of European forests, see Noack (2014). For the global decline of conventional forms of bioenergy (the vast majority of which occurred in industrialized countries), see Krausmann et al. (2013). For a discussion of the role that declining wood use for energy had on the recovery of eastern U.S. forests, see Hanson et al. (2015).
205. EIA (2013).
206. EIA (2013).
207. EIA (2013).
208. 1 exajoule = 238,902,957,619,000 kilocalories.
209. Authors' calculations based on biofuel production estimates from the U.S. Energy Information Agency, published information from diverse sources of feedstocks for ethanol and biodiesel in different countries, standard conversion factors for estimating energy in different crops, and data from FAOSTAT on total 2010 crop production. These calculations do not include the portion of food crops that produce useable by-products.
210. A 10% transportation fuel target would generate 2.5% of global final delivered energy on a gross basis, but because ethanol and biodiesel production requires more energy to produce than gasoline and diesel, the net gain would probably be no more than 2%.
211. GlobAgri-WRR model.
212. Haberl et al. (2010).
213. This calculation assumes 395 bushels of maize per hectare (equivalent to about 160 bushels per acre), 2.8 gallons of ethanol per bushel, and thus 1,106 gallons per hectare. It also assumes that 30% of the maize traditionally enters the animal feed supply chain as an ethanol by-product. This implies that 0.7 hectares produce the 1,106 gallons, and thus a full hectare would produce 1,580 gallons, which rounds up to 1,600 gallons.
214. The yields used by the EPA are described in Plevin (2010).
215. To match the yields of maize ethanol, perennial grasses must achieve yields of 16 metric tons of dry matter per hectare per year (t/ha/yr), and very high conversion efficiencies of 100 gallons (376 liters) per metric ton. Hudiburg et al. (2014) estimates that replacing maize and soybean rotations with switchgrass in the United States would achieve yields of 9.2 tons per hectare and miscanthus would achieve yields of 17.2 tons per hectare. The EPA estimated average switchgrass yields of 8.8 tons per hectare (Plevin [2010]), and average switchgrass yields today are 4.4 t/ha/year to 8.8 tons per hectare (Schmer et al. 2010). Although miscanthus might achieve slightly higher yields than maize, it presents a number of challenges, including reproducing rhizomatically, so that new rhizomes must be dug up and separated from existing plants and replanted elsewhere.
216. Searle and Malins (2014).
217. Searle and Malins (2014).
218. International Energy Agency Statistics (2018).
219. Chum et al. (2011); Creutzig et al. (2014).
220. The International Energy Agency, for example, has called for supplying 20% of global energy by 2050 with biomass. Although ambiguous, the IEA (2017) encourages this goal on top of any traditional uses of biomass for fuelwood.
221. This 20% is based on projected global energy use of around 900 EJ in 2050 (OECD 2011). Although 20% of 900 is only 180, biomass cannot be used as efficiently as fossil fuels, so more biomass would be needed. Exactly how much would depend on the form in which the bioenergy or fossil fuel is used. Primary energy measures the energy in the original fuel, e.g., wood or crude oil. Delivered energy is the energy in a useable form, such as electricity, gasoline, or ethanol. There is substantial loss of energy in the conversion process because of the energy needed to mine, produce, or refine feedstocks into liquid fuel, or the energy lost (primarily through waste heat) in turning a fuel into electricity. Our assumption is that, overall, the conversion of biomass into delivered energy would occur at 80% of the efficiency of fossil fuels, which is optimistic for bioenergy. This calculation looks at the total amount of useable energy generated, such as the energy in ethanol, versus the total biomass and fossil energy used to generate it. For calculations of the relative efficiency of converting crude oil and biomass into useable energy forms, see JRC (2011), chapter 9.

222. IPCC (2014); Rogelj et al. (2018).
223. Technically, this estimate is based on estimates of total biomass harvest for the year 2000 estimated in Haberl et al. (2007). These harvests in dry tons of biomass are multiplied by an average energy content of 18.5 GJ per ton of dry matter. There has probably been some modest growth since that time. A similar figure was used by the IPCC in Chum et al. (2011).
224. Malhi et al. (2002). Failing to maintain these carbon stocks by adding more carbon from new plant growth, as microorganisms consume and release the carbon to the air from old biomass, would increase atmospheric carbon dioxide concentrations and contribute to climate change.
225. Searchinger (2010).
226. Moomaw and Moreira (2001), Table 3.31.
227. Souza et al. (2015); van Vuuren et al. (2009); Hoogwijk et al. (2005).
228. Papers estimating the effects of bioenergy in woody savannas while counting the lost carbon have consistently found long periods before bioenergy would reduce emissions, and include Fargione et al. (2008); Gibbs et al. (2008); and Searchinger, Estes, Thornton, et al. (2015).
229. Smeets et al. (2007); Davis et al. (2012); Cowie et al. (2018).
230. See papers summarized in Searchinger et al. (2018). Researchers have made this finding while analyzing a broad range of forest types and a broad range of harvesting regimes. See, e.g., Holtsmark (2012); Hudiburg et al. (2011); Manomet Center for Conservation Sciences (2010); and Mitchell et al. (2012). The basic reason that harvesting forests for bioenergy leads to a carbon debt is that each ton of carbon in a forest that is harvested only leads to a quarter to a third of a ton of carbon savings in its typical use for electricity generation. This is because (a) some of the live carbon in roots and branches is left behind to decompose, and (b) burning wood is less efficient than burning fossil fuels to generate electricity. In addition, young or middle-aged forests, which are most frequently harvested in commercial operations, would typically grow faster and therefore accumulate more carbon for at least some years than a newly regrowing forest, which starts with seedlings or natural regeneration. That factor increases the carbon debt of using trees for energy. Eventually, forests that are not cut reach slow rates of growth, and regrowing forests will start to catch up. Eventually, the GHG reductions from reduced fossil fuel use will equal and ultimately exceed the increase in carbon in the air from the transfer from the forest. At that point, there are GHG benefits. But governments that have explicitly recognized and addressed this accounting have generally agreed to account for these bioenergy impacts in periods of 20 or 30 years, up to which bioenergy leads to likely emissions increases.
- One source of confusion in this analysis lies in the difference between the rate of uptake in any given year and the total carbon stored. Cutting a mature forest will typically increase the rate of carbon uptake (at least over many decades as a new forest grows), but at the expense of a large initial loss of carbon. And it will still result in a net release of carbon from the forest, and even a net release of carbon for decades, even when accounting for the reductions in fossil carbon emissions from the bioenergy use.
231. The exception is in cases where a tract of land generates biomass feedstocks that are additional to what otherwise would have grown, such as if a farmer were to plant winter cover crops during fallow seasons on some cropland and use those crops for bioenergy. Searchinger et al. (2018).
232. Agostini et al. (2014).
233. Although bioenergy is not typically called an "offset," offsetting is the physical mechanism by which bioenergy reduces carbon dioxide in the atmosphere. The principle of "additionality" is the same as for a regulatory offset for climate change. In regulatory systems, power plants are sometimes allowed to offset their emissions from burning coal by planting a new forest elsewhere on the theory that the carbon absorbed and stored by the additional trees offsets the carbon released from the coal. But a power plant cannot claim an offset by pointing to a forest that would grow anyway. Only *additional* forest growth counts for a forest-planting offset; the same principle is true for bioenergy. In effect, a forest-planting offset uses the additional plant growth to store more carbon in trees to offset fossil-based energy emissions, while bioenergy uses the additional plant growth to replace fossil fuels and leave more carbon underground. The concept of "additional" is the key to both forms of offsets.
234. Searchinger (2009); Haberl et al. (2012).
235. For more examples of bioenergy greenhouse gas accounting scenarios, see Appendix B in Searchinger and Heimlich (2015).
236. For two comparisons, see Decara et al. (2012) and Edwards et al. (2011).
237. Searchinger, Edwards, Mulligan, et al. (2015).
238. HLPE (2013); Dorward (2012).
239. See the discussion in Searchinger, Edwards, Mulligan, et al. (2015) of the IFPRI model, and the discussion in Berry (2011) of the GTAP model. Berry (2011) also includes a good discussion of the limited real economic evidence that higher demands spur yield growth.
240. See discussion in the supplement of Searchinger, Edwards, Mulligan, et al. (2015).
241. Berry (2011); Berry and Schlenker (2011).
242. Searchinger, Edwards, Mulligan, et al. (2015) discuss the IFPRI model used by the European Commission, which is structured so that the vast majority of increases in crop production to replace crops diverted to biofuels results from additional yield increases by farmers. Even so, estimated greenhouse gas reductions from grain-based biofuels are modest.

243. Dumortier et al. (2011), for example, assumed that expanded cropland in the United States and much of the world would first use idle cropland, which is the equivalent of assuming that expanded crop production results from an increase in cropping intensity (the percentage of cropland cropped in a given year).
244. World croplands continually shift and truly abandoned cropland regenerates carbon. There is also a category of land that comes in and out of crop production in part in response to fluctuations in demand and yields and in part in response to physical limitations on crop growth every year. Those fluctuations will continue to exist in a future with more biofuels, and that means there will always be this kind of cropland that comes in and out of production. The argument that biofuels will use this cropland confuses a structural change in demand with the effect of annual fluctuations in the demand for cropland. E4tech (2010) made similar assumptions for European biofuel production.
245. This assumption, for example, was implicitly built into the regulatory analysis by the EPA for its biofuel greenhouse gas regulations, and was also part of the assumptions in E4tech (2010). It derives from satellite studies that identify extensive "savanna" in Indonesia, while the savannas in Indonesia are in fact originally forest that has been cut and is typically in some kind of mosaic use if not in some level of reforestation.
246. Searchinger et al. (2017) review 12 modeling analyses of BECCS. In 9 of them, biomass is automatically treated as carbon neutral and effects on terrestrial carbon storage are not counted. In 3 models, the modelers project potential but only at high cost and only based on a number of unlikely conditions, including that governments worldwide perfectly protect forests and other high-carbon lands. The combination of this protection and high bioenergy demand saves land in the different models either because the cost of ruminant products rises so high that hundreds of millions of hectares of grazing land are converted to bioenergy or because governments also spend large sums of money to intensify agricultural production on existing agricultural land.
247. Searchinger et al. (2017).
248. When starches are fermented into ethanol, one gram of carbon is lost for each two grams of carbon in the ethanol, as shown in Searchinger, Edwards, et al. (2015).
249. Haberl et al. (2010).
250. Haberl et al. (2010) discusses the various estimates.
251. The Haberl et al. (2011) estimate is of 25 EJ of unused residues, which could generate 12.5 EJ of transportation biofuels according to high conversion efficiency estimates.
252. Smil (1999) provides a compelling analysis of the uses and needs for crop residues worldwide. Even in the United States, Blanco-Canqui and Lal (2009) found that at least in a part of the U.S. maize belt, the removal of residues resulted in substantially negative effects on maize yields.
253. Liska et al. (2014). Many studies have estimated conditions under which the removal of residues might not reduce soil carbon, but the more salient factor is the difference in soil carbon with and without the residues. If the residues would add to soil carbon, then their removal reduces carbon sequestration.
254. Author's calculations based on data from FAOSTAT and assumption that all tops and branches are available and equal to 30% of harvested roundwood.
255. Booth (2018).
256. Haberl et al. (2010).
257. IEA (2017).
258. Haberl et al. (2010).
259. Kladvko et al. (2014).
260. Hughes et al. (2012).
261. NRC (2012), 2.
262. Wigmosta et al. (2011). The water challenge exists in large part because algal biofuel production is expensive (estimated at US\$300–US\$2,600 per barrel in 2010, in Hannon et al. 2010), and strategies to achieve a reasonable cost require production in open ponds, from which much water evaporates. Although some other estimates of potential water use are lower, nearly all still estimate the need for large quantities, according to the NRC (2012). One possibility might be to use saline waters, but NRC (2012) concluded that some fresh water would be necessary.
263. Moody et al. (2014).
264. Waite et al. (2014).
265. See note 211.
266. Kissinger et al. (2012).
267. For example, one paper estimated land-use demands to meet existing electricity production in the United States in 2005 as varying from 1% to 9% for states east of the Mississippi (Denholm and Margolis 2008). This figure would obviously need to increase to meet the greater electrical generation needs of 2014. But it would decline if power were imported from the sunnier, drier, and less populated states in the U.S. West, as PV conversion efficiencies grow (and they have grown greatly even since 2008) and as costs come down, which permits more dense packing of PV cells in tilted configurations.
268. Authors' calculations. These numbers require information only about the solar radiation received in an area of production, the crop or biomass yields, the quantities of biofuels per ton of crop, and the energy of the biofuel. Brazilian sugarcane ethanol numbers assume average solar radiation of 2,000 kilowatt hours per square meter per

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

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

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

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

271. See the explanation in the following note.

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

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

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

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

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

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

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

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

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

274. Searchinger et al. (2017).

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

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

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

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

277. IEA (2014).

278. See HLPE (2013).

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

280. Sperling and Yeh (2010).

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

282. Kitzing et al. (2012).

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

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

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

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

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

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

289. Abbott (2012).

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

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

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

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

293. UNDESA (2017). Total population by major area, region, and country (medium-fertility variant).
294. For studies showing strong statistical correlations between declines in fertility and increases in girls' education, increased access to family planning, and declines in infant mortality, see Shapiro and Gebreselassie (2008); Leeson and Harper (2012); and Upadhyay and Karasek (2010).
295. The correlation between female education, a decrease in fertility rates, and an increase in contraceptive use is well documented in both developed and developing countries, including across sub-Saharan Africa. For example, see Shapiro and Gebreselassie (2008); Bbaale and Mpuga (2011); and Bloom and Canning (2004). Shapiro and Gebreselassie (2008); Bloom and Canning (2004); and Bbaale and Mpuga (2011) also show that education is correlated with declining family size and increased use of condoms in Uganda.
296. Ethiopia Central Statistical Agency (2017).
297. Schmidt et al. (2012).
298. Chaaban and Cunningham (2011).
299. Shapiro and Gebreselassie (2008); Bongaarts (2005); Bbaale and Guloba (2011); Bbaale and Mpuga (2011).
300. UNDESA (2015). According to Sing and Darroch (2012), 58 million women in Africa—including 53 million in sub-Saharan Africa—would like to space or limit their next birth but do not use contraception.
301. WHO and UNICEF (2013).
302. Shapiro and Gebreselassie (2008) found that in 24 sub-Saharan African countries, progress in women's education and reductions in infant and child mortality were the key factors contributing to sustained declines in fertility rates since the early 1990s. They also found that in countries where these education and mortality indicators had stopped improving or were deteriorating, fertility rates tended to stall instead of drop further. Hossain et al. (2005) found that reduced mortality rates correlated with reduced fertility in Bangladesh.
303. WHO (2013a); WHO (2013b); CIA (2013).
304. Pool (2007).
305. Bloom et al. (2003); Bloom and Williamson (1998); Bloom et al. (2000); Mason (2001). Locations where the demographic dividend contributed to economic growth include Hong Kong, Malaysia, Singapore, South Korea, Taiwan, and Thailand.
306. Sippel et al. (2011).
307. According to UNDESA (2017), the "low variant" simply uses a projection of 0.5 children below the fertility rates in the "medium variant" over most of the projection period—starting from a downward adjustment of -0.25 child from 2015 to 2020, -0.4 child from 2020 to 2025, and -0.5 child from 2025 onward.
308. UNDESA (2017). This replacement level (2.16) is higher than 2.1, likely due to higher-than-global-average rates of female infant and child mortality in sub-Saharan Africa.
309. To estimate the lower population under this scenario, we made several assumptions. We first compared UNDESA's (2017) "high-fertility" scenario for sub-Saharan Africa (3.7 fertility rate) to its "medium-fertility" scenario (3.2 fertility rate) and found a difference in population of 226 million people in 2050 between the two scenarios. We then compared the "medium-fertility" scenario to the "low-fertility" scenario and found a difference in population of 216 million people. We then assumed that the population difference between a "low-fertility" and a "replacement fertility" scenario with a 2.16 fertility rate would be proportional to the differences between "high fertility" and "medium fertility," and between "medium fertility" and "low fertility," estimating a population difference of 230 million people between "low fertility" and "replacement-level fertility." We distributed that population difference of 230 million people (across sub-Saharan Africa) proportionally across all countries. The "replacement-level fertility" scenario led to a population of 1.8 billion in sub-Saharan Africa in 2050—very similar to an earlier estimate of 1.76 billion by the Oxford Institute of Population Ageing for a paper earlier in this report series (Searchinger, Hanson, Waite, et al. 2013).
310. Authors' calculations from GlobAgri-WRR model. Projected growth in crop calorie production in sub-Saharan Africa between 2010 and 2050 is approximately 1,840 trillion kcal.
311. Robinson (2016) notes that two-thirds of sub-Saharan African countries adopted national population policies since the 1980s to reduce population growth, and that countries with such policies experienced statistically greater declines in fertility rates between 1987 and 2002 than those without.
312. Shapiro and Gebreselassie (2008). The 14 countries with a declining trend in national total fertility rates between the 1990s and mid-2000s were Benin, Burkina Faso, Chad, Côte d'Ivoire, Eritrea, Ethiopia, Madagascar, Malawi, Namibia, Nigeria, Senegal, Togo, Zambia, and Zimbabwe. Three countries (Mali, Niger, and Uganda) were classified as "pre-fertility transition," with no significant declines in fertility rates; and seven countries were classified as "stalled fertility decline," with fertility rates that had initially declined but then stalled during the study period. Across all countries, fertility declines tended to be stronger in urban areas.
313. UNDESA (2013). Since this 2013 publication, the United Nations has twice revised sub-Saharan Africa's projected population upward (in 2015 and 2017), presumably for the same reasons.
314. World Bank (2011a).

315. Athena Ballesteros (senior associate, Institutions and Governance Program, World Resources Institute), personal communication, July 12, 2013.
316. Oxfam (2007); Inter Press Service (2016).
317. Pingali et al. (2008); Lynd et al. (2015); Lynd and Woods (2011).
318. HLPE (2011); Wright (2014).
319. Oxfam (2012); ActionAid (2012).
320. Pingali et al. (2008).
321. Lau et al. (2015).
322. World Bank (2008).
323. Dorward (2013).
324. World Bank overview of poverty numbers, available at <http://www.worldbank.org/en/topic/poverty/overview>.
325. Filipinski and Covarrubia (2010); Jayne et al. (2010).
326. Dorward (2012); Ivanic et al. (2011).
327. Headey (2014); Jacoby (2013); Ivanic and Martin (2014).
328. FAO (2012b), 104, Fig. 33; van Ittersum et al. (2016).
329. See discussion in Searchinger, Edwards, Mulligan, et al. (2015). When there are independent (exogenous) sources of growth in demand for crops, crop prices rise as a consequence. These price increases stimulate additional supply and production by farmers, and reduced demand and less consumption by preexisting consumers. The percentage of the crops that are not replaced due to reduced consumption depends on the ratio between these responses, which is reflected in the ratio of the supply and demand elasticities. Although there is some uncertainty about those elasticities, estimates of individual crop supply and demand elasticities usually place the demand response as lower than the supply response but still a substantial fraction of that response. For typical estimated supply and demand elasticities, see elasticities referenced in Hochman et al. (2014). One paper (Roberts and Schlenker 2013) estimated the global supply and demand responses for calories from the world's major crops and indicated that 20% of crops going to satisfy new demands will not be replaced.
330. HLPE (2011); Muhammad et al. (2011).
331. Bobenrieth et al. (2013). The trends in crop prices discussed in this paper provide an excellent example and reflect the fact that demand growth that results in temporary shortages has a greater price effect in the short term than the long term. See also discussion in Wright (2014) and in the supplement to Searchinger, Edwards, Mulligan, et al. (2015).

REFERENCES

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