WORLD RESOURCES INSTITUTE

# CREATING A SUSTAINABLE FOOD FUTURE

*A menu of solutions to sustainably feed more than 9 billion people by 2050*

**WORLD RESOURCES REPORT 2013–14: INTERIM FINDINGS**

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# FOREWORD

The world urgently needs to improve the way it produces and consumes food. In the coming decades, agriculture—which employs two billion people today—must provide enough food for a growing population and be an engine of inclusive economic and social development. However, the environmental impacts of agriculture are large and growing, creating risks for future food production.

Today, we use roughly one-half of the planet's vegetated land to grow food. The amount of land used for agriculture has grown by more than 10 million hectares per year since the 1960s, and expanding croplands and pasture lands are placing increasing pressure on tropical forests. Agriculture now accounts for nearly one-quarter of global greenhouse gas emissions and 70 percent of all freshwater use. As the human population continues to grow, with billions joining the global middle class in the coming decades, these trends are set to intensify. By 2050, agriculture alone could consume 70 percent of the total allowable "budget" of greenhouse gas emissions consistent with limiting global warming to two degrees.

This is the great challenge: To adequately feed more than nine billion people by 2050, the world must close a 70 percent gap between the amount of food produced today and that needed by mid-century. At the same time, to advance sustainable development, we must close this "food gap" in ways that enhance the livelihoods of poor farmers and reduce agriculture's impact on the environment. Failure to address the environmental impacts would hamper food production in coming decades—through land degradation, water shortages, and adverse effects from climate change.

This report presents the interim findings of the World Resources Report 2013–2014: *Creating a Sustainable Food Future*, a collaboration of the World Resources Institute, the United Nations Development Programme, the United Nations Environment Programme, and the World Bank. The report analyzes the challenge and identifies the most promising technical options from a comprehensive "menu" of practical, scalable strategies that could close the food gap, while simultaneously reducing pressure on the environment and providing valuable economic and social benefits. The final *Creating a Sustainable Food Future* report will quantify each menu item's potential contribution to closing the food gap and to mitigating greenhouse gas emissions and other environmental impacts. It will also identify the practices, policies, and incentives necessary to implement the solutions at the necessary scale.

This important analysis demonstrates that big changes are possible. The solutions on our menu would allow the world to sustainably increase food production and reduce excess consumption. Governments, the private sector, farming organizations, and civil society must urgently come together in a determined alliance in order to deliver on the promise of a sustainable food future. We cannot afford to wait.

**Andrew Steer**
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## NOTES

All dollars are U.S. dollars unless otherwise indicated.
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# EXECUTIVE SUMMARY

The world's agricultural system faces a great balancing act. To meet different human needs, by 2050 it must simultaneously produce far more food for a population expected to reach about 9.6 billion, provide economic opportunities for the hundreds of millions of rural poor who depend on agriculture for their livelihoods, and reduce environmental impacts, including ecosystem degradation and high greenhouse gas emissions. The forthcoming 2013-14 World Resources Report, *Creating a Sustainable Food Future*, responds to this challenge with a menu of solutions that could achieve this balance. This report provides an initial analysis of the scope of the challenge and the technical prospects of different menu items.

## The Food Gap and its Implications for Food Security, Ecosystems, and Greenhouse Gas Emissions

**HUNGER AND THE SCOPE OF THE FOOD GAP |** More than 800 million people today remain "food insecure," which means they are periodically hungry. According to our projections, the world faces a 69 percent gap between crop calories produced in 2006 and those most likely required in 2050. To close this gap through agricultural production increases alone, total crop production would need to increase even more from 2006 to 2050 than it did in the same number of years from 1962 to 2006—an 11 percent larger increase. During the same period, milk and meat production from pasture would need to increase 40 percent more than it did from 1962 to 2006. If the world's wealthy consumed less meat and other resource-intensive foods, the food gap would narrow. However, because the rich outcompete the poor when food supplies fall short of demand, the world's poor would most acutely feel the consequences of any gap between supply and demand.

**THE DEVELOPMENT AND POVERTY CHALLENGE |** Roughly 2 billion people are employed in agriculture, many of them poor. To address poverty fully, agriculture therefore needs to grow in ways that provide economic opportunities to the poor. Women make up the majority of agricultural workers in many developing countries. Raising women's income has disproportionate benefits for alleviating hunger, so assisting women farmers is a particularly effective way to reduce poverty and enhance food security.

**THE LAND USE AND BIODIVERSITY CHALLENGE |** Croplands and pasture occupy roughly half the global land that is not covered by ice, water, or desert. The ongoing expansion of cropland and pastures is the primary source of ecosystem degradation and biodiversity loss. Between 1962 and 2006, cropland and pasture expanded by roughly 500 million hectares—an area equal to roughly 60 percent of the United States. The conversion of forests, savannas, and peatlands to agriculture accounts for roughly 11 percent of global greenhouse gas emissions.

**THE CROP AND PASTURE YIELD CHALLENGE |** To meet projected crop needs just by increasing production and without expanding the annual area harvested, crop yields on average would need to grow by 32 percent more from 2006 to 2050 than they did from 1962 to 2006. Although substantial potential remains for yield increases, boosting yields at an even more rapid rate going forward is a tall order. Between 1962 and 2006, most of the world's farmers adopted scientifically bred seeds and fertilizer, and the area under irrigation doubled. Today, little water is left to expand irrigation, and no similarly dominant new technologies appear available. Climate change will probably also depress yields substantially, making gains more elusive.

The land use challenge extends to pasture, which accounts for more than two-thirds of agricultural land globally. Pasture expansion at least matches cropland expansion as a cause of forest and woodland conversion. To meet projected demands for milk and meat from cows and sheep without expanding pasture, annual output from pasture lands per hectare will need to grow more than 80 percent by 2050.

**THE CLIMATE CHANGE CHALLENGE |** The production of crops and animal products today releases roughly 13 percent of global greenhouse gas emissions, or about 6.5 gigatons (Gt) of carbon dioxide equivalent ($CO_2e$) per year, without counting land use change. Even assuming some increases in the carbon efficiency of agriculture, emissions could plausibly grow to 9.5 Gt of $CO_2e$ by 2050. When combined with continuing emissions from land use change, global agriculture-related emissions could reach 15 Gt by 2050. By comparison, to hold global warming below 2° Celsius, world annual emissions from all sources would need to fall to roughly 21-22 Gt by 2050 according to typical estimates—meaning that agriculture could consume roughly 70 percent of the allowable budget for all greenhouse gas emissions by mid-century. To contribute its full fair share to meeting the 2° C target by 2050, agriculture would need to cut its current emissions by two-thirds, even while boosting food production.

**THE FISHERY CHALLENGE |** Fish from both the wild and aquaculture contributed 16 percent of global animal-based protein in 2009 and are the primary source of animal-based protein for 1.3 billion people. Yet 57 percent of wild marine fish stocks are exploited to their full potential, and another 30 percent are overexploited and are likely to decline in the future, barring improvements in fisheries management. Globally, the wild fish catch peaked in the 1990s, has since modestly declined, and will need to decline further for at least some temporary period if fisheries are to recover enough to produce present catch levels sustainably.

**THE COMBINED CHALLENGE |** These various challenges interact. Overfishing reduces attainable fish catch. Deforestation may have harsh regional as well as global climate consequences for food production. Left unchecked, climate change may cause severe disruptions to the global food supply. Even modest warming is likely to harshly impact many of the most food-insecure countries.

## Menu of Solutions

In *Creating a Sustainable Food Future*, we explore a menu of potential solutions that could sustainably close the food gap by 2050. Each solution contributes to—or at least does not undermine—five key sustainability criteria: advancing rural development, generating benefits for women, protecting ecosystems, reducing greenhouse gas emissions, and avoiding overuse and pollution of freshwater. Solutions on the menu fall into three categories:

1. Solutions that help to close the food gap by reducing growth in food consumption in ways that advance or safeguard human well-being;
2. Solutions that help to close the food gap by increasing food production on existing agricultural land; and
3. Solutions that do not necessarily produce more food but reduce the environmental impact of food production, particularly greenhouse gas emissions.

### Options for reducing excessive food consumption

Reducing excessive food consumption can help close the food gap. We analyze five main options for doing so that could have economic, environmental, and health benefits. Of these solutions, one has health benefits but little impact on the food gap, two are challenging but worth pursuing, and another two present greater opportunities than typically appreciated.

**REDUCE OBESITY |** The world faces an obesity epidemic, with the number of overweight people reaching 1.4 billion in 2008, including 500 million people who are obese. Although health considerations warrant efforts to tackle obesity, eliminating obesity and halving the number of overweight people would reduce the 2050 calorie gap by only 6 percent.

The solutions on our menu are designed to sustainably close the food gap. Each solution contributes to–or at least does not undermine–economic and social development and environmental protection.

**REDUCE LOSSES AND WASTE |** Between the farm and the fork, roughly a quarter of food calories are lost or wasted. Although high, that figure is lower than the commonly cited figure of one-third, which measures losses by weight. In industrialized countries, consumer waste makes up roughly half the food loss and waste. In developing countries, two-thirds of food loss occurs during harvesting, handling, and storage. Cutting these losses is an immediate and cost-effective option for increasing food availability, particularly in sub-Saharan Africa. Globally, cutting losses and waste in half by 2050 would reduce the food gap by roughly 20 percent. Although reaching this goal will be challenging, a variety of viable strategies exist for reducing food loss and waste along the value chain.

**REDUCE EXCESSIVE CONSUMPTION OF ANIMAL PRODUCTS |** There is a strong case for some consumption of animal products, including meat, milk, fish, and eggs. These foods have many nutritional benefits, and the world's poor could greatly benefit from modest increases in consumption of animal products. Livestock production also generates roughly half of all agricultural income worldwide, including important income for large numbers of smallholder farmers.

However, most of the world's people consume more milk and meat than necessary, and many consume more than is healthy. Obtaining calories and protein through animal products is also highly inefficient from a resource use standpoint. Although methods to estimate efficiency vary, even poultry, the most efficient source of meat, convert only around 11 percent of gross feed energy into human food according to the most comprehensive methods. We project an 82 percent increase in meat consumption between 2006 and 2050, and holding down growth in consumption by the world's upper and growing middle class would reduce land demands and greenhouse gas emissions. (The level of savings, however, is more complex than nearly all analyses suggest because these analyses do not compare meat-based diets with realistic alternatives.) The large differences in animal product consumption between wealthy countries also suggest that this strategy is feasible.

Yet this menu item may be necessary not to close the food gap but just to keep it from growing larger. FAO already projects relatively little growth in meat consumption by more than 2 billion people in sub-Saharan Africa because of poverty and by 1.5 billion people in India because of poverty and culture. High-consuming regions will probably need to eat less meat just to provide room within the FAO projections for billions of people in low-consuming regions to eat a little more.

**SHIFT TO A MORE EFFICIENT MIX OF ANIMAL PRODUCTS |** Beef is a particularly inefficient way of generating edible calories and protein. By the best global average estimates, beef converts only 1 percent of gross animal feed energy into food for people. Beef production also is projected to grow by more than 92 percent between 2006 and 2050, which implies large land requirements to produce feed. Many analyses underappreciate this inefficiency because they focus only on the land demands of human-edible animal feeds, such as maize, and ignore the growing demand for grasses. Focusing exclusively on human-edible animal feeds misses important environmental impacts, because impacts are high whether forests and woody savannas are converted to soybeans and maize or to pasture. Eliminating beef production would not be wise. Native grazing lands contribute to sustainable food production and support many pastoral societies, and improvements in integrated crop/livestock systems by small farmers hold promise for poverty and hunger reduction. But holding down the growth of global beef consumption would help maintain these valuable contributions to the food supply while also reducing deforestation. Ambitious global reductions seem feasible, as beef consumption per person in the United States and Europe has already dropped by roughly one-third from peak levels. Shifting just 20 percent of the anticipated future global consumption of beef to other meats, fish, or dairy would spare hundreds of millions of hectares that provide carbon storage

and other ecosystem services, or could be used to help meet the world's demand for food crops.

**HELP AFRICA IN ITS EFFORTS TO REDUCE FERTILITY RATES |** If all of the world's regions achieved replacement level fertility by 2050, the projected growth in food demand would decline modestly in global terms, yet substantially in the world's hungriest areas. "Replacement level fertility" is the total fertility rate—the average number of children born per woman—at which a population replaces itself from one generation to the next, without migration. This rate is roughly 2.1 children per woman for most countries, although it may modestly vary with mortality rates. While most of the world's regions have already achieved or are close to achieving replacement level fertility, sub-Saharan Africa is the exception, with a regional rate of 5.4 children per woman. Even with the region's growing urbanization, present estimates are that the region's fertility rate will only decline to 3.2 by 2050. As a result, the region's population is projected to nearly triple from its 2006 level to more than 2 billion people by 2050. To adequately feed that higher population by mid-century, production of crop calories will have to increase to a level 3.6 times higher than production in 2006, even with continued heavy reliance on imports.

In general, fertility rates fall even in poor countries once a high percentage of girls attend lower secondary school, child mortality rates decline, and women have access to reproductive health services. Improving these education and health measures, which are exceptionally low in sub-Saharan Africa, would have large parallel benefits for food security, social and economic development, and environmental stewardship. Most countries in sub-Saharan Africa have endorsed the goal of reducing fertility rates. Achieving replacement level fertility in sub-Saharan Africa by 2050 would reduce the global food gap by 10 percent, and would reduce the food gap for the region—the world's hungriest—by 25 percent.

## Options for increasing food production without adverse land expansion

**FARM SMARTER |** Severe limitations on water availability and the already heavy use of fertilizer in most regions limit the current capacity to boost yields simply by adding more inputs. These strategies would in any case fail to meet the sustainability criteria set for the menu. Smarter farming will therefore have to fuel yield growth. In the last two decades, improved use of agricultural technology in the broadest sense maintained a high level of growth in food production even with less growth in agricultural inputs. Globally, increased use of land, water, chemical, and other inputs contributed to roughly 70 percent of growth in annual agricultural output in the 1970s and 1980s, but less than 30 percent in the 1990s and 2000s. Yet even with these improvements, agricultural land expansion contin-

ues, so the need for smarter farming is even greater going forward. Key opportunities for improved farm management include more careful selection of seed varieties adapted to local conditions, more judicious use of fertilizer, more attention to micronutrients, and improved weather forecasting to inform the selection of planting dates.

**BREED BETTER SEEDS |** Improved breeding has always been critical to agricultural progress and will remain fundamental. Genetic engineering can play a role, particularly because improved techniques now allow insertion of genes in particular locations, reducing the amount of trial and error necessary to produce crops with improved traits (such as pest or drought resistance). In the short run, genetic engineering can most help by enabling faster breeding responses to new pests. More fundamental crop improvements from genetic engineering, such as improved uptake of nutrients and reduced losses of water, are uncertain and will take decades to come to fruition. But the strongest breeding opportunities will continue to rely on conventional breeding, in part because they can take advantage of modern biological methods. Those methods make it easier and faster to identify and select for the combinations of genes that result in higher yields, and justify increases in conventional breeding budgets.

**LEAVE NO FARMER BEHIND |** Yield growth will also rely on "leaving no farmer behind" by closing the gap between what many farmers currently achieve and what they could potentially achieve. Global yield gaps are unquestionably large, but global studies have large methodological limitations. Studying gaps using locally verified crop models is a priority to identify not just where the largest gaps occur, but also the causes of those gaps so they can be addressed.

**CROP THE SAME LAND MORE FREQUENTLY |** FAO data indicate that more than 400 million hectares of cropland go unharvested each year, suggesting that this amount of land is left fallow. On the other hand, farmers plant roughly 150 million hectares twice or more each year. Planting and harvesting existing cropland more frequently, either by reducing fallow or by increasing double cropping, could in theory boost production without requiring new land. FAO projects an increase in such planting frequency ("cropping intensity"), which would avert the need to clear an additional 62 million hectares for crops by 2050. Unfortunately, our review suggests that the practicalities of double cropping are little understood. Meanwhile, some fallow "croplands" are either in very long-term rotations or have been abandoned. These lands commonly revert to forest or grassland, helping to store carbon and provide other ecosystem services. Planting them more frequently sacrifices these benefits. Greater cropping intensity is a promising option but requires closer analysis both of double-cropping potential and of the "croplands" that countries now identify as unused.

**BOOST YIELDS IN AFRICA IN PART THROUGH IMPROVED SOIL AND WATER MANAGEMENT |** Although sub-Saharan Africa today consumes only 9 percent of the world's calories, its likely growth in demand accounts for more than one-third (37 percent) of all additional calories required by 2050. The region also has the highest hunger rate, imports 25 percent of its grain needs, and has the world's lowest staple crop yields. Boosting those yields is therefore critical both for reducing hunger and for avoiding large-scale deforestation.

Soil degradation, particularly the loss of soil carbon, presents a particular challenge to agricultural production in sub-Saharan Africa, and 285 million people now live in dry regions where soil degradation has even harsher effects. Yet in Niger, farmers have rebuilt soil fertility and boosted yields on 5 million hectares of land by husbanding the natural regeneration of nitrogen-fixing trees and other native vegetation. Over sub-Saharan Africa's 300 million hectares of dry cropland, this type of agroforestry has even greater potential to boost yields when combined with water harvesting and microdosing of individual plants with small quantities of fertilizer. Conservative estimates suggest that scaling up these practices could potentially provide the present dryland population an additional 615 kcal per person per day.

**EXPAND CROPS INTO LOW-CARBON DEGRADED LAND |** Even if cropland must expand, it can do so with modest environmental cost if it expands into non-agricultural lands that have low biodiversity value, store little carbon, and are also unlikely to store much carbon in the future. Millions of hectares of such lands exist in Indonesia and Malaysia, where *Imperata* grasses have overrun logged forests and hold back reforestation. Our analysis suggests that more than 14 million hectares of low-carbon degraded land in Indonesia's Kalimantan region of Borneo may be suitable for palm oil production—enough to accommodate additional oil palm plantations in Indonesia to 2020. Directing oil palm expansion to these lands is critical in the near term because oil palm is now expanding heavily into primary forests and peatlands. Peatland conversion leads to vast, ongoing annual carbon releases as the peat degrades over decades, which could within the next decade or two generate annually 5 to 7.5 percent of all current greenhouse gas emissions.

Globally, most of the lands considered by many analyses as "potential but unused" croplands do not truly qualify as environmentally low cost. Grazing lands produce valuable forage, and tropical savannas and sparse woodlands have high carbon storage and biodiversity value. Abandoned croplands, in areas capable of supporting trees, typically reforest, sequester carbon, and play an important role in holding down climate change.

**INTENSIFY PASTURE PRODUCTIVITY |** Among relatively wet pastures already converted from natural forests and savannas, large opportunities exist to intensify the output of milk and meat. Standard techniques include adding fertilizer, growing legumes, and confining cattle to small grazing areas and rotating them quickly. More sophisticated systems combine grasses with nitrogen-fixing shrubs and multiple layers of trees. These pasture intensification efforts require far more technical attention and incentives than they now receive because the alternative implies vast deforestation.

**AVOID OR MANAGE SHIFTS IN AGRICULTURAL LAND |** Shifts in agricultural land from region to region and within regions cause millions of hectares of deforestation in excess of net agricultural expansion. The losses in carbon storage and other ecosystem services due to new deforestation generally exceed the gains from eventual reforestation elsewhere. It will be important to avoid shifts in agricultural land, and to restore abandoned lands more quickly when these shifts do occur.

**INCREASE PRODUCTIVITY OF AQUACULTURE |** As wild fish catch has plateaued, aquaculture has expanded rapidly to produce nearly half of all the fish people consume. On average, farmed fish are as efficient at converting feed to food as chicken, making them an environmentally desirable source of animal protein, if produced sustainably. Aquaculture's rapid growth initially led to several adverse environmental

impacts, but these effects have since been reduced; for example, by slowing conversion of mangroves to shrimp ponds and by reduced reliance on wild-caught fish as feed. To maintain the role of fish in diets, aquaculture production will have to more than double from current levels by 2050. Even with enormous progress in feeding efficiency, the industry still faces a static supply of fishmeal and fish oil, which could limit future growth unless progress is made in algae production or breeding plants to produce such oils. Aquaculture ponds also cover a significant area, and suitable lands for expansion are limited. Future production growth will require increased fish per hectare of pond, which in turn requires more energy use to circulate and aerate water. Such intensification has potential to lead to other adverse environmental and social impacts; minimizing these impacts will be a key challenge.

## Options for reducing greenhouse gas emissions from agricultural production

The great balancing act requires not just producing more food and consuming less, but also reducing greenhouse gas emissions from both existing and additional production.

**CARBON SEQUESTRATION STRATEGIES |** Carbon sequestration strategies, particularly using agricultural soils, have received much of the limited academic and policy attention on agricultural climate mitigation but are harder to achieve than previously thought. Whether changes in plowing practices increase carbon and reduce greenhouse gas emissions is now scientifically uncertain. The implications for soil carbon of changes in grazing management vary greatly. Some strategies for increasing soil carbon do not truly increase total terrestrial carbon storage but only move carbon to one location from another, or divert carbon in biomass from other valuable uses, such as using crop residues for animal feed. Increasing soil carbon can be an important part of a strategy to boost long-term crop production in some areas, and boosting productivity will often in turn help to increase soil carbon. The most promising strategies are those that generate other economic benefits quickly, such as forms of agroforestry. There may also be strategies to reforest some highly degraded lands while intensifying neighboring croplands that together both store more carbon and make better use of productive resources. Restoring 5 million hectares of drained abandoned peatlands in Indonesia also offers the promise of large carbon sequestration gains.

**INCREASE EFFICIENCY IN USE OF INPUTS |** In a world that needs more food, agricultural climate mitigation policy should focus on strategies that reduce greenhouse gas emissions per unit of food—even if they increase emissions for any particular farm or cow—because that will reduce emissions globally. At least in the short run, increasing production efficiency provides the strongest opportunity for reducing emissions from agricultural production globally. Such strategies include:

- **Improve the feeding and health of cows and sheep.** Ruminants generate nearly half of all direct agricultural emissions, but improving the feeding and health of cows can cut the emissions per kilogram of milk or meat in many developing regions by two-thirds. Small farms that mix livestock and crops provide promising opportunities.

- **Balance fertilizer use worldwide.** Although nitrogen fertilizer is underused in Africa, fertilizer is used inefficiently in much of Asia, the United States, and Europe, leading to high emissions as well as unnecessary expense.

- **Reduce emissions from paddy rice.** Various ways of drawing down water during the growing season and removing rice straw from rice paddies can cut emissions by more than half compared to those farms that do not employ these measures.

Nearly all of these efficiency measures can boost production, reduce input costs, or create new economic opportunities. Today, few policies encourage these measures, and relatively little analysis addresses the practicality of these changes in particular locations.

The most effective way to reduce greenhouse gas emissions from agricultural production is to increase efficiency in the use of land, water, cows and fertilizer.

### Avoiding competition from bioenergy

The 69 percent food gap assumes that biofuel production remains at its 2010 level of roughly 2.5 percent of transportation fuel. Larger bioenergy targets would add greatly to the food challenge. Several governments—including the United States and Europe—have endorsed goals to supply 10 percent of transportation fuel by 2020 with biofuels. Meeting such a 10 percent global goal in 2050 would generate less than 2 percent of the world's delivered energy on a net basis but would require 32 percent of the energy contained in all global crops produced in 2010. Such a goal would also significantly widen the food gap, from 69 percent to roughly 100 percent. Furthermore, meeting a broader bioenergy goal endorsed by the International Energy Agency—to produce 20 percent of world energy from biomass—would require a level of biomass equivalent not merely to all global crop production in 2000, but to the total harvest of crops, grasses, crop residues, and trees as well. Some potential exists to use various forms of waste biomass for bioenergy, which would avoid competition with food, carbon, and ecosystems. Giving up the use of crop-based biofuels for transportation—a strategy more in line with a sustainable food future—would close the crop calorie gap in 2050 by roughly 14 percent.

* * *

Can the world achieve this great balancing act? Our assessment is sober but hopeful. The challenge is larger and more complex than broadly appreciated. Some commonly proposed solutions are overemphasized or would have little impact. In contrast, others deserve substantially more emphasis than they have received to date.

The potential solutions can not only help close the food gap, but also generate co-benefits. Reducing losses and waste saves greenhouse gas emissions; reduces demands on land, energy, and water; and, in most cases, saves money. Helping small farmers to feed cows more efficiently improves their income, and reduces emissions and land use demands. To achieve these win/win solutions, governments, the private sector, and civil society will need to act quickly and with conviction. Future installments in the *Creating a Sustainable Food Future* series will explore additional ways of doing so in greater detail.

Chapter 1

# THE GREAT BALANCING ACT: THREE NEEDS

How can the world adequately feed more than 9 billion people by 2050 in a manner that provides economic opportunities to alleviate poverty and reduces pressure on the environment? This is one of the paramount questions the world faces over the next four decades.

Answering it requires a “great balancing act” to meet three great needs.

## BOX 1 | THE WORLD RESOURCES REPORT

The World Resources Report (WRR) provides decision-makers from government, business, and civil society around the world with analysis and insight on major issues at the nexus of development and the environment. Spearheaded by the World Resources Institute, the WRR has been the product of a unique long-term partnership with the United Nations Development Programme (UNDP), the United Nations Environment Programme (UNEP), and The World Bank. This year, the Institut National de la Recherche Agronomique (INRA) and the Centre Internationale de Recherche Agronomique pour le Développement (CIRAD), two major agricultural research institutions in France, have joined as analytical collaborators. For more information about the WRR or to access previous editions, visit: <www.worldresourcesreport.org>.

First, the world needs to close the gap between the food available today and that needed by 2050. This gap, which we measure from 2006, is roughly two-thirds a function of increasing population and one-third a function of increasing wealth. The Population Division of the United Nations Department of Economic and Social Affairs (UNDESA) projects that global population, which was roughly 6.5 billion in 2006 and 7 billion in 2012,will grow to 9.6 billion by 2050.[1] At least 3 billion more people are likely to enter the global middle class by 2030,[2] and they will almost certainly demand more resource-intensive foods such as meats and vegetable oils.[3] At the same time, approximately 840 million of the world's poorest people remain undernourished even today.[4] When food production falls short of people's demands, the world's rich can outcompete the poor, and hunger increases.[5] Without successful measures to restrain food demand growth by the world's more affluent or to reduce waste, worldwide annual crop production[6] will need to increase by 69 percent from 2006 levels if everyone is to be sufficiently fed.[7]

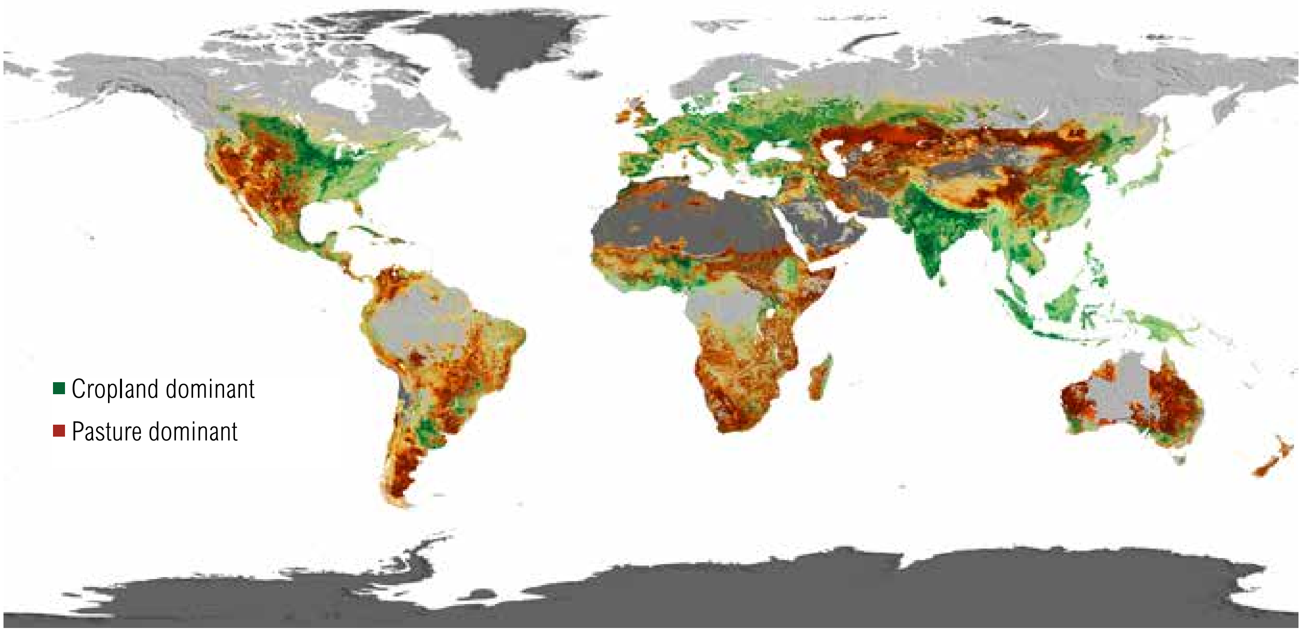
Second, the world needs agriculture to contribute to inclusive economic and social development. Seventy-five percent of the developing world's poor live in rural areas, and many depend on agriculture for their principal livelihood.[8] Although agriculture directly accounts for approximately 3 percent of global gross domestic product (GDP), it employs more than 2 billion people around the world at least part-time.[9] Growth of the agricultural sector in many contexts can reduce poverty more effectively than growth of other economic sectors, in part by providing employment and in part by lowering the cost of food.[10] Women make up 41 percent of the agricultural workforce worldwide and the majority of agricultural workers in South Asia and sub-Saharan Africa.[11] Because increasing women's income has disproportionate benefits for alleviating hunger,[12] assisting women farmers is a particularly effective way to reduce poverty and enhance food security.

Third, the world needs to reduce agriculture's impact on the environment and natural resources. Three environmental impacts are especially important:

- **Ecosystems.** Since the invention of agriculture 8,000–10,000 years ago, growing crops and raising livestock have been the primary causes of ecosystem loss and degradation.[13] Today, 37 percent of the planet's landmass outside of Antarctica is used to grow food—12 percent as croplands and 25 percent as grazing lands.[14] When deserts, permanent ice, and lakes and rivers are excluded, the figure rises to nearly 50 percent (Figure 1). Yet agriculture continues to expand and is the dominant driver of tropical deforestation,[15] the conversion of carbon-rich peatlands, and associated impacts on biodiversity.[16]

- **Climate.** Agriculture accounted for approximately 24 percent of global greenhouse gas emissions in 2010. This figure includes 13 percent from agricultural production, namely methane from livestock, nitrous oxide from fertilizer use, and carbon dioxide from tractors and fertilizer production. Land use change, which is primarily driven by agriculture, contributed about another 11 percent.[17]

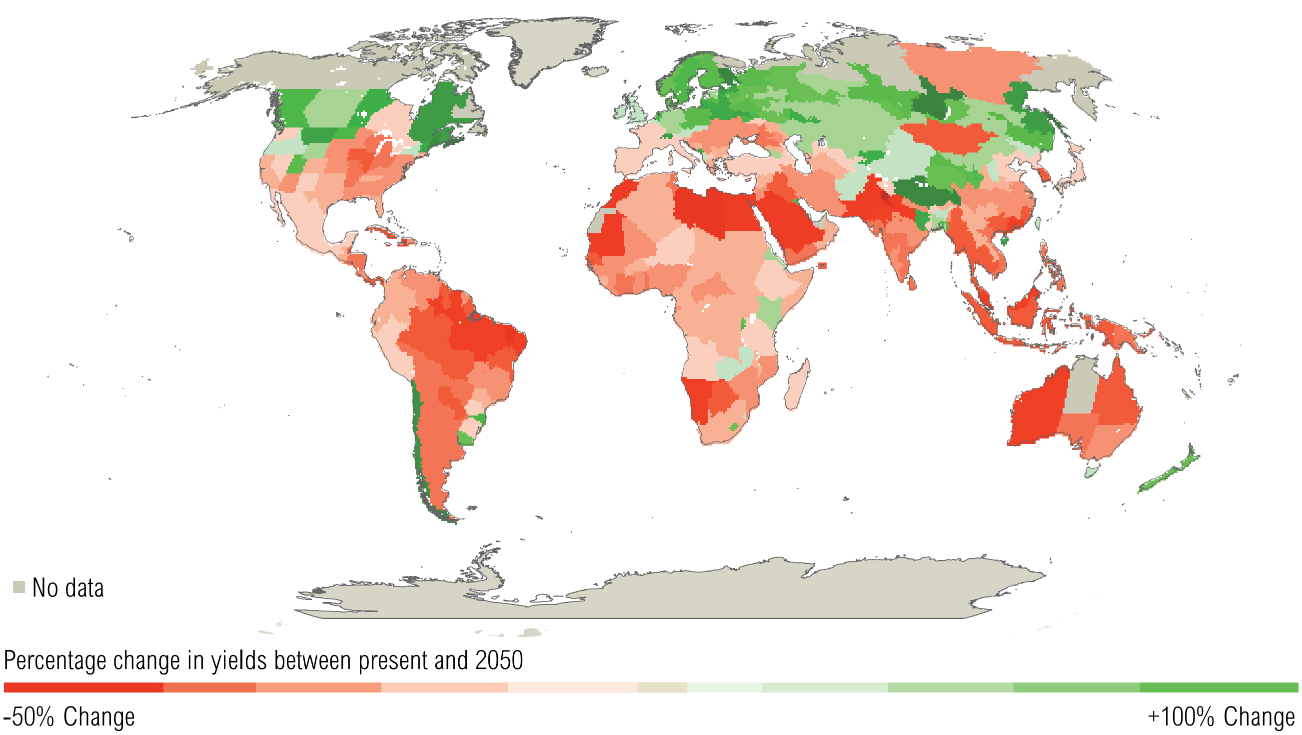
Figure 1 | **Croplands and pasture occupy half of the world's vegetated lands (distribution of croplands and pastures, 2000)**




*Data source:* Ramankutty et al. (2008), *Map source:* Navin Ramankutty, McGill University.

*Note:* Areas in gray contain neither croplands nor pasture.

Figure 2 | **Most studies now project adverse impacts on crop yields due to climate change (3°C warmer world)**




*Source:* World Bank (2010a).

## BOX 2 | WHAT'S NEXT

During 2013 and 2014, WRI is releasing a series of *Creating a Sustainable Food Future* working paper installments on a rolling basis. Each installment analyzes a menu item from our proposed "menu for a sustainable food future" and recommends policies and other measures for implementation. The series will not, however, cover all menu items.

Questions each installment considers include:

- What is the menu item?
- How big an impact could it have on food availability, economic development, and environmental benefits?
- Where might the menu item be most applicable?
- What are the three to five most promising, practical, and scalable approaches for achieving the menu item?
- What are the obstacles—economic, political, technical, or other—to implementing these approaches?
- How can these obstacles be overcome?
- What "bright spots" of success exist, and what can be learned from them?

Each installment is coauthored by its own cohort of WRI researchers, WRR partners, and renowned experts. Authors engage representatives from target audiences during the research and writing phases. After the series has concluded, WRI will consolidate the installments into a final World Resources Report. If you would like to participate in the research or dissemination of any of the *Creating a Sustainable Food Future* installments, please visit the WRR website at: <www.worldresourcesreport.org>.

This interim report focuses on technical opportunities rather than policies, which will be addressed in subsequent installments. For that reason, it does not cover such important topics as international investments in agricultural land ("land grabs"); the merits of small-scale versus large-scale agricultural systems; the influence of land tenure, property rights, and general succession laws and norms on agricultural productivity; and policies for providing access to clean energy services for agriculture.

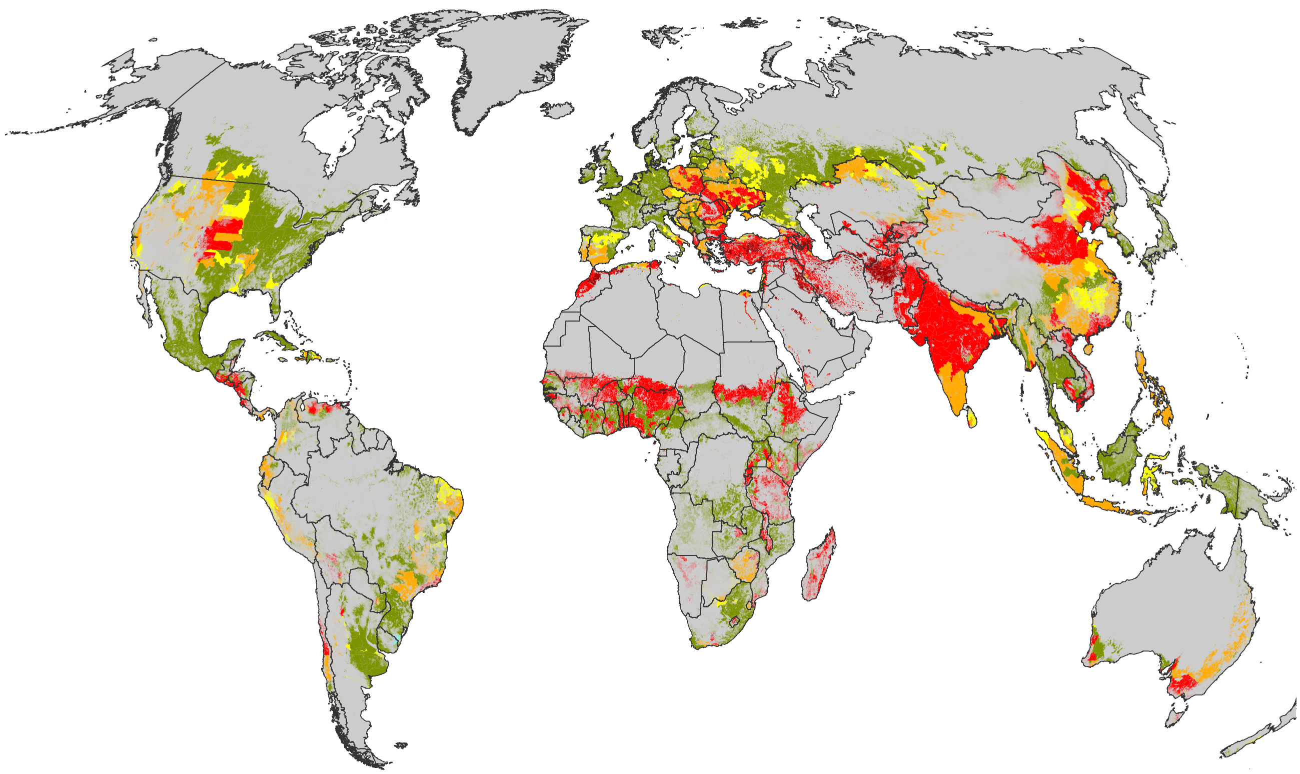
Many of the analyses in this series are global in nature and use global data sets. As such, they cannot fully account for the ethical, cultural, and socioeconomic factors of specific locations. The menu for a sustainable food future is designed for the long term, so it is not a menu for tackling acute, near-term food crises.

- **Water.** Agriculture accounts for 70 percent of all freshwater withdrawn from rivers, lakes, and aquifers, and for 80 to 90 percent of such water that is actually consumed and not returned.[18] Agriculture is the primary source of nutrient runoff from farm fields, which creates "dead zones" and toxic algal blooms in coastal waters and aquatic ecosystems.[19]

Failure to address these environmental impacts would in turn hamper food production in coming decades in a variety of ways. Various methods estimate that land degradation affects approximately 20 percent of the world's cultivated areas (although these estimates suffer from limited data and imprecise definitions).[20] Forest loss is likely to lead to regional drying and warming,[21] causing additional stress on agriculture. According to recent studies, climate change will have large adverse effects on yields due to higher temperatures, extended heat waves, flooding, and shifting precipitation patterns (Figure 2).[22] Rising sea levels from climate change will also reduce cropland productivity and viable cropland area in some coastal regions.[23] Water stress on cropping, already substantial in some areas, is likely to increase due both to growing water demand and climate change (Figure 3). The droughts of 2011 and 2012 in parts of Australia, East Africa, Russia, and the United States are cases in point.

The forthcoming World Resources Report (Box 1), *Creating a Sustainable Food Future*, will describe a set of solutions for how to meet these three pressing needs and achieve the great balancing act. This interim report, which is an extended version of a working paper entitled "The Great Balancing Act," explores the scope of the challenge and analyzes a menu of solutions. Although we offer some judgment about the practicality of these solutions, we defer detailed discussion of the obstacles to implementing them and promising policy responses to forthcoming working papers and the final, consolidated World Resources Report (Box 2).

Figure 3 | **Water stress will increase in many agricultural areas by 2025 due to growing water use and higher temperatures (based on IPCC scenario A1B)**



**Water Stress Condition**

Lower — Near Normal — Higher

*Source:* WRI and The Coca-Cola Company (2011). Cropped areas from Ramankutty et al. (2008).

*Note:* Areas in gray contain no croplands

Between 1962 and 2006, cropland and pasture expanded by roughly 500 million hectares.

Chapter 2

# THE SCOPE OF THE CHALLENGE AND MENU OF SOLUTIONS

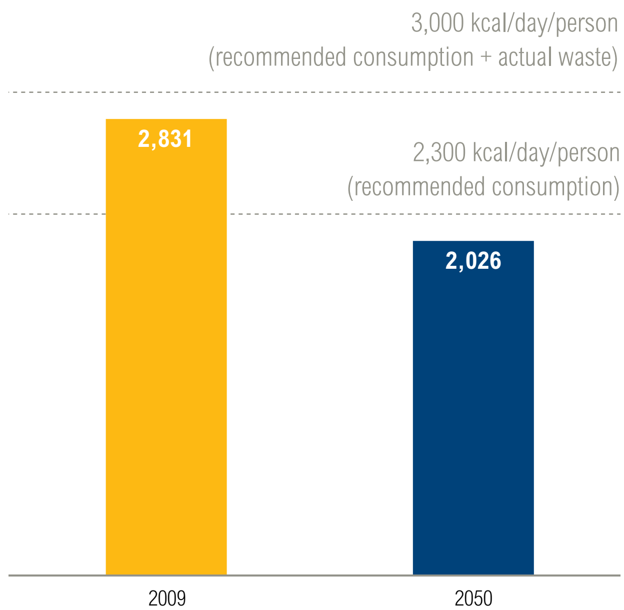
To adequately feed more than 9 billion people by 2050, the world must close a nearly 70 percent gap between the amount of food produced in 2006 and that needed by mid-century. Without measures to limit food demand, the world would need to increase crop calorie production even more over the period from 2006 to 2050 than it did in the period from 1962 to 2006. This report explores a menu of potential solutions to this challenge–strategies to close the "food gap" by 2050 while contributing to economic and social development and reducing environmental impacts.

Will the world really need more food? Given the enormously unequal distribution of food around the planet, one might think that distributing food more equally could solve the food challenge. Yet, as Figure 4 shows, even if all the food calories available in the world in 2009 were equally distributed across the projected population for the year 2050 and no food calories were lost between farm and fork, those calories would still fall short of the Food and Agriculture Organization's (FAO) "average daily energy requirements"—roughly 2,300 kilocalories (kcal) per person per day—by more than 200 kcal per person per day. If the current rate of food loss and waste were to remain in 2050, the gap would grow to more than 950 kcal per person per day.[24] In short, current global food availability is insufficient to feed the world in 2050.

How much more food will the world need? To answer this question, we rely on an FAO projection of food demand and production by 2050 by longtime experts Jelle Bruinsma and Nikos Alexandratos.[25] They project a 55 percent increase in total direct human calorie consumption from 2006 to 2050. To focus on the full challenge of feeding the world adequately, we adjust this projection for two reasons. First, the FAO projects that sub-Saharan Africa and South Asia in 2050 will still have insufficient calories to feed everyone adequately, so we adjust to calculate the production needed to ensure 3,000 calories are available per person per day in all regions. Second, the FAO estimate uses an older U.N. population projection for 2050, and we adjust to reflect the new estimate of 9.6 billion people. The required increase in food calories directly available for human consumption rises to 65 percent.[26]

The 65 percent figure represents the food available to people to eat, including milk and meat. However, it does not include the increase in crops needed to produce that milk and meat, nor does it include modest growth of crops for industrial uses. FAO estimates also include modest growth of crops for biofuels just sufficient to maintain biofuels at roughly their 2010 share of global transportation fuel of 2.5 percent.[27] When including our adjustments for population and food availability, the FAO projection for increases in total crops (as opposed to the increase just in food) implies a 69 percent increase in crop calories from 9,500 trillion kcal per year in 2006 to 16,000 trillion kcal in 2050.[28]

Figure 4 | **Even if all food produced in 2009 were distributed evenly to all people in 2050, the world would still need 974 more calories per person per day**




*Note:* Data reflects food for direct human consumption. It excludes food crops grown for animal feed and biofuels. See endnotes for assumptions used to generate the global average daily energy requirement per person.

*Source:* WRI analysis based on FAO (2012a) and UNDESA (2013), medium fertility scenario.

The result is a 6,500 trillion kcal per year "gap" between production in 2006 and the need in 2050.

Without measures to limit demand, this projection implies that the world needs to increase crop calorie production by 11 percent more over the 44-year period from 2006 to 2050 than it did in the previous 44-year period from 1962 to 2006. Although the future need for cereal growth is slightly lower than the previous period's growth, the growth needed for many other crops is higher, including oilseeds, potatoes, fruits, and vegetables.

In the period from 1962 to 2006, the Green Revolution drove increased yields with scientifically bred seeds, synthetic fertilizers, and a doubling of irrigated area. Even with vast increases in yields, cropland and pastureland expanded by roughly 500 million hectares (Mha), according to FAO data.[29]

This expansion of agriculturally productive land and increased use of water, fertilizer, and pesticides significantly affected ecosystems, freshwater resources, and greenhouse gas emissions. If the world's agricultural system is to achieve the great balancing act, however, the next four decades must exceed previous achievements in food production growth without expanding agricultural land area, without large increases in irrigation, and while reducing agriculture-related greenhouse gas emissions.

## Menu of Potential Solutions

In *Creating a Sustainable Food Future*, we explore a menu of potential solutions to this challenge. This menu of solutions is designed to close the gap of 6,500 trillion kcal per year by 2050, conceptually illustrated by Figure 5, while contributing to economic and social development and reducing environmental impacts. Calories, of course, provide only one measure of human food needs, but as long as solutions focus on ways of providing calories that simultaneously provide the broad balance of nutrients, calories can serve as a viable metric for measuring the gap and its solutions (Box 3).

We honed the menu to those solutions that can contribute to—or at least not negatively impact—economic and social development and environmental protection. Although there are numerous criteria relevant to economic and social development, we chose two:

- **Poverty Alleviation.** The menu should reduce poverty and advance rural development, while still being cost effective.

- **Gender.** Given present inequities and women's disproportionate role in combating poverty and reducing food insecurity, the menu should generate benefits for women.

We also selected three criteria that represent the significant impacts of agriculture on the environment:

- **Ecosystems.** The menu should not result in agricultural expansion into remaining natural terrestrial ecosystems and, in the case of oceans, should reduce pressure on overstrained fisheries. As a result, it would help reduce the loss of biodiversity.

### BOX 3 | WHY WE USE CALORIES AS OUR MEASURE OF THE FOOD GAP

Food comes from a wide variety of crops and animal products, and provides not merely calories but also proteins, vitamins, minerals, fiber, and other nutritional benefits to people. There is no one perfect way to measure quantities of food or a "food gap." FAO's estimate in 2009 of a 70 percent food gap between 2006 and 2050, which many papers have cited, measured food by its "economic value." But because prices change over time, economic value does not provide a consistent unit of measure. Food "volume" includes water, but water in food does not provide nutrition. "Nutrients" are not amenable to a uniform unit of measure because people need many types of nutrients. "Calories," however, are consistent over time, avoid embedded water, and have a uniform unit of measure. Data on calories is also globally available.

Even for calories, our analysis could focus on the total increase in calories from 2006–2050 from crop production, or the total increase in calories from all food available directly for human consumption. Measuring food directly available to people does not count calories in animal feed but does count calories in animal products. Each approach has its merits. As it turns out, the estimated food gap by either measure is similar, ranging from 69 percent for the needed increase in crop production to 65 percent for the needed increase in food calories available for direct human consumption.

The use of calories to measure the food gap would lead to distorted solutions if we considered solutions that provided calories at the expense of nutrients. For example, it might encourage the production of cereals with high yields in place of fruits and vegetables, beans, and animal products. But by focusing only on solutions that provide at least comparable nutrition to those in our baseline projection, all the solutions include a balanced growth in food products. Calories then become a suitable means of measuring the food gap among nutritionally balanced alternatives.

Table 1 | **A menu for a sustainable food future**

| COURSE | MENU ITEM | DESCRIPTION | PERFORMANCE AGAINST CRITERIA | |
|---|---|---|---|---|
| | | | POVERTY ALLEVIATION | GENDER |
| **Hold down consumption** | Reduce food loss and waste | Reduce the loss and waste of food intended for human consumption between the farm and the fork. | ● | ● |
| | Reduce obesity | Reduce the number of people who are overweight or obese. | ● | ● |
| | Reduce growth in demand for animal products (in general) | Reduce the share of animal-based foods in daily diets in wealthy countries. | ● | ● |
| | Shift meat consumption away from beef | Among animal-based foods, reduce the amount of beef consumed in a person's daily diet and substitute with fish and poultry. | ● | ● |
| | Achieve replacement level fertility | Have the total fertility rate of every continent achieve the replacement rate of 2.1 children per woman by 2050. | ● | ● |
| | Reduce biofuel demand for food crops | Reduce the diversion of both edible crops and land into biofuel production. | ● | ○ |
| **Produce more food without land expansion** | Boost yields through attentive crop and animal breeding | Increase yields through the steady annual selection and adoption of higher yielding seeds, supplemented by occasional technology breakthroughs. | ○ | ○ |
| | "Leave no farmer behind" | Bring inefficient farmers up to standard farming efficiency levels. | ● | ● |
| | Plant existing cropland more frequently | Plant and harvest crops more frequently on already existing cropland (more than one rotation per year), *where conditions are suitable.* | ● | ● |
| | Improve soil and water management | Increase crop yields on existing agricultural land by implementing improved soil and water management practices such as agroforestry, water harvesting, and biological nitrogen fixation. | ● | ● |
| | Expand onto low-carbon degraded lands | Expand resource-efficient crop or livestock production onto land that is currently not used to produce food, not biologically diverse, and neither stores nor is likely to sequester significant carbon. | ● | ○ |

● = positive ○ = neutral/it depends ⊗ = negative

| | PERFORMANCE AGAINST CRITERIA | | | COMMENT | ↑ FOOD AVAILABILITY | ↓ GHG EMISSIONS |
|---|---|---|---|---|---|---|
| | ECOSYSTEMS | CLIMATE | WATER | | | |
| | ● | ● | ● | One out of every four calories produced is lost or wasted between the farm and the fork. | X | X |
| | ● | ● | ● | More people in the world today consume too much food than consume too little. | X | X |
| | ● | ● | ● | In most of the world except sub-Saharan Africa, consumption of animal products is already high and leads to more protein intake than is necessary for human health. | X | X |
| | ● | ● | ● | Among animal-based foods, beef stands out for its environmental effects. | X | X |
| | ● | ● | ● | This menu item can be achieved via improving girls' education opportunities, increasing access to reproductive health services, and reducing infant and child mortality, especially in Africa. | X | X |
| | ● | ● | ● | The challenge of feeding the planet gets harder as alternative uses for food (and the land used to grow food) emerge. | X | X |
| | ○ | ○ | ○ | Whether or not the impacts are positive, neutral, or negative will depend on the environmental performance and property rights aspects of the seed varieties. | X | X |
| | ● | ● | ● | This menu item implies focusing on the least efficient farms rather than bringing already high-yielding farms up to nearly perfect standards from a yield perspective. | X | X |
| | ○ | ● | ○ | Whether or not the water and ecosystem impacts are positive, neutral, or negative will depend on the management practices used. | X | X |
| | ● | ● | ● | This strategy is applicable across most farming regions, has particular benefits for sub-Saharan Africa, and can complement strategies that utilize input technologies (e.g., fertilizer micro-dosing). | X | X |
| | ● | ● | ○ | Water impacts will be a function of the watering regime. Some areas often called "degraded land" are not low cost from an environmental perspective (e.g., forests will grow back if left on their own), and therefore should not be considered for restoration into agriculture. | X | X |

Table 1 | **A menu for a sustainable food future (continued)**

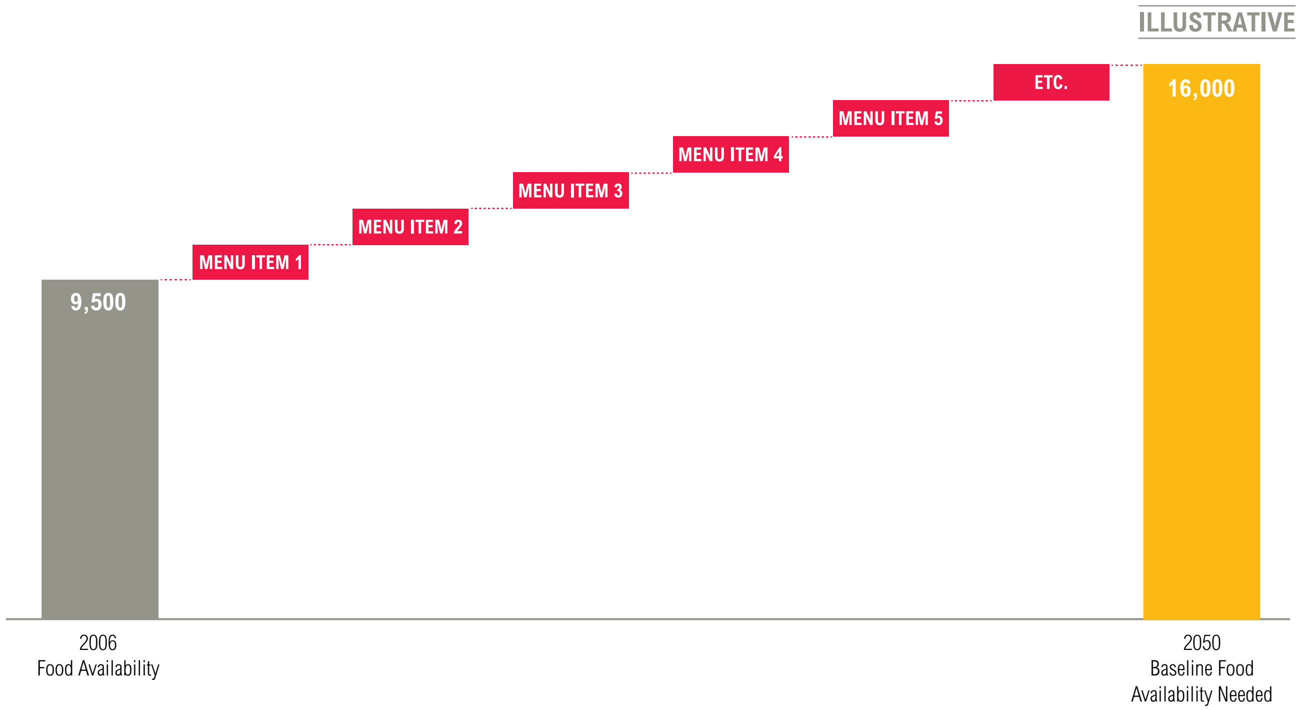
| COURSE | MENU ITEM | DESCRIPTION | PERFORMANCE AGAINST CRITERIA | |
|---|---|---|---|---|
| | | | POVERTY ALLEVIATION | GENDER |
| **Produce more food without land expansion (continued)** | Increase productivity of pasture and grazing lands | Increase yields of milk and meat per hectare on existing pasture and grazing lands through sustainable intensification of grazing management and related practices. | ● | ○ |
| | Reduce then stabilize wild fish catch | In overharvested fisheries, reduce wild fish catch from marine and freshwater systems until fish populations rebound. | ○ | ○ |
| | Increase productivity of aquaculture | Increase aquaculture production while increasing resource (feed, land, water, energy) efficiency. | ● | ● |
| **Reduce emissions and other impacts from other agricultural activities** | Improve the feed efficiency of ruminant livestock | Reduce the amount of greenhouse gas emissions and other pollutants per unit of meat and dairy output via improved livestock breeding, feeds, fodder digestibility, and more. | ● | ○ |
| | Make fertilization more efficient | Reduce overapplication of fertilizer and increase plant absorption of fertilizer. | ● | ○ |
| | Manage rice paddies to reduce emissions | Reduce methane emissions from rice paddies via species selection and improved water, soil, and straw management. | ● | ○ |

*Note:* GHG emissions = greenhouse gas emissions.

● = positive ○ = neutral/it depends ⊗ = negative

| | PERFORMANCE AGAINST CRITERIA | | | COMMENT | ↑ FOOD AVAILABILITY | ↓ GHG EMISSIONS |
|---|---|---|---|---|---|---|
| | ECOSYSTEMS | CLIMATE | WATER | | | |
| | ● | ● | ○ | Water impacts will be a function of how livestock water supplies are managed. | X | X |
| | ● | ○ | ● | Impacts may be negative (e.g., reduced food quantity, lower local income) in the short term for those whose catch is reduced, but positive over the long run as the strategy prevents fishery collapse. | X | |
| | ○ | ● | ○ | Water recycling, type of feed, and other factors will determine whether this strategy's impacts on water and ecosystems are positive or negative. | X | X |
| | ● | ● | ● | Poor livestock quality and inadequate feed leads to more methane emissions per kg of milk or meat because more feed is turned into methane in livestock stomachs and because livestock grow less fast or produce less per kg of feed. | | X |
| | ● | ● | ● | This strategy is of particular relevance to regions in China, India, the United States, and Europe. | | X |
| | ● | ● | ● | Rice is of particular importance given the number of people who depend on it as a basic food crop, the amount of area dedicated to its production, and its sizable contribution to greenhouse gas emissions—10 percent of all global agricultural production emissions. | | X |

Figure 5 | **A menu of solutions is required to sustainably close the food gap (global annual crop production, kcal trillion)***




** Includes all crops intended for direct human consumption, animal feed, industrial uses, seeds, and biofuels*

*Source:* WRI analysis based on Bruinsma (2009) and Alexandratos and Bruinsma (2012).

- **Climate.** The menu should help reduce greenhouse gas emissions from agriculture to levels consistent with stabilizing global atmospheric temperature at no more than 2° Celsius above pre-industrial levels.

- **Water.** The menu should not deplete or pollute aquifers or surface waters.

Given the urgency of achieving the great balancing act, we focus primarily on menu items that could be implemented now or in the near future rather than game-changing but uncertain technological innovations.

Table 1 summarizes our preliminary menu and shows how individual menu items should perform against the criteria. For example, reducing loss and waste would make more food available, could improve the finances of small farmers and others in the food value chain, and should avoid a broad range of environmental impacts associated with food production. In contrast, some approaches to increase food production—such as converting natural forests and savannas into croplands or grazing lands—fail to meet environmental criteria and therefore are not included in the menu.

The menu items for a sustainable food future fit into three courses:

1. Solutions that help to close the food gap by reducing growth in food consumption;
2. Solutions that help to close the food gap by increasing food production on the same agricultural land area; and
3. Solutions that reduce the environmental impact of food production without directly closing the food gap.

To sustainably close the food gap, the world must reduce growth in food consumption, increase food production on the same land area, and reduce agriculture's environmental impact.

For the third, we focus on those that would hold down the greenhouse gas emissions from agricultural production. Measures that address this concern will also tend to reduce other pressures on the environment.

The menu items must work together and not undermine each other. We do not presume that all items are likely to work equally well; their potential is what we explore in this working paper series. No item on the menu can achieve a sustainable food future by itself, and the relevance of menu items will vary between countries and food chains. Finally, the menu only addresses the challenge of sustainable food supply and demand; it does not directly address critical additional dimensions of food security, such as reducing poverty and improving distribution (Box 4).

## BOX 4 | FOOD SECURITY AND SUSTAINABILITY

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

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

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

The sustainability dimension is an oft-overlooked but important pillar, particularly since it underpins many of the others. For instance, crop production depends on supplies of freshwater at appropriate times during the growing season. Soil degradation undermines agricultural productivity. Natural ecosystems provide pollination, wild foods, natural pest controls, and more. Climate change, left unabated, is likely to have dramatic impacts on food production both on average and in particular locations through exceptional droughts, heat waves, and floods.

This WRR working paper series focuses on the interplay of food availability and sustainability. Both touch on the pillars of stability and access by influencing prices. But although assuring availability and sustainability are critical to food security, they are not sufficient. There are many other issues related to income, distribution, nutrient balance, and disaster interventions that are important for food security, but that we do not address in this series.

* FAO (2006a).

** The following definitions are paraphrased from Gross et al. (2000).

*** Richardson (2010), Daily et al. (1998).

Chapter 3

# CLOSING THE FOOD GAP BY HOLDING DOWN THE GROWTH IN CONSUMPTION

The size of the food production challenge depends on the scale of the increase in demand for crops and animal products. Much of that increase results from changes in diets that occur as people become wealthier. In general, a wealthier person consumes more food, wastes more food, and consumes more resource-intensive foods. Our food gap provides a reasonable estimate of "business as usual" growth in consumption, but such levels of growth are not inevitable. In this chapter, we explore menu items to reduce consumption growth that would have ancillary benefits for social and economic development.

## MENU ITEM | Reduce Food Loss and Waste

Reducing food loss and waste would increase food supplies and provide significant economic and environmental benefits. “Loss and waste” refers to the edible parts of plants and animals produced for human consumption but not ultimately consumed by people.[30] “Loss” refers to food that spills, spoils, incurs an abnormal reduction in quality such as bruising or wilting, or otherwise gets lost before it reaches the consumer.[31] “Waste” refers to food that is of good quality and fit for consumption, but is not consumed because it is discarded after it reaches consumers—either before or after it spoils.[32] Food loss and waste occurs along the entire food value chain (Figure 6) and represents waste of labor, investment, water, land, material, and energy—and unnecessary greenhouse gas emissions.

FAO (2011) estimates that roughly 32 percent of all food produced in the world in 2009 was lost or wasted.[33] This estimate is based on weight. However, food types vary widely in their water and caloric content per kilogram, so weight does not reflect the energy in food products that could have been consumed by people. Using the FAO Food Balance Sheets,[34] we converted FAO’s waste estimates into calories. Measured this way, global food loss and waste equates to approximately 24 percent of all food produced—a lower but still substantial amount. Essentially, people fail to consume one quarter of all calories produced for them.

### Where does food loss and waste occur?

FAO estimates shed light on where loss and waste occur.[35]

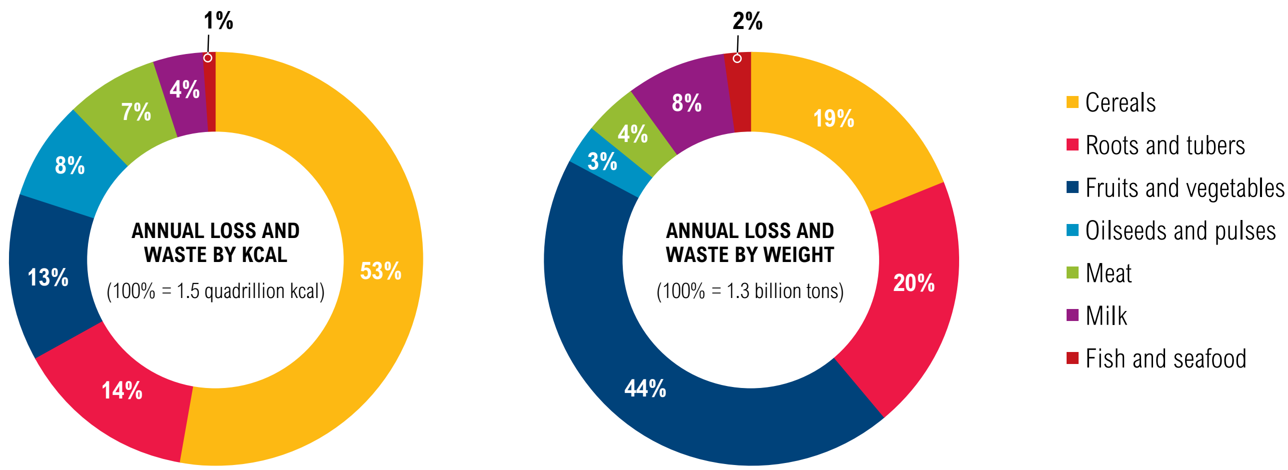
By commodity type and measured by calories, cereals are the largest source of food loss and waste, at slightly more than half (Figure 7). At 7 percent, meat is a relatively small share. However, not all loss and waste is created equal. The relatively large environmental impacts of meat per calorie in greenhouse gas emissions, land, and water[36] suggest that reducing meat loss and waste also merits attention.

Figure 6 | **Food is lost or wasted along the entire value chain**

| Production | Handling and Storage | Processing and Packaging | Distribution and Market | Consumption |
|---|---|---|---|---|
| During or immediately after harvesting on the farm | After produce leaves the farm for handling, storage, and transport | During industrial or domestic processing and/or packaging | During distribution to markets, including losses at wholesale and retail markets | Losses in the home or business of the consumer, including restaurants and caterers |

*Source:* WRI analysis based on FAO (2011d).

Figure 7 | **Cereals make up the most loss and waste of calories but fruits and vegetables are the biggest category by weight**



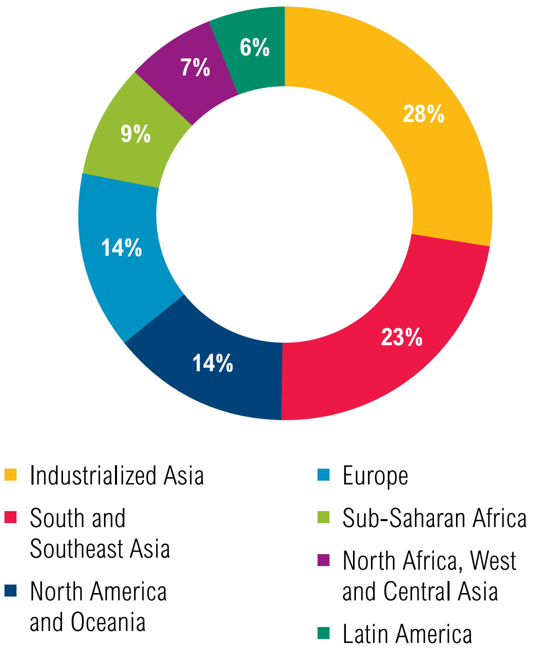

*Source:* WRI analysis based on FAO (2011d).

Regionally, about 56 percent of total food loss and waste occurs in the industrialized world—North America, Oceania, Europe, and the industrialized Asian nations of China, Japan, and South Korea—while non-industrial countries account for 44 percent of the loss (Figure 8). By stage in the value chain, 24 percent of global food loss and waste occurs at production, another 24 percent during handling and storage, and 35 percent at consumption.

The stage in the value chain at which most food loss and waste occurs varies between developed and developing regions (Figures 9 and 10). More than half of the food loss and waste in North America, Oceania, and Europe occurs at the consumption stage. In contrast, in South and Southeast Asia and sub-Saharan Africa, two-thirds to three-quarters of loss and waste occurs in the production and storage stages. This distribution suggests that efforts to reduce food loss and waste should focus on stages “close to the farm” in most developing regions and focus on stages “close to the fork” in developed regions. However, the losses from the production

Nearly a quarter of all food calories produced in 2009 were lost or wasted. Cutting food loss and waste in half by 2050 could close 20 percent of the food gap.

Figure 8 | **More than half of the world's food loss and waste occurs in Asia (100% = 1.5 quadrillion kcal)**



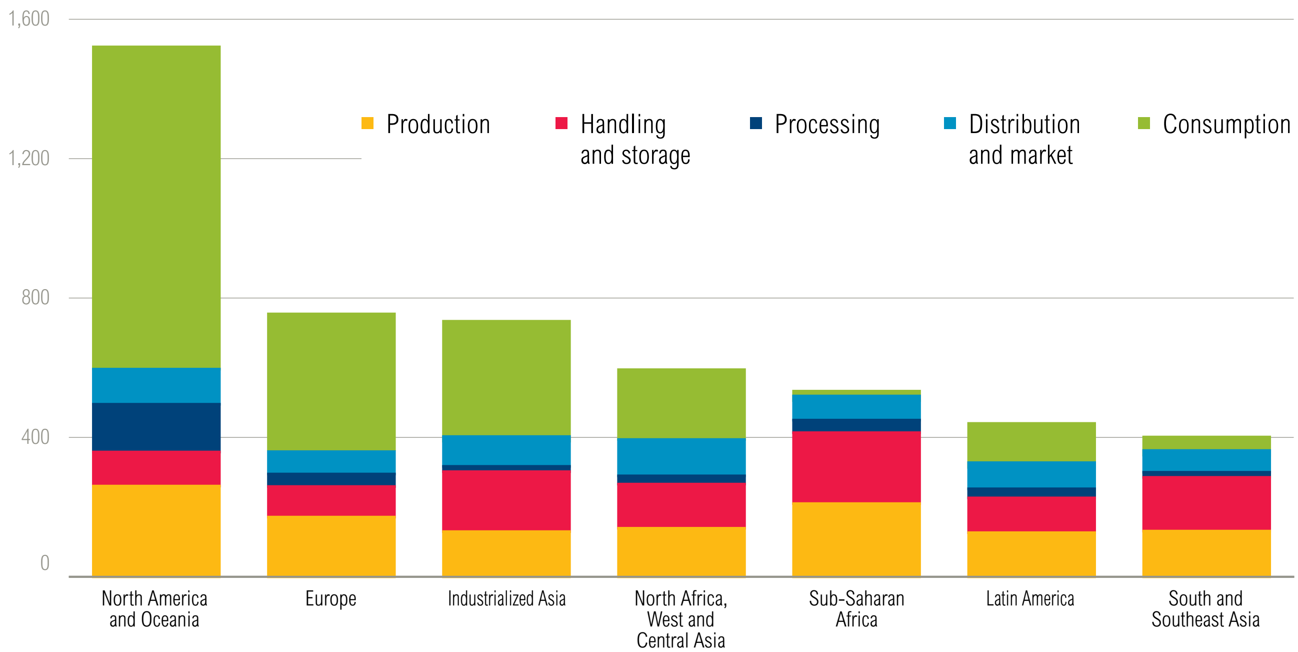

*Note:* Numbers may not sum to 100 due to rounding.

*Source:* WRI analysis based on FAO (2011d).

through marketing stages in the richer regions per capita remain comparable to total per capita losses in sub-Saharan Africa (Figure 9), so it makes sense to pursue savings even in the earlier parts of the food chain in these richer regions as well.

The total share of food lost or wasted ranges from 15 percent to 25 percent across most regions (Figure 10). The exception is North America and Oceania, where loss and waste is approximately 42 percent of all available food—a remarkable 1,520 calories per person per day.

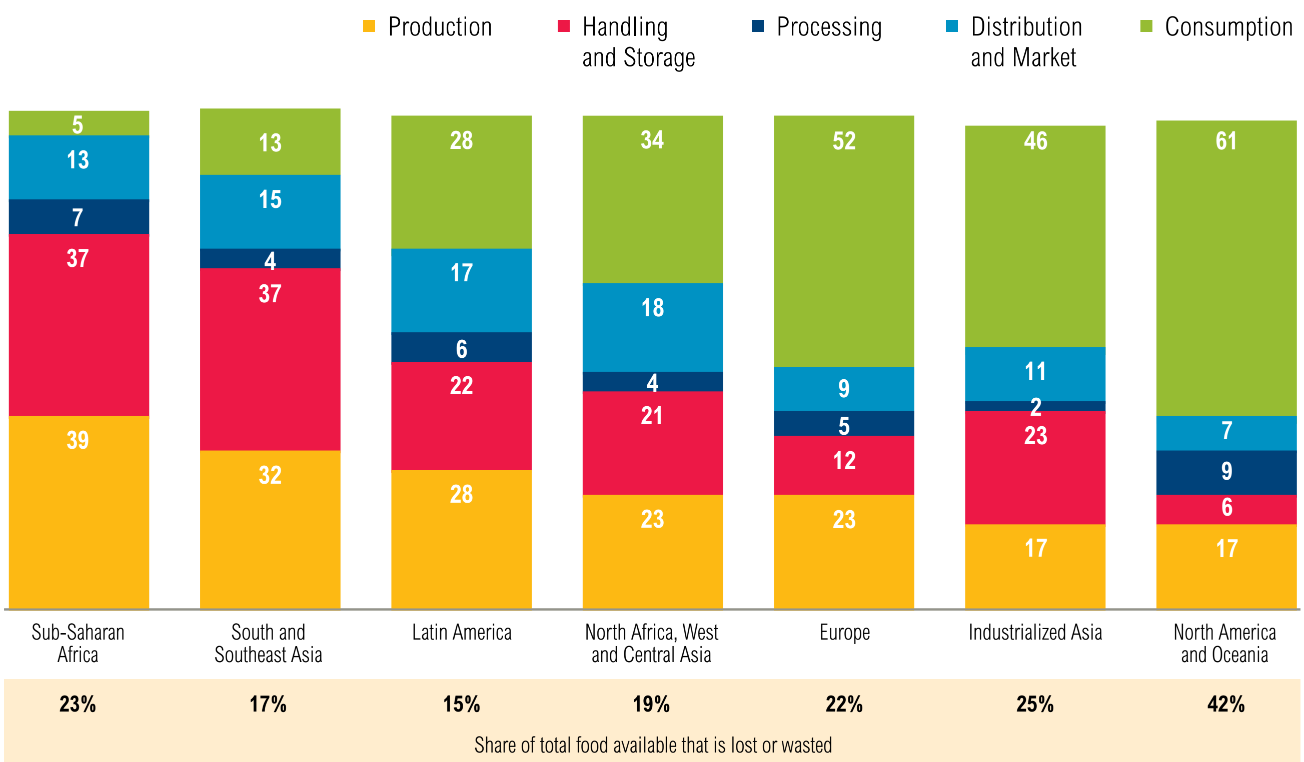
Figure 9 | **North America and Oceania have the highest per capita food loss and waste, due to high consumption waste (kcal/capita/day of loss/waste)**




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

*Source:* WRI analysis based on FAO (2011d).

Figure 10 | **As regions get richer, the percentage of production and storage losses declines and that of consumer waste increases (percent of kcal lost or wasted)**




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

*Source:* WRI analysis based on FAO (2011d).

## What approaches can reduce losses and waste?

Figure 11 outlines a range of approaches for reducing food loss and waste along the value chain. We offer a few additional observations:

- At the production stage, strict aesthetic standards appear to motivate farmers to not harvest a high level of tubers and vegetables.

- At the handling and storage stage, simple, low-cost food storage systems can provide solutions for low-income farmers. For example, researchers at Purdue University invented a three-layer, pest-resistant polyethylene bag capable of storing 100 kilograms of cowpeas—an important crop in West Africa. The bag suffocates insects that otherwise would prey on the cowpeas, and also appears to work with chickpeas, soybeans, and some grains.[37] Because products can double in value in West Africa within four months of harvest, the cost of $1 per bag seems cost effective. Over the longer term in low-income countries, any factors that help to maintain or transport food more efficiently will reduce losses, including better roads, storage facilities, electricity, refrigeration, and food processing in general.

- The Waste and Resources Action Program (WRAP), a public-private partnership in the United Kingdom, has worked closely with retail food chains and has discovered surprising opportunities to improve inventory control systems. It has also helped national grocery chains to reduce food waste by tweaking packaging to allow food to remain fresh longer.

- In the United Kingdom, a collaborative public relations campaign by WRAP and food retailers ("Love Food, Hate Waste") has helped reduce post-consumer waste by providing practical tips on food storage and how to avoid confusing "sell by" and "use by" dates. Retailers have adjusted promotions from "buy-one-get-one-free" to "buy-one-get-one-later" and changed package labeling so that households will not confuse sell-by dates with consume-by dates. Household food waste in the United Kingdom declined by 13 percent from 2007 to 2010.

Figure 11 | **A range of approaches exists for reducing food loss and waste along the value chain (not exhaustive)**

| Production | Handling and Storage | Processing and Packaging | Distribution and Market | Consumption |
|---|---|---|---|---|
| Facilitate donation of unmarketable crops | Improve access to low-cost handling and storage technologies (e.g., evaporative coolers, storage bags, metal silos, crates) | Re-engineer manufacturing processes | Facilitate increased donation of unsold goods | Facilitate increased donation of unsold goods from restaurants and caterers |
| Improve availability of agricultural extension services | Improve ethylene and microbial management of food in storage | Improve supply chain management | Change food date labeling practices | Conduct consumer education campaigns |
| Improve market access | Introduce low-carbon refrigeration | Improve packaging to keep food fresher for longer | Change in-store promotions | Reduce portion sizes |
| Improve harvesting techniques | Improve infrastructure (e.g., roads) | | Provide guidance on food storage and preparation to consumers<br>Improve inventory systems | Ensure home economics taught in schools, colleges and communities |

Across the value chain, progress will depend on better measurement and monitoring. If "what gets measured gets managed," then the current high rate of food loss and waste makes sense because systematic data on food loss and waste is sparse. A standardized protocol for auditing food loss and waste—akin to the Greenhouse Gas Protocol developed by WRI, the World Business Council for Sustainable Development, and others for assessing greenhouse gas emissions and mitigation opportunities[38]—could help countries and companies measure and reduce their rates of food loss and waste.

### What is the potential to reduce losses and waste?

In 2012, the European Commission set a target of reducing food loss and waste by 50 percent by 2020 throughout Europe.[39] Cutting food loss and waste in half by 2050 globally would close roughly 20 percent of the gap between calories available today and those needed by 2050 (Figure 5).[40] The 20 percent figure suggests that reducing food loss and waste might be an important menu item. Efforts to reduce food loss and waste are particularly worthwhile because reducing waste at the consumer stage not only helps to close the food gap, but also to save energy and other resources devoted to food across the distribution chain. Some analyses have suggested that wasted energy and resources can double the amount of greenhouse gas emissions at the production stage in developed countries.[41]

Yet meeting a global 50 percent reduction goal by 2050 is daunting. Even if developing countries reduce losses at the production and storage stages through better harvesting technology and storage facilities, experience elsewhere suggests that food waste at the consumer end could easily grow and offset these gains as their middle classes grow. And changing consumer behavior in developed countries will be difficult as long as food remains relatively cheap. Still, the potential scale and multiple benefits of reducing food loss and waste make the effort worthwhile.

## Shift to Healthier Diets

Food projections implicitly assume diets that are unhealthy for many people. Overconsumption of calories, animal products in general, and red meat in particular correlate with a range of chronic human health problems, including high blood pressure, diabetes, coronary heart disease, and several forms of cancer.[42] What are the prospects for improving diets to help close the food gap?

### MENU ITEM | Reduce obesity

One possible way to reduce total food consumption would be to curb obesity. The World Health Organization (WHO) estimates that 1.4 billion people are overweight (a body mass index of more than 25) and 500 million of these people are obese (a body mass index of more than 30).[43] The number of overweight people actually exceeds the 840 million who are undernourished.[44] Obesity, of course, has human health and financial costs. According to one OECD study, obese people on average incur 25 percent higher healthcare costs than people of normal weight.[45]

Both the absolute number and the share of people who are obese are likely to grow. In poor countries, the obese are typically wealthy, and rates of obesity typically grow with a country's wealth until annual incomes reach roughly $5,000 per person.[46] In China, obesity rates tripled from 1991 to 2006, and in Brazil obesity rates tripled among men and almost doubled among women from 1973 to 2003.[47] As more countries move toward these income levels, obesity rates are likely to grow. Obesity can even grow in countries that continue to have high levels of child stunting from insufficient food. In Egypt, South Africa, and Mexico, adult obesity rates of more than 30 percent coexist with child stunting rates of 30 percent, 23 percent, and 15 percent, respectively.[48] Once countries reach a reasonable level of wealth, factors other than increasing wealth appear to lead to rises in obesity. In 2008, for example, only 7 percent of Japanese women were obese, compared with 35 percent of U.S. women.[49] Yet, obesity is also generally rising in developed countries and will probably continue to grow absent changes in public policy or consumer behavior.[50]

There have been many efforts to explain the rise in obesity, but ultimately most experts identify the key drivers as an increased and more convenient supply of cheap and energy-dense foods, and persuasive marketing.[51] This observation has led some advocates to suggest that the world would be better off allowing the cost of food production to rise, at least in developed countries.[52] Some evidence indicates that taxes on unhealthy foods at the retail level can reduce demand for those foods,[53] and that such taxes in wealthy countries would not affect people in poorer countries. But any strategy that relies on limiting production to generate higher wholesale crop prices would lead to higher crop prices worldwide, and the people who already eat too little are those most likely to reduce consumption in response to higher prices.[54]

Can combating obesity contribute meaningfully to closing the gap between global food needs and supply in 2050? To answer that question, we performed a hypothetical calculation of a world that eliminates obesity and cuts the number of people merely overweight in half. Our calculation first assumes that both the number of people in the world who are obese and those merely overweight will increase by 50 percent from 2008 levels to 2050. It assumes that each obese person on average consumes 500 more calories per day than a person eating at recommended levels and that the merely overweight consume half that many additional calories.[55] The calculation also assumes that eating fewer calories would save an additional 24 percent of calories otherwise lost or wasted. The result is 261 trillion kcal, an amount that would close about 6 percent of the food consumption calorie gap between 2006 and 2050 (Figure 5).[56]

Although 6 percent would be a step in the right direction, this result assumes that no one in the world is obese in 2050—an unlikely scenario. Combating obesity is critically important for improving human health, but this strategy is likely to contribute only slightly to closing the food gap while reducing environmental impacts.

## MENU ITEM | Reduce excessive demand for animal products

A second diet shift would reduce the expected growth in consumption of animal products by reducing the consumption of people who eat too many. “Animal products” include meat, milk, fish, and eggs.

Meat has certain nutritional benefits. It can provide a concentrated source of some vitamins and minerals that are particularly valuable to young children in developing countries whose diet is otherwise poor.[57] Studies have demonstrated large benefits from modest increases in meat in the diets of the poor in sub-Saharan Africa.[58]

Livestock production also generates roughly half of all agricultural income worldwide and provides


important benefits for large numbers of small and poor farmers. Outside of Latin America, livestock are also fairly broadly distributed across farm sizes. In one survey of poorer countries, nearly two-thirds of all rural households kept at least some livestock. Another survey of 13 poor countries in Asia, Latin America, and Africa found that livestock provided from 10–20 percent of the average income of rural households in each of the lowest three of five income categories.[59]

However, the realistic issue is not whether the world should continue to produce and consume meat and milk—as it surely will—but by how much that consumption should grow between now and 2050. In much of the world, consumption of meat and other livestock products already exceeds healthy levels. FAO recommends an average daily consumption of 58 grams of protein per person per day, a level that already builds in an ample margin of safety to assure enough protein for all.[60] In developed countries, spurred by large consumption of animal products, the average person consumes 102 grams of protein per day. Of all the world's major regions, only in sub-Saharan Africa do people on average consume less protein than they need.[61] In developed countries, health officials have long recommended reductions in meat consumption, citing links to cancer and heart disease.[62]

Even so, meat consumption is likely to rise along with rising income levels.[63] Based on projected income and population growth, FAO estimates a 70 percent increase in total caloric consumption of animal products by 2050. That increase rises to 82 percent with our adjustments for higher population growth and to assure adequate food is available in all regions.

Given the underlying inefficiency of meat production, this projected growth has a number of implications for ecosystems, climate, and water.[64] Measures of efficiency of animal products compare the quantities of "feed in" versus the "food out." Although the inefficiency of meat production is broadly recognized, the numbers cited vary and can understate or overstate the inefficiency.

When assessing the efficiency of meat production, the most important question is whether the efficiency measure should count only "human-edible" feeds (e.g., soybeans, maize), or should also include "human-inedible" feeds (e.g., grasses). Both critics and defenders of meat production often focus only on human-edible feeds even if they differ in other parts of their analyses.[65] Doing so excludes feed from crop residues, food processing wastes, and above all grasses, whether hayed or grazed. Yet these human-inedible products constitute roughly 80 percent of all livestock feed as measured by digestible energy, and an even greater share when measured by weight.[66]

The general argument for only including human-edible feeds is that they are the only animal feeds


that compete directly with human food supplies, and that without meat production, these inedible feeds would go to waste. This approach means that if an animal eats primarily grasses, hays, and other human-inedible feeds, the efficiency measure may even be more than 100 percent because grass-based livestock can generate more human-edible food than the human-edible feed the livestock take in.[67] Even for beef raised in feedlots, this approach leads to higher efficiencies because it excludes all the grasses eaten by mother cows and their calves before calves are moved from pastures to feedlots.

Counting only human-edible feeds has merits for some purposes. If people consumed no animal products at all, many native grazing lands would go unused and many residues and wastes would be thrown out or used for purposes of limited economic value. And while many grazing lands were originally wooded and are wet enough to grow crops, these lands generally are less suitable for crop production, because of slope, poor soils, or even frequent flooding. If an analyst's sole focus is how to maximize human food supply—and whether to eat some meat or no meat at all—the focus on only human-edible feeds has significant merit.

Yet the present analysis focuses both on meeting food needs and avoiding the ecosystem destruction and carbon dioxide emissions from conversion of forests and savannas. Furthermore, the realistic question the world faces is not the merits of eliminating or halting growth in the consumption of animal products, but rather the merits of holding down the growth in animal product consumption below our baseline projection of 82 percent. Merely reducing growth of meat consumption between now and 2050 will not cause native grazing lands, residues, and food wastes to fall into disuse—they are more or less fully used today and will remain so. Instead, holding down the growth in meat consumption will help to reduce the need to produce more animal feed of all kinds, including both human-edible crops and additional pasture and hay. The current trend is for growth in pasture land to come from clearing forests and savannas.

Put simply, whether a hectare of forest is converted to soybeans or pasture, it is still being converted for animal feed. There is no reason to count the soybeans and not the grass just because people could in theory eat the soybeans—as clearing forests for either purpose releases carbon and degrades ecosystems.[68] Even if, in an extreme case, meat consumption so declined that the world needed less total pasture area than it uses today, some forests already cleared for livestock could be used to grow crops or could revert to forests, with large climate and ecosystem benefits.

In the language of opportunity costs, if people abandoned meat and milk altogether, they would give up many feed supplies with limited opportunity costs in food supply or carbon storage. Yet in a world where demand for animal products is likely to increase by more than 80 percent by 2050, the additional (or "marginal") sources of feed are likely to come with high opportunity costs in the alternative uses of land either to grow crops or to store carbon and provide other ecosystem services. A proper efficiency measure to gauge the merits of holding down meat consumption—for both people and the planet—must therefore count all feeds.

A proper efficiency measure must also count all stages of production (including the feed consumed by mothers, by grazing calves, and by animals that die), and use equivalent units to measure "feed in" and "food out." Many efficiency comparisons focus only on the feedlot stage of production. And many—including the "feed conversion ratio" often used by the livestock industry—show the weight of meat out versus the weight of feed in, which improperly compares the weight of a relatively wet output (meat) to the weight of a relatively dry input (feed grains). Focusing only on feedlot beef and using weight measures, even critics of meat will often quote efficiency figures of 15 or so percent for beef, which is far higher than our calculations.[69]

Although no comparison is perfect, the best way to measure conversion efficiencies across all livestock products is to count all feed and compare "energy out" versus "energy in," and "protein out" versus "protein in." This approach requires estimates of the use by animals of grasses, hays, and residues, which are typically unreported. One excellent analysis that estimated these sources and counted efficiencies these ways is by Wirsenius et al. (2010), and it may be the only published analysis that provides global estimates for all animals. The conclusions of Wirsenius et al. (2010) are reproduced in

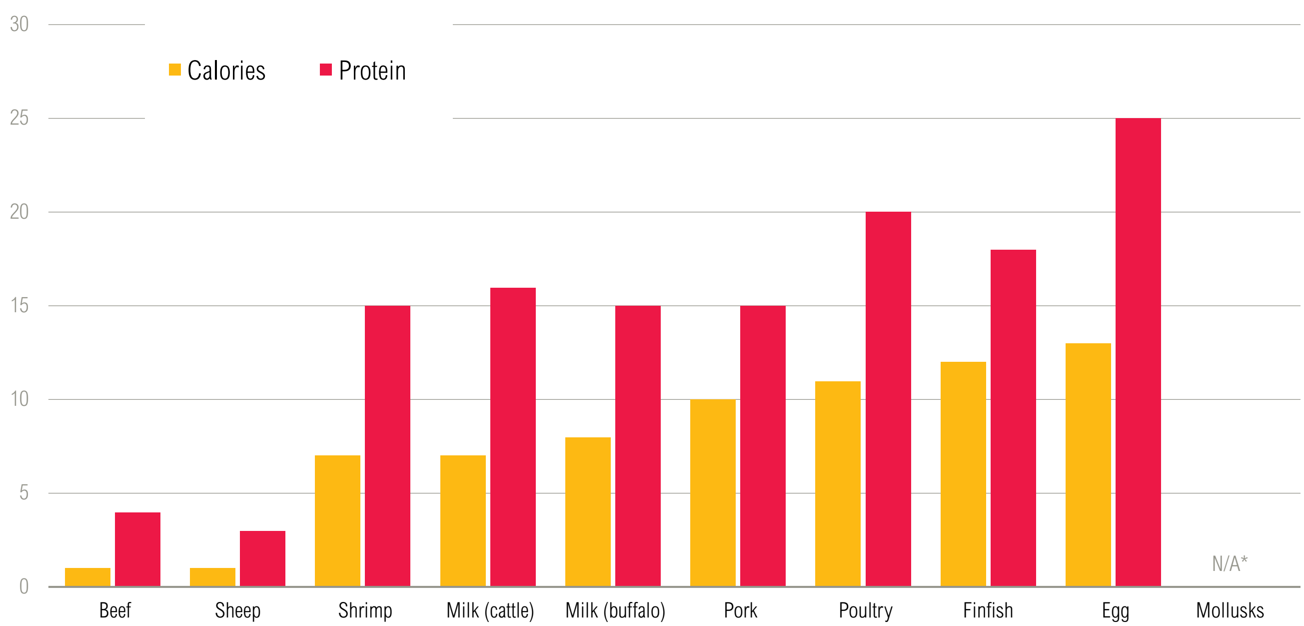
Figure 12. As a global average, energy conversion efficiencies range from 13 percent for eggs to 1 percent for beef, and protein efficiencies range from 25 percent for eggs to 3–4 percent for sheep and beef.[70]

In Figure 12, with the help of the paper's lead author, we adjusted the numbers by excluding bones from edible food in order to provide reasonable comparisons between meat, milk, and fish and also to provide figures that match how the FAO counts "edible" food calories. Excluding bones from the measures of "food out" modestly lowers the efficiencies as typically presented, and as shown in Wirsenius et al. (2010). Yet these calculations are broadly consistent with other analyses that count both human-edible and human-inedible feeds.[71]

Papers using global models generally do account for all sources of feed, including grasses. Not surprisingly, they have found that large reductions in animal products could more than offset the land use demands from the growth in food demand to 2050. For example, one paper by Dutch researchers using the IMAGE model examined reductions in beef by 52 percent, poultry by 44 percent, and pork by 35 percent compared to projected levels in 2050. It found these changes would actually free enough existing agricultural land to allow substantial reforestation, which could help slow climate change.[72] Regardless of the details, the basic conclusion flows from several simple facts: one-quarter to one-third of all human crops are used for livestock feed,[73] and more than twice as many hectares of land are used for grazing by livestock as are used for all crops combined.[74] Reductions in meat consumption of this size, however, are probably unrealistic.

In order to accurately estimate land use savings from reducing meat consumption, it is also important to use realistic alternative diets. Yet many studies

Figure 12 | **Beef is a far less efficient source of calories and protein than milk and other meats (percent or "units of edible output per 100 units of feed input")**




** Mollusks independently produce calories and protein without any human-managed inputs.*

*Note:* "Edible output" refers to the calorie and protein content of bone-free carcass.

*Sources for terrestrial animal products:* Wirsenius et al. (2010) (extra unpublished tables), Wirsenius (2000). *Sources for finfish and shrimp:* WRI analysis based on USDA (2013), NRC (2011), Tacon and Metian (2008), Wirsenius (2000), and FAO (1989).

fail to do so and therefore overestimate the gains from reducing meat consumption. For example, some studies assume that if people ate less meat and milk, they would replace the animal products in their diets with the maize, wheat, and soybeans otherwise fed to livestock, resulting in enormous land use savings.[75] In reality, people eating less meat would generally substitute more beans, fruits, and vegetables.[76] These alternative crops tend to produce fewer calories per hectare than animal feed crops,[77] so shifting to these crops would generate smaller, but still highly significant, land use savings. Stehfest et al. (2009) did not make this full mistake, and instead assumed that meat would be replaced by beans (or other pulses). But this study also assumed enormous replacement of meat with fish at levels of fish production that would not be feasible.[78]

One of the very few studies that compare baseline levels of meat consumption with realistic alternative diets found that a U.S. diet based on animal products required three to four times as much land—and two to four times as much nitrogen fertilizer—as a realistic U.S. vegetarian alternative.[79] This estimate implies a large and important gain in efficiency from a vegetarian diet, but not as large as studies using unrealistic human diets of animal feeds have found.

Overall, the evidence is strong that holding down the growth in animal products could make it far easier both to meet nutritional needs and to hold down land use demands. But is it possible to shift diet preferences on a large scale?

The sheer scope of meat production in many countries suggests that it is. By 2050, FAO projects that roughly 3 billion people in the United States, Canada, Europe, Russia, Brazil, and China will consume more than 750 kcal per person per day of livestock products. Yet the variation in current levels of animal product consumption between wealthy countries suggests that such growth is not inevitable. For example, meat consumption per person in the United Kingdom is one-third less than in the United States.[80]

Even in the United States, meat consumption fell 9 percent from 2007 through 2012.[81] The early part of the decline was probably at least partly due to the economic recession of 2007–09, but declines in meat consumption have continued each year even as the economy has recovered. (Rising meat prices due to rising grain costs may be another factor.) Although evidence on the efficacy of public information efforts is limited, a broad Finnish program led to substantial dietary changes over two decades and helped reduce heart disease. A few school programs aimed at targeted populations have also had some success in altering diets.[82]

Whether efforts targeting dietary changes can hold down global meat consumption below FAO projections is a separate question. Most of the projected 82 percent increase in meat and milk results from population gains, not increases in consumption per person. FAO projects that per capita meat and milk consumption will only increase by 22.5 percent, rising to a global average of 506 kcal per person per day in 2050 (Table 2). However, this global average figure is at least a third less than the 2006 levels of consumption in nearly all wealthier countries. The global average remains relatively low because FAO projects that roughly 2 billion people in sub-Saharan Africa in 2050 will be consuming only 185 kcal of animal products per day, and that 1.6 billion people in India will be consuming on average only 357 kcal. The African figure is the equivalent of one cup of whole milk a day. The FAO estimate of "only" an 82 percent rise in meat consumption (with our population adjustment) is therefore arguably conservative. Studies that assume meat consumption will rise in ways that match the global patterns for increases in income project larger growth than FAO.[83]

In short, curtailing meat consumption by those wealthy who eat more than they need appears to be a feasible and important strategy for sustainably feeding the planet. Yet these reductions may be a menu item just to keep the gap from growing more than FAO projects. Some reductions in meat and milk consumption by those relatively wealthy are probably necessary just to hold consumption to the FAO projections if the world's poor are also to eat closer to their fair share.

### MENU ITEM | Shift to a more efficient mix of animal products

An alternative to reducing meat consumption altogether would be to shift consumption patterns to a more efficient mix of animal products.

Table 2 | **Although FAO estimates per capita consumption of milk and meat will increase by 23 percent by 2050, this estimate presumes that more than 4 billion people will continue to consume relatively little**

| REGION | LIVESTOCK (KCAL/PERSON/DAY) | | | BEEF AND MUTTON (KCAL/PERSON/DAY) | | |
|---|---|---|---|---|---|---|
| | 2006 | 2050 | % CHANGE | 2006 | 2050 | % CHANGE |
| European Union | 864 | 925 | 7% | 80 | 75 | -6% |
| Canada & USA | 907 | 887 | -2% | 117 | 95 | -19% |
| China | 561 | 820 | 46% | 41 | 89 | 116% |
| Brazil | 606 | 803 | 33% | 151 | 173 | 15% |
| Former Soviet Union | 601 | 768 | 28% | 118 | 156 | 32% |
| Other OECD | 529 | 674 | 27% | 64 | 84 | 31% |
| Latin America (ex. Brazil) | 475 | 628 | 32% | 59 | 86 | 45% |
| Middle East and North Africa | 303 | 416 | 37% | 59 | 86 | 45% |
| Asia (ex. China, India) | 233 | 400 | 72% | 24 | 43 | 79% |
| India | 184 | 357 | 94% | 8 | 19 | 138% |
| Sub-Saharan Africa | 144 | 185 | 29% | 41 | 51 | 26% |
| **World** | **413** | **506** | **23%** | **50** | **65** | **30%** |

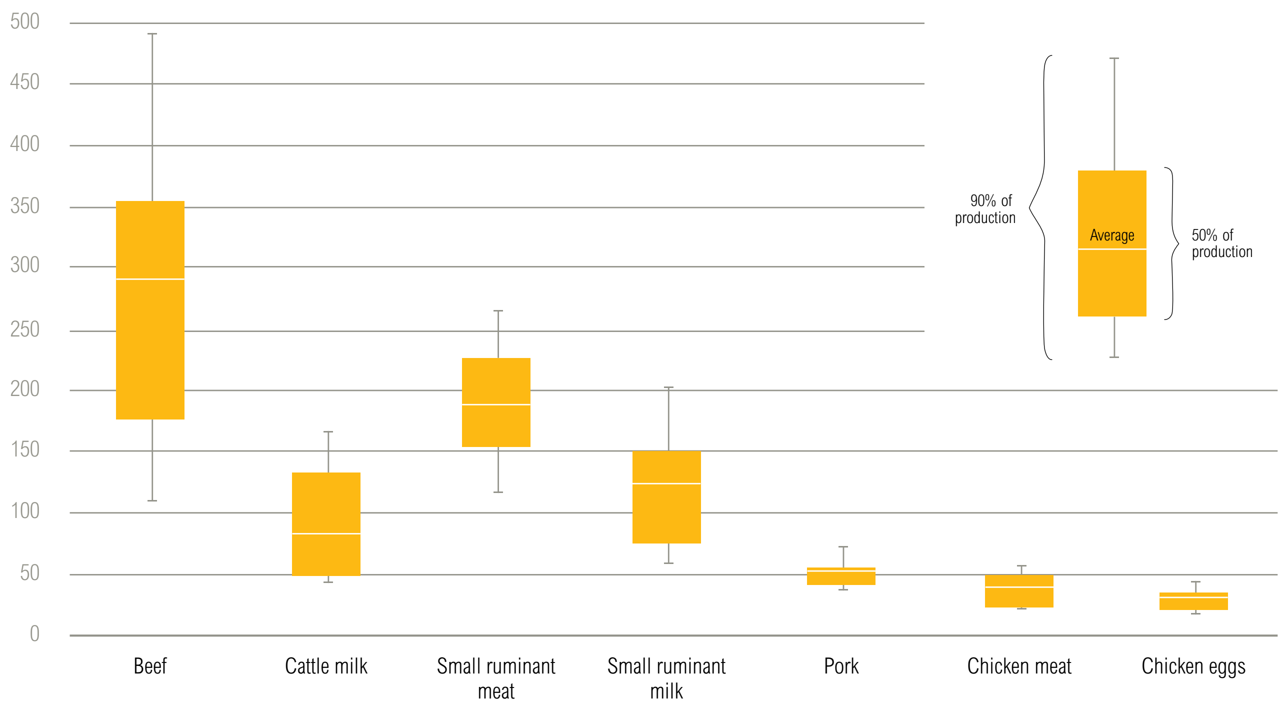
*Source:* WRI analysis based on Alexandratos and Bruinsma (2012).

Such a shift would essentially entail reducing the overconsumption of beef and replacing some of the projected growth in beef consumption with other animal products. Using our adjustments to FAO's projections, beef consumption is expected to rise 92 percent by 2050. This high consumption of beef would have both high health impacts and high environmental impacts.

As Figure 12 shows, beef is particularly inefficient. According to Wirsenius et al. (2010), edible beef ultimately provides people only about 1 percent of the gross energy and 4 percent of the protein fed to cattle.[84] Even in North America, where farmers raise cattle most efficiently, the efficiencies estimated by Wirsenius rise to only 2.5 percent for gross energy and 6 percent for protein.[85] By contrast, poultry globally convert around 11 percent of gross energy and 20 percent of protein to edible flesh. Finfish convert about 12 percent of calories and 18 percent of protein inputs into edible flesh.[86] As a result, beef and other ruminant meats require several times more units of land per unit of meat output than other forms of animal-based foods.

Wirsenius et al. (2010) estimated that shifting just 20 percent of the projected consumption of beef and other forms of ruminant meat in 2030 into poultry and pork would cause little increase in demand for crops for feed, such as maize and soybeans. Although pigs and chicken rely heavily on crop-based feeds, beef production uses enough crop-based feed with lower efficiency that a shift to pork and chicken would not significantly increase the total use of crops for feed. Yet this shift would result in large savings in the quantity of grasses fed to livestock, whether cultivated or in pastures. The result would be a decline by 15 percent in total use of all animal feeds worldwide, including a 20 percent decline in demand for grass from permanent pasture. That decline would free up hundreds of millions of hectares compared to business as usual.[87]

Figure 13 | **Beef production generates 6 times more greenhouse gas emissions per unit of protein than pork, chicken, and egg production (kilograms of $CO_2$e per kilogram of protein)**




*Source:* Gerber et al. (2013).

Beef also contributes more greenhouse gas emissions per unit of output relative to other sources of meat. This difference results in part from the feeding inefficiency of beef and in part because cattle generate methane, a powerful global warming gas, through the digestion of forage in their stomachs—a process known as "enteric fermentation." They also pass a far higher percentage of the nitrogen they consume into their wastes than other livestock, which leads to more emissions of nitrous oxide. Overall, cattle and other ruminants are responsible for the majority of the combined emissions of methane and nitrous oxide emitted by agriculture, which makes them responsible for about 6 percent of all human greenhouse gas emissions, even without counting their demands for land.[88]

Even in intensive feeding systems, beef production generates two to four times the greenhouse gas emissions of other livestock products per unit of protein, according to a comparison of various "life-cycle" analyses that left out land use change.[89] (Intensive systems also present a range of other challenges due to concentrated waste, reliance on antibiotics and animal welfare.) On a global basis, a recent analysis by FAO found that beef production overall causes roughly six times more greenhouse gas emissions per kilogram of protein than pork, chicken, or egg production (Figure 13).[90]

The potential gains from shifting diets away from beef have typically been underappreciated because of the common convention discussed above of ignoring human-inedible feeds. Even a 2011 FAO report encourages a shift from edible crop feeds to pasture.[91] Yet the growth in demand for pasture generally leads to conversion of tropical forests and savannas, and ignoring these sources of feed implies ignoring the associated environmental costs. When such feeds are counted, production of beef and other ruminant meats—which overwhelmingly rely on such feeds—consumes more than half of all animal feed calories globally (Figure 14), yet contributes just one-eighth of all animal product calories in human diets (Table 2).

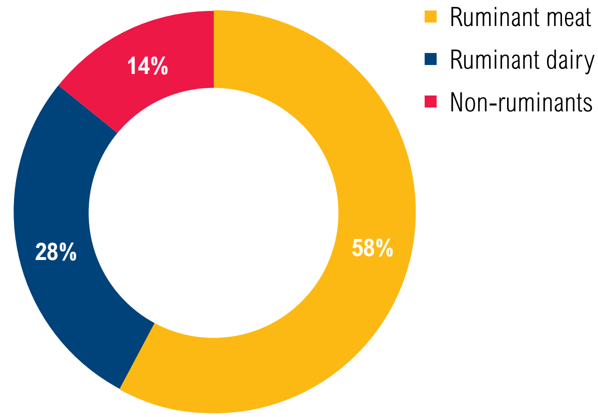
A 20 percent shift in beef consumption, as analyzed in Wirsenius et al. (2010), appears to be a realistic goal. In both the United States and Europe, per capita beef consumption has dropped by roughly one-third from peak levels.[92] The drivers of this change are probably a combination of health concerns and decreasing relative costs of favored cuts of poultry and pork. A boneless chicken breast, once a luxury item, is now cheap enough in the United States to be part of fast-food sandwiches. And there seems to be ample potential for beef consumption to decline below FAO projections for 2050. In the United States, per capita consumption has only returned roughly to 1960 levels, when Americans were already over-consuming beef from a health standpoint.

There also seems to be ample potential to reduce excessive beef consumption globally in 2050 based on FAO projections. By 2050, FAO projects that on a per capita basis, most of the world's people will consume even more beef than Europeans did in 2006 (Table 2). By that year, FAO projects that the Chinese will eat as much beef on average as Americans, and that Latin Americans on average will eat 20 percent more beef than North Americans. Beef has become a cultural staple in Latin America because abundant grazing land has made it relatively cheap. Nevertheless, Latin Americans have begun to adopt modern chicken and pork production. It is plausible that a combination of health concerns, increased availability of other livestock products, and public campaigns could help reduce consumption of beef in Latin America and reduce growth in beef consumption in China.

Mixing more soy-based products into minced meat such as hamburgers provides another promising strategy. Because half of beef eaten in the United States is eaten minced,[93] substituting 20 percent of mixed beef with some soy-based product would reduce beef consumption in the United States by 10 percent.

Holding down the rise in beef consumption by those who over-consume it does not mean eliminating beef or even reducing present production levels. Eliminating beef from the human diet would have many negative implications. A world with no beef consumption would eliminate the livelihoods of pastoralists and would not make full use of the productive capacity of native grazing lands and many

Figure 14 | **Ruminant meat and dairy consume a majority of the world's total animal feed—overwhelmingly grass—but provide only 1/8 of milk and meat calories (100% = 6,705 million tons of dry matter per year, 2010)**




*Source:* Wirsenius et al. (2010).

waste products. Traditional pastoralists, in general, use their dry, native grazing lands with great efficiency, and they manage only a small fraction of the world's cattle and other ruminants. Some beef consumption is also an offshoot of dairy production, which is reasonably efficient. There are also many opportunities for increasing the efficiency and income-generating potential of integrated crop and livestock production by small farmers. Such efforts have benefits for crop production as well. A later section discusses the opportunities to increase the efficiency of beef production, which is an equally important menu item for a sustainable food future.

The 20 percent shift away from ruminants toward poultry and pork analyzed by Wirsenius et al. (2010) would still leave total beef consumption in 2050 roughly 54 percent higher than in 2006. Yet doing so would save enormous areas of land relative to business as usual.

## MENU ITEM | Help all Regions in Their Efforts to Achieve Replacement Level Fertility

If every region in the world achieved replacement level fertility by 2050, projected food demand would grow less than our baseline estimate of 69 percent. "Replacement level fertility" is the total fertility rate at which a population replaces itself from one generation to the next, without migration. It generally refers to 2.1 children per woman.[94] (The "total fertility rate" is the average number of children a woman would have assuming that birth rates remain constant throughout her reproductive lifetime.)[95]

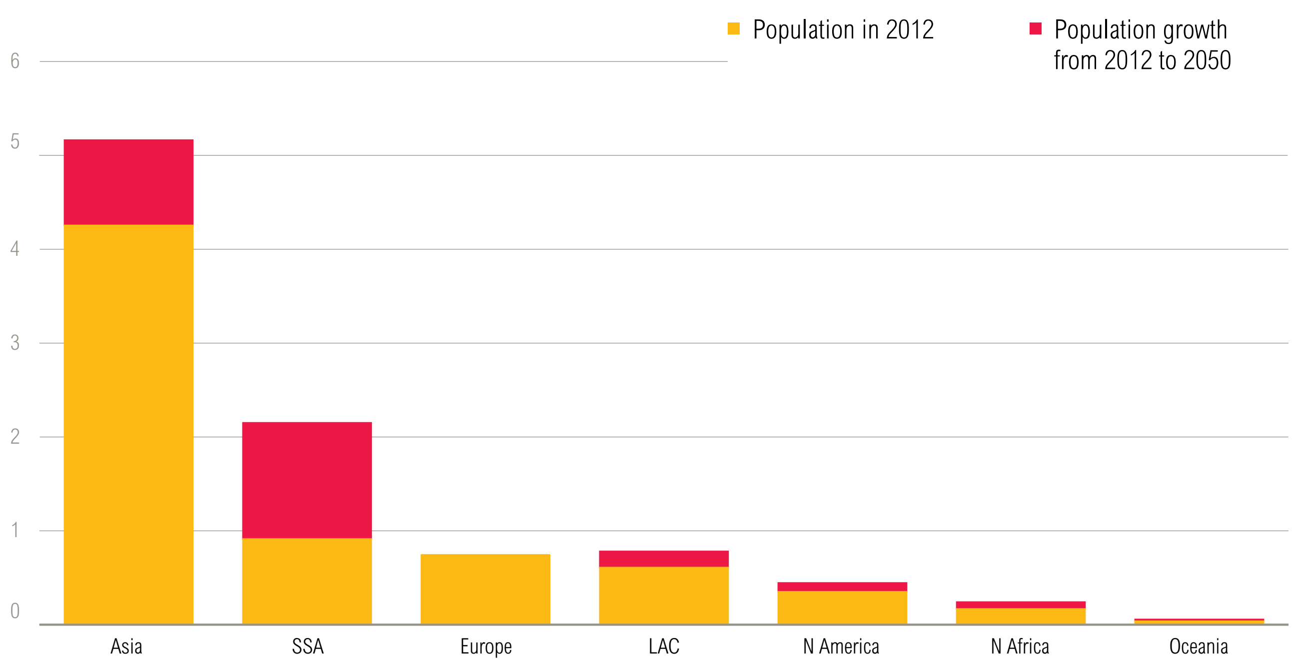
Strong statistical evidence shows that achieving replacement level fertility in a way that respects human rights requires improving education opportunities for girls, reducing infant and child mortality, and increasing access to reproductive health services.[96] These measures are valuable in their own right for promoting social and economic development, and the benefits to food security and environmental protection provide additional reasons to focus on them.

### Growth projections

According to the medium-growth scenario of the Population Division of the United Nations Department of Economic and Social Affairs (UNDESA), global population will rise from just over 7 billion in 2012 to 9.6 billion by 2050.[97] Half of this growth will occur in sub-Saharan Africa. Most of the remainder will occur in Asia (Figure 15). Yet the reasons for continued population growth in sub-Saharan Africa and Asia greatly differ.

Most of the world's regions have already achieved, or nearly achieved, replacement level fertility rates, including Asia (Figure 16). By 2010, Asia's average total fertility rate had already fallen to 2.3. Asia's population will grow over coming decades because high fertility rates in the past have created a demographic bulge in the number of young people who are entering childbearing age.

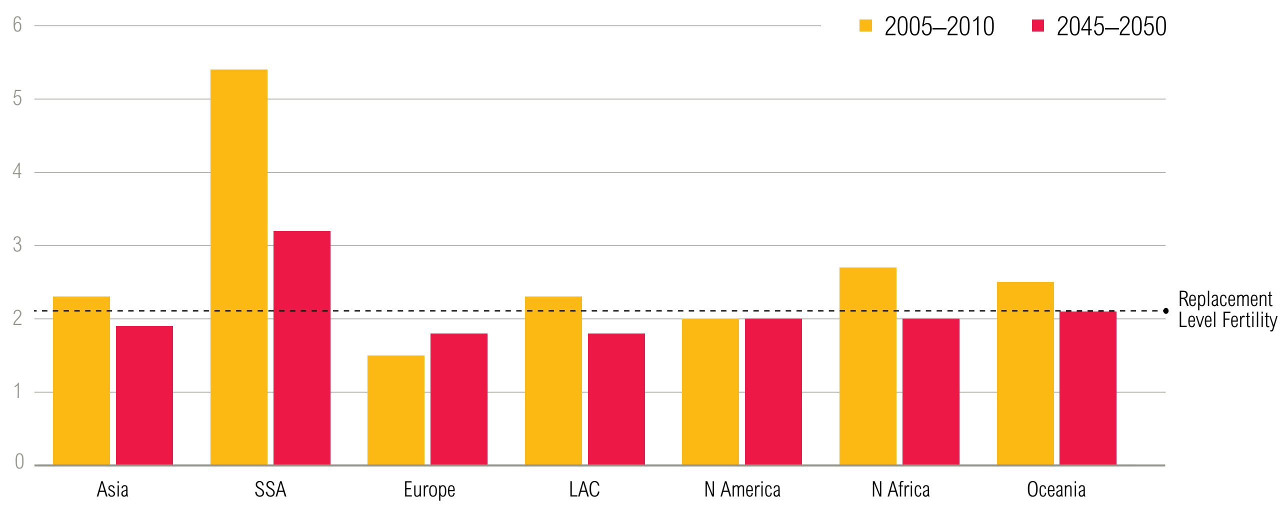
Figure 15 | **The global population is projected to grow from 7 billion in 2012 to 9.6 billion in 2050, with half of growth in sub-Saharan Africa (population in billions)**




*Note:* "SSA" = Sub-Saharan Africa. "LAC" = Latin America and Caribbean. "N America" = North America. "N Africa" = Rest of Africa.

*Source:* UNDESA (2013). Total population by major area, region, and country. Medium fertility scenario.

Figure 16 | **All regions except sub-Saharan Africa are projected to reach replacement level fertility by 2050 (total fertility rate)**




*Note:* "SSA" = Sub-Saharan Africa. "LAC" = Latin America and Caribbean. "N America" = North America. "N Africa" = Rest of Africa.

*Source:* UNDESA (2013). Total population by major area, region, and country. Medium fertility scenario.

The global exception is sub-Saharan Africa, which had a total fertility rate of 5.4 from 2005 to 2010. UNDESA projects that this rate will most likely decline gradually over the coming four decades, but only to 3.2 in 2050. This trajectory will result in a population increase of 1.2 billion in the region by 2050, more than doubling the population of sub-Saharan Africa from 0.9 billion in 2012 to 2.1 billion by mid-century. The high fertility in the region will in turn result in a large group of young people who will enter their childbearing years over the subsequent decades, so the region's population will grow to a total of 3.9 billion in 2100—more than a four-fold increase from 2012 levels.[98]

## Challenges for sub-Saharan Africa

Africa is already the world's hungriest continent. According to FAO, 25 percent of sub-Saharan Africa's people are undernourished.[99] The region also relies on imports for one-quarter of its cereals, two-thirds of its vegetable oil, and 14 percent of its animal products.[100] Because people in sub-Saharan Africa have limited income to purchase imported food, this reliance on imports makes access to food unstable.

The prevalence of hunger, combined with heavy reliance on food imports, makes sub-Saharan Africa the region most in need of additional food production. Yet sub-Saharan Africa also has the world's lowest crop yields, with cereal yields of 1.5 tons per hectare per year—roughly one-half of the world average.[101] In addition, soil quality is poor throughout much of the region, depleted of organic matter and nutrients.[102] These factors make increasing food production in sub-Saharan Africa particularly difficult and most likely to result in the clearing of natural landscapes. By 2050, even if the region continues to rely heavily on imports of crops as FAO projects, it will need to boost crop production to a level 3.6 times higher than production in 2006 to provide adequate food per capita with its projected population growth.[103]

FAO does predict high rates of yield growth for the region by 2050—including cereal yields at a level 2.5 times higher than in 2006—but even with this growth rate and a continued high level of import reliance, the region would need to harvest another 125 million hectares of crops per year in light of the new population projections. Moving to total self-sufficiency in crop production (i.e., no imports) by 2050 would require crop production at a level 4.4 times higher than in 2006.[104]

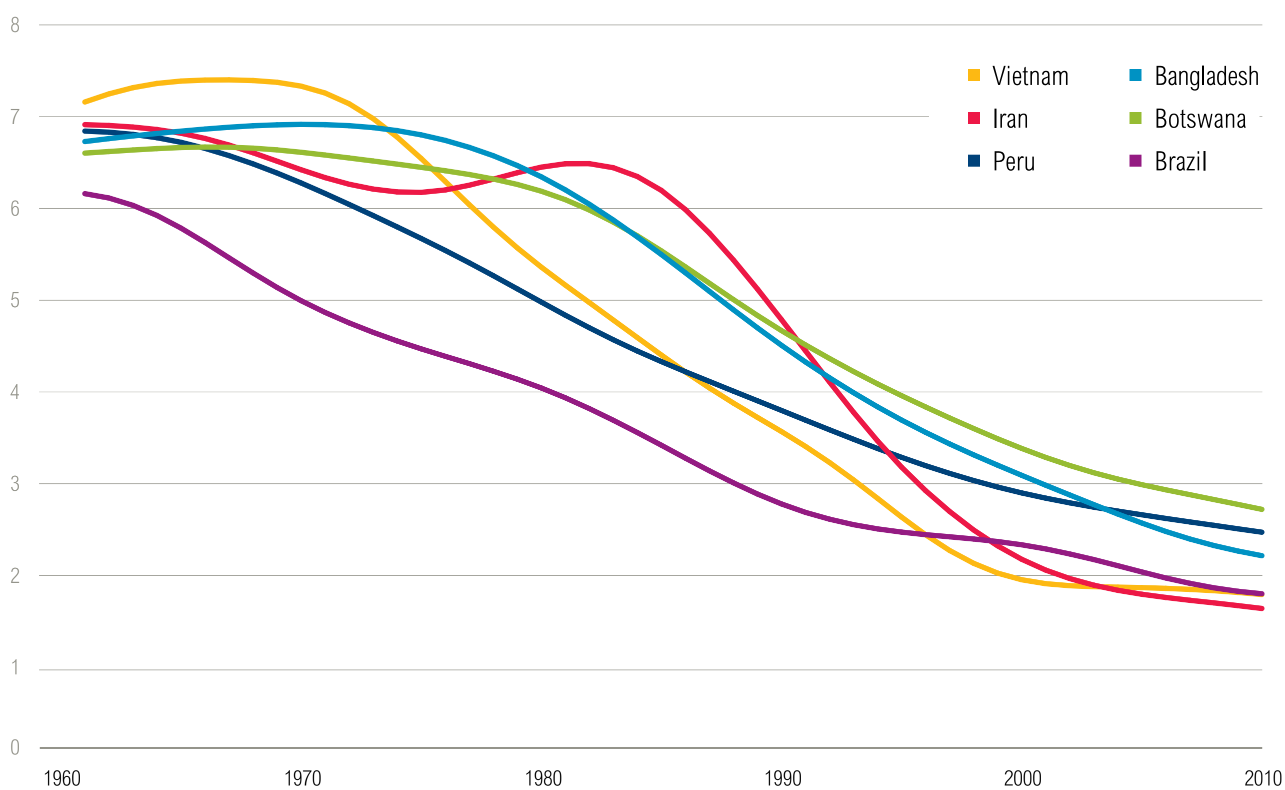
Sub-Saharan Africa could reduce the challenge of feeding its population if it were to steadily lower its present total fertility rate of 5.4 enough to reach replacement level fertility by 2050, instead of the projected rate of 3.2. According to the Oxford Institute of Population Ageing, reaching replacement level fertility would result in a sub-Saharan African population of 1.76 billion by 2050.[105] This figure is almost 400 million fewer people than UNDESA's medium-fertility scenario projection for 2050. If the region maintained replacement level fertility thereafter, the population would be 3.1 billion by 2100 instead of the 3.9 billion projected by UNDESA's medium-fertility scenario—roughly a tripling rather than a quadrupling of population.[106]

This change would reduce food demand in 2050 enough to close 10 percent of the global calorie gap. More significantly, it would reduce the food gap in sub-Saharan Africa by roughly 25 percent.[107] At the yields estimated by FAO, this reduction would also reduce the need for additional cropland equal to the size of Germany.

## Effective approaches for achieving replacement level fertility

Could sub-Saharan Africa achieve a replacement level fertility by 2050? Experience in other regions suggests it could. Although some researchers once believed that only developed countries could dramatically lower their birth rates,[108] 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 around 2.5 by 2010, through voluntary family planning programs, increases in education, and improvements in child survival.[109] Yet these

Figure 17 | **Total fertility rates can decline rapidly (total fertility rate)**




*Source:* World Bank. (2012a).

countries were still relatively poor in 2011, ranking 87th, 139th, and 166th in per capita income.[110] Being "economically developed" is not a precondition for lowering total fertility rates.

Reductions in fertility rates can occur rapidly and in a variety of cultures without coercion. In Vietnam, the fertility rate dropped from 7.4 to 2.0 in 30 years, partly in response to government penalties for larger families. In Brazil, the fertility rate dropped from 6.2 to around 2.8 in an equivalent time period, without any government mandates. Similarly, Iran's fertility rate declined from 5.2 to 2.2 in the 11 years between 1989 and 2000, also without mandates (Figure 17).

Experience and statistical studies point to three critical approaches that have enabled countries to reduce their fertility rates, each with significant collateral benefits:[111]

- **Increase educational opportunities for girls.** In general, the longer girls stay in school, the later they start bearing children and the fewer children they ultimately have.[112] In most countries with total fertility rates of 2.1 children per woman or lower, between 80 and 100 percent of women of childbearing age have attained at least a lower secondary education—that is, some high school (Figures 18 and 19). As Figures 18 and 19 show, sub-Saharan Africa illustrates this relationship in reverse: the region has a low share of women with lower secondary education and high fertility rates.

  This relationship occurs within countries, too. A survey in Ethiopia in 2012, for instance, found that women without any formal education have on average six children, while those with a secondary education have only two.[113] Education increases the age at which a woman gives birth to her first child, which is a strong indicator of how many children she will ultimately have.[114] Education also helps a woman diversify and increase her income opportunities, which typically enhances her role in deciding how many children to have.[115]

- **Increase access to reproductive health services, including family planning.** Millions of women—both educated and not—want to space and limit their births but do not have adequate access to reproductive health services. The World Health Organization (WHO) found that 53 percent of women in Africa who wish to control their fertility lack access to birth control, compared to 21–22 percent in Asia and Latin America.[116] Not surprisingly, sub-Saharan Africa also has the lowest share of women of childbearing age who use contraception (Figure 20).[117] Access to family planning counseling and technology makes it possible for women and men to have the family sizes they want, and can also lower maternal mortality and rates of HIV and other diseases.[118]

- **Reduce infant and child mortality.** Reducing infant and child mortality assures parents that they do not need to conceive a large number of children to assure survival of a desired number.[119] On average, countries with low fertility rates have low infant and child mortality rates. Once again, sub-Saharan Africa illustrates this relationship in reverse, with the highest infant and child mortality rates of any region (Figure 21).[120]

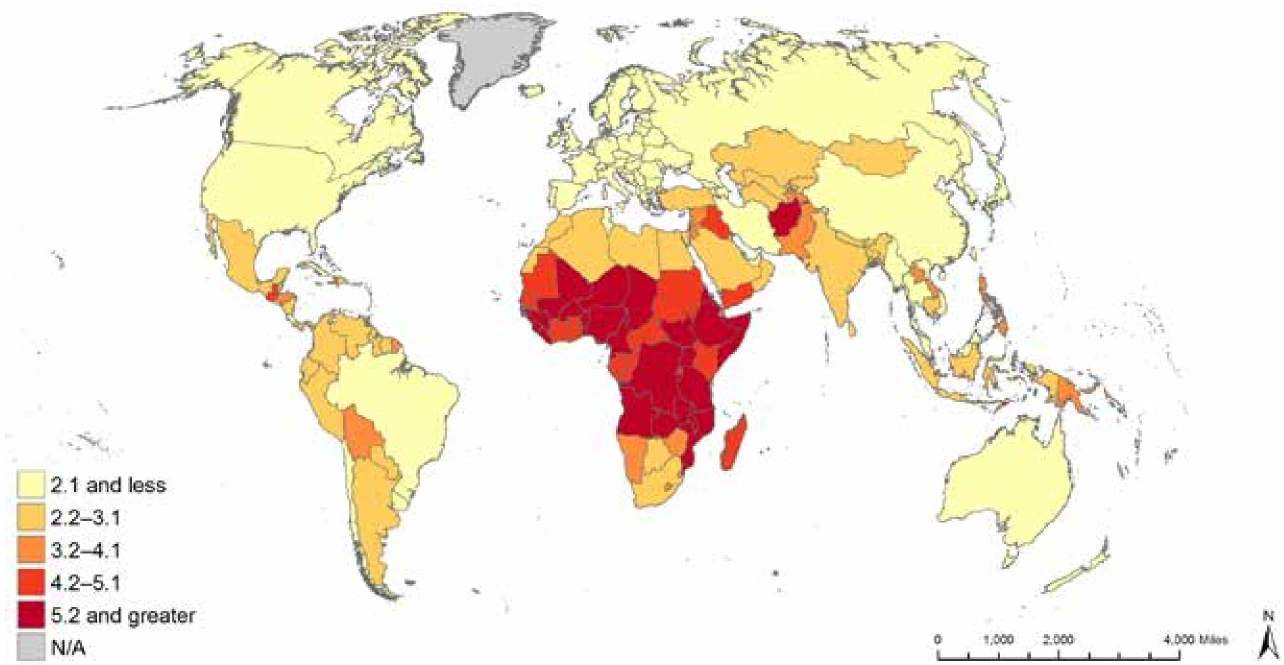
Botswana's experience suggests that sub-Saharan Africa need not be an exception. The country has implemented a system of free health facilities that integrates maternal and child healthcare, family planning, and HIV and AIDS services.[121] Mortality rates for children under five declined from 81 per 1,000 in 2000 to 26 per 1,000 in 2011.[122] Contraceptive use increased from 28 percent in 1984 to 53 percent in 2007.[123] 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 2.8 in 2010.[124]

Improving the productivity of farm labor may be another strategy that could help reduce total fertility rates in Africa. 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.[125] The demand for labor can be an incentive for farming families to have many children, so improving yields per unit of work might counter the perceived need for many children.

All these measures have rewards beyond food security in the form of saved lives, improved education and health, and greater autonomy and gender equality. Reducing fertility rates also tends to produce an economic "demographic dividend."[126] During and for several years after a rapid decline in fertility, a country simultaneously has fewer children to care for—freeing up resources—and has a greater share of its population in the most economically productive age bracket. Researchers have estimated that this demographic shift was responsible for up to one-third of the economic growth of the East Asian "Tigers" between 1965 and 1990.[127] Sub-Saharan African countries should be able to reap a demographic dividend if fertility levels fall, as long as governance otherwise supports conditions for economic growth.[128]

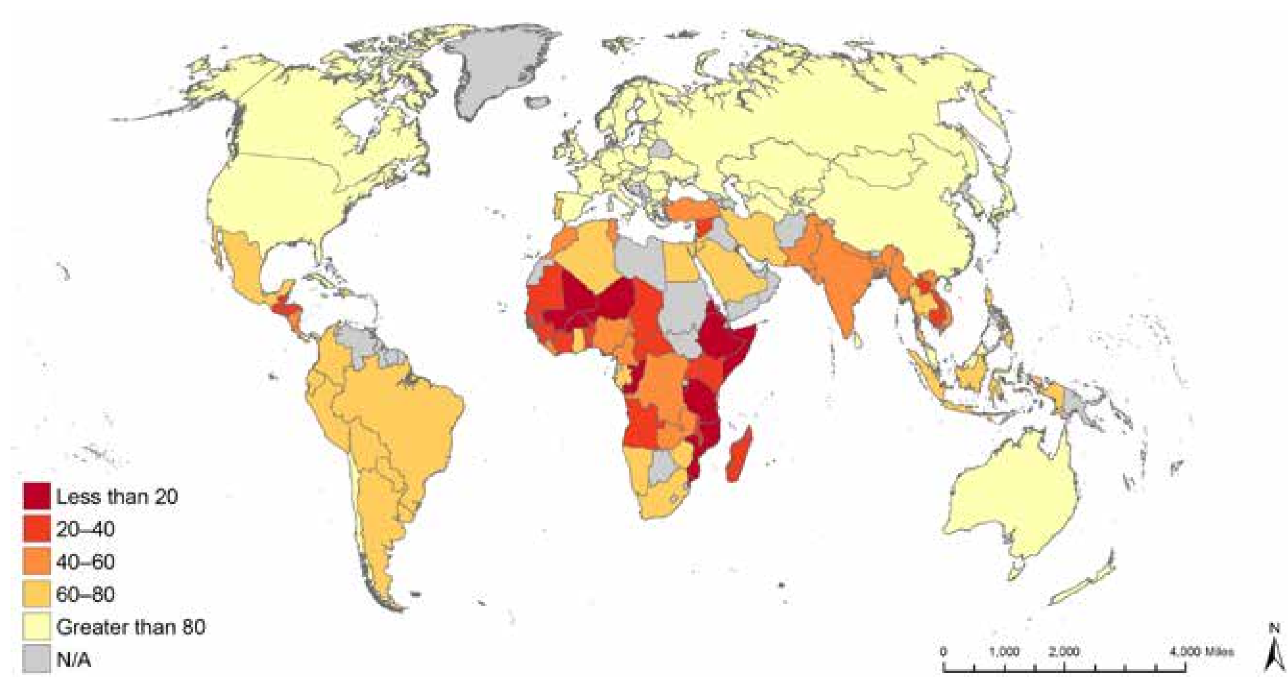
Improving girls' education, reducing infant and child mortality, and increasing access to reproductive health services could help the world achieve replacement level fertility by 2050—closing sub-Saharan Africa's food gap by 25 percent, saving an area of woodlands the size of Germany, and supporting economic growth.

Figure 18 | **Sub-Saharan Africa has the highest total fertility rates (total fertility rate, 2005–2010)**



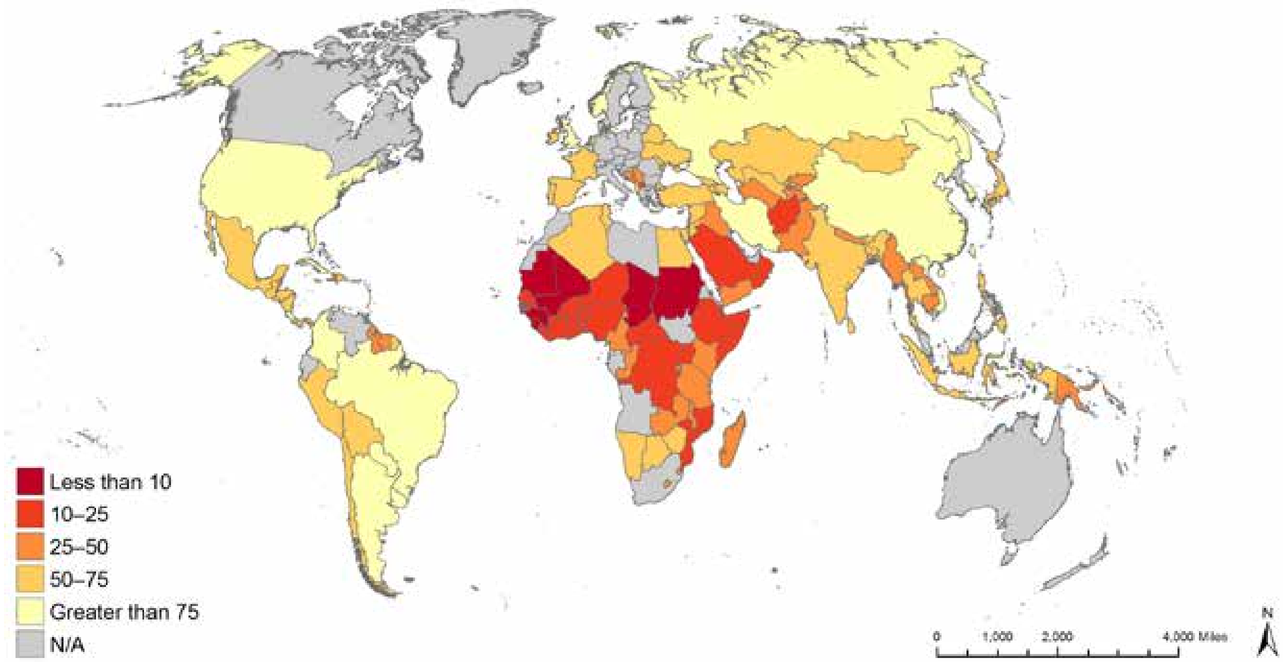

*Source:* UNDESA (2013).

Figure 19 | **Sub-Saharan Africa has the lowest total share of women with at least lower secondary education (percent of women ages 20–39 with at least lower secondary education, 2005–2010)**



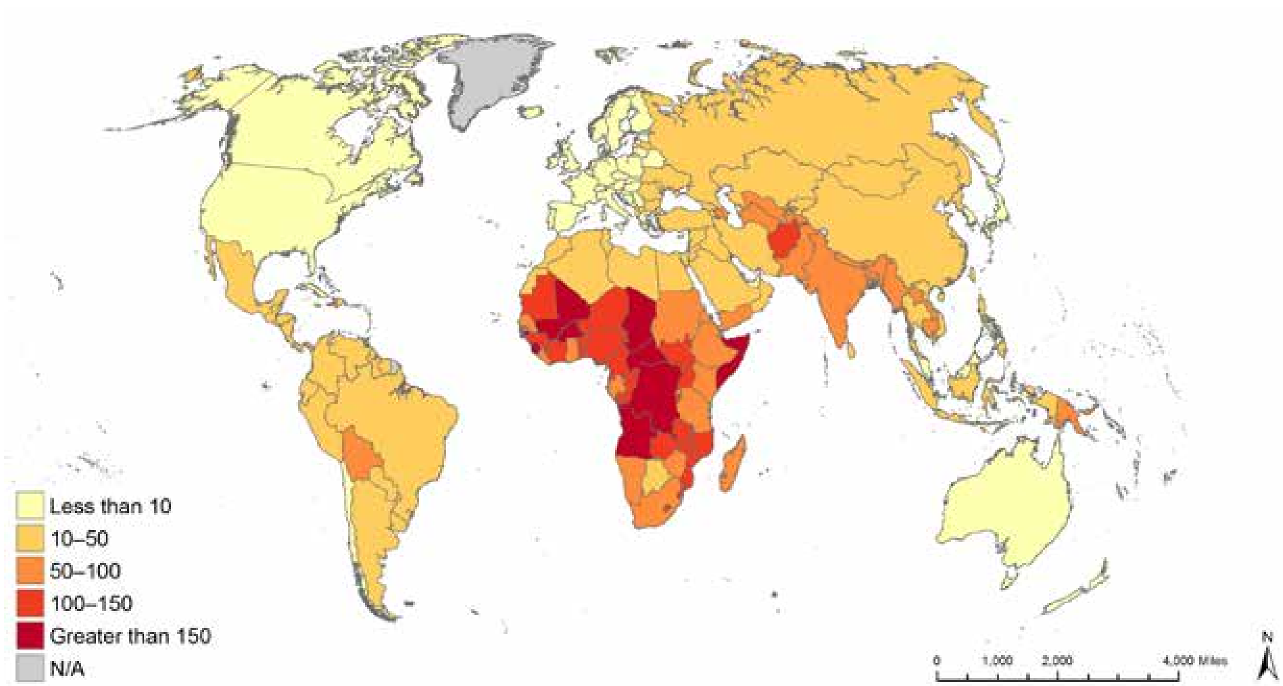

*Source:* Harper (2012).

Figure 20 | **Sub-Saharan Africa has the lowest share of women using contraception (percent of women ages 15–49 using contraception, 2005–2010)**




*Source:* World Bank (2012e).

Figure 21 | **Sub-Saharan Africa has the highest child mortality rates (mortality of children under age 5 per 1,000 live births, 2005–2010)**




*Source:* World Bank (2012f).

Chapter 4

# PRODUCING MORE FOOD ON THE SAME LAND

Even if strategies to reduce food demand prove successful–and they may not–the world will also need to produce more crops and animal products. If the world could sufficiently boost yields of crops and grass-based livestock, it could close the food gap without expanding agricultural land area and thereby protect ecosystems and eliminate additional greenhouse gas emissions from that expansion. This chapter discusses the challenge and the opportunity for yield gains of both crops and livestock, as well as the potential to direct any necessary agricultural expansion into areas with modest environmental impacts.

## Scope of the Cropland and Land Use Challenge

Agriculture has historically been and remains the dominant driver of deforestation, loss of wetlands, and conversion of grasslands. By one estimate, "worldwide agriculture has already cleared or converted 70 percent of grassland, 50 percent of the savanna, 45 percent of the temperate deciduous forest, and 27 percent of tropical forests."[129] By 2000, that conversion accounted for roughly one-third of the increased carbon in the atmosphere since 1850.[130] There is some uncertainty about precisely how much land expansion continues to occur and how much carbon that releases.[131] UNEP recently estimated that land use change emitted 5.2 Gt of $CO_2$e in 2010, accounting for both forest loss and the release of soil carbon in cleared and drained peatlands.[132] We consider that estimate reasonable.[133]

Eliminating these emissions would require eliminating agricultural land expansion, which would in turn require producing the additional food the world needs by 2050 on today's agricultural land area. Between 1961 and 2005, growth in yields supplied 80 percent of all new crops by weight, but cropland area still expanded by 220–250 Mha.[134] Do the projected food needs in 2050 create a large or only a small challenge for yield gains?

### Different projections of cropland expansion and yield gains

Organizations have used a variety of models to estimate very different levels of future agricultural land expansion by 2050 under "business as usual" (BAU) growth (Table 3). These estimates are for food and feed and are mostly independent of the growth of biofuels.[135] Using the GLOBIOM model, researchers at the International Institute of Applied Systems Analysis (IIASA) project BAU cropland expansion of 266 Mha by 2050, which implies high ongoing levels of land use change. An OECD estimate, prepared by researchers at the Netherlands Environmental Assessment Agency (PBL), projects essentially no net expansion of cropland for food between now and 2050.[136] According to the OECD analysis, agricultural area would expand substantially until 2030 but would then shrink and dip below present land use levels by 2050. Each of these estimates uses a computer model that starts with a range of assumptions regarding population growth and economic output and tries to estimate a range of economic and agronomic interactions.

The FAO estimate that we use in this paper projects net cropland expansion of only 69 Mha, which implies more modest land use change for cropping. FAO relies heavily on extrapolations of consump-

Table 3 | **Different analysts project different changes in agricultural land area by 2050 under a "business as usual" scenario**

| FEATURE | MODEL | | |
|---|---|---|---|
| | GLOBIOM | FAO | OECD/IMAGE |
| Time period | 2000–2050 | 2006–2050 | 2010–2050 |
| Cropland | + 266 Mha | + 69 Mha | - 8 Mha |
| Pastureland | + 121 Mha | N/A* | - 52 Mha |
| Decline in natural ecosystems | + 503 Mha gross | N/A* | N/A* |
| Comment | Decline in natural ecosystems offset by 103 Mha of plantation forest growth | Cropland increase of 107 Mha in tropics, offset by decline of 48 Mha in temperate zone | Cropland increase of 110 Mha from 2010–2030, but net decline of 8 Mha by 2050 |

* Data not available or not discussed in the respective study.

*Source:* GLOBIOM analysis provided by IIASA based on model described in Schneider et al. (2011), FAO projection from Alexandratos (2012), OECD projection prepared by the Netherlands Environmental Assessment Agency in 2011 and reported in OECD (2011).

tion and production trends that have been modified regionally through expert judgment.

These different projections, with different implications for ecosystems and carbon emissions, reflect in large part different estimates of future yield growth and therefore the need for more cropland. Differences are to be expected in light of the inherent uncertainties in predicting the world 40 years from now, but they may also reflect different conceptions of a baseline. Some analysts adopt a baseline that represents their best guess of the future, including changes they anticipate in government policies, technology, and private company behavior. Unfortunately, there is a high risk that readers might interpret such scenarios as a signal that there is no problem that needs fixing, rather than as an assumption that problems will be fixed. We think the most useful baseline should reflect the progress that is reasonably likely to occur without any enhanced new government strategies, major new technical breakthroughs, or behavior shift by the private sector. By that standard, we consider the FAO and IMAGE projections overall as too optimistic.

To understand the different projections, it is useful to compare their projected yield growth and production needs from 2006 to 2050 with the growth rates from 1962 to 2006. This comparison requires a decision about the best quantitative way of measuring crop yield growth rates. Many papers have been highly pessimistic about future yields because they point to declining compound annual growth rate percentages over time.[137] Treating yield growth rates as an annual percentage in this way, annual yield growth rates for cereals in the 1960s were about 3 percent, and they are now slightly above 1 percent. But throughout the past four decades, each average hectare has continued to produce roughly the same absolute quantity of additional grain each year relative to the previous year, about 42 kg.[138] The compound annual growth rate has declined because this additional quantity of crop growth per year has remained the same, while the total amount of crop produced per hectare has continued to grow. In effect, the numerator has stayed the same while the denominator has grown. When average world yields were only 1.4 tons per hectare per year (1.4 t/ha/yr), producing an additional 42 kilograms each year meant 3 percent growth. Now that average world yields are closer to 3.7 t/ha/yr, that same 42 kilograms achieves growth rates closer to 1 percent. Therefore, declining rates of compound growth are not by themselves a cause for alarm. On

## BOX 5 | THE SIGNIFICANCE OF LINEAR YIELD GROWTH FOR PREDICTING FUTURE LAND USE NEEDS

A poorly grounded assumption that explains many projections of future crop yields and land use needs is that yields grow by a stable percentage each year. In other words, if yields grow by 1.5 percent this year, they will continue to grow at 1.5 percent each year, and like a bank account, the growth will compound. That assumption leads to large absolute yield growth over time.

However, yield growth (kg/ha/yr) is mostly linear, as Figure 22 shows for grains. The level of yield growth per year sometimes varies from region to region, time to time, and crop to crop–there are periods of high growth as well as plateaus for individual crops within different regions. But when yields grow, they tend to grow in a linear, not compound, fashion. In fact, there is no agronomic reason that growth should be compound.

The implications of the assumption of compound yield growth are large. On the one hand, the percentage rate of growth tends to decline over time as the total yield grows. Mathematically, the numerator–the growth in kilograms per hectare per year–stays the same, but the denominator–the total yield per hectare–grows. Papers that focus on this declining percentage rate of yield growth therefore can paint an overly alarmist picture if they infer a decline in technical improvements.* On the other hand, papers and models that project today's percentage yield growth rates out into the future paint an overly rosy scenario. Figure 22 shows, for example, that treating the average percentage growth rate for cereals in the 1988/1990 to 2008/2010 period as a compound percentage growth rate out to 2050 results in very high yield predictions. Those 2050 yields are roughly 1.5 tons per hectare higher than implied by the more historically accurate, linear trend line. One recent paper claiming that the world had reached "peak farmland" relied on such a compound annual growth rate.**

Closely related to the estimate of yield growth is the estimate of demand growth for food. The FAO projection our analysis uses also assumes linear yield growth rates to 2050, but it expresses demand growth for food as a compound growth rate. By that method, future growth in food demand is less than growth over the last 44 years. But if the purpose is to evaluate land use demands, we believe demand growth should be calculated in the same way as yield growth, and that shows a slightly higher rate of calorie growth in the next 44-year period compared to the last.

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

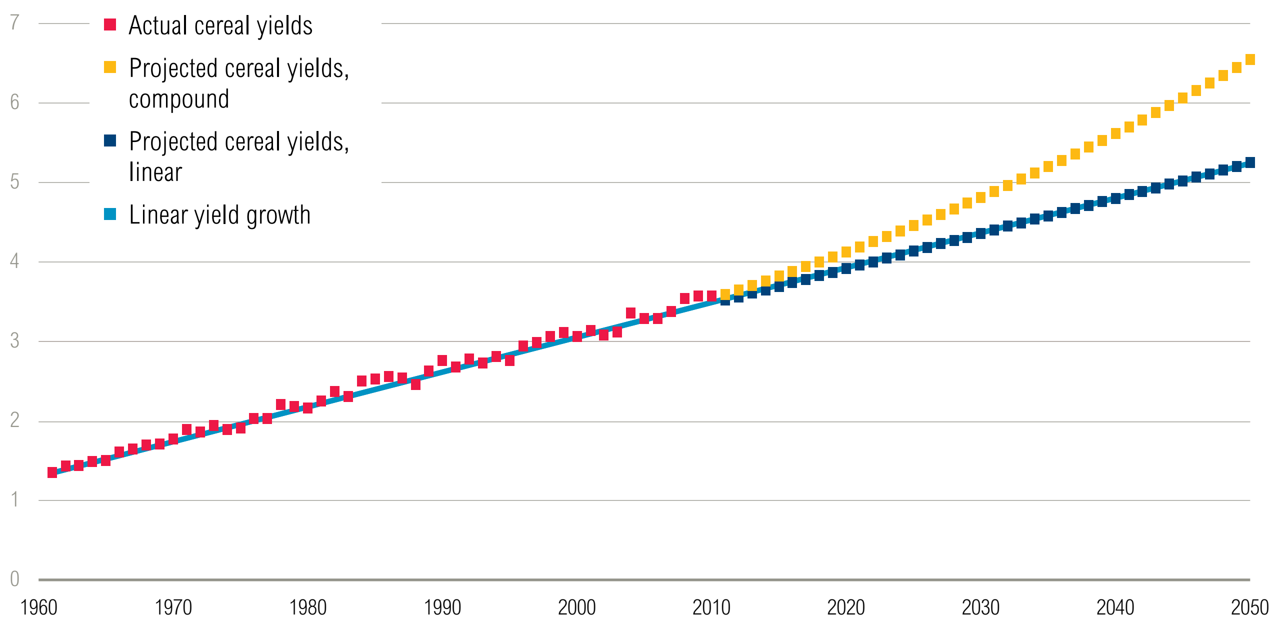
** Ausubel et al. (2012). In this paper, the compound growth rate is complicated by the fact that the paper analyzed different contributions to yield growth, but the overall effect was to use a compound rate.

the other hand, historical data do not justify the optimistic projection of today's compound growth rates into the future (Box 5). The way to measure yield growth that best reflects experience is also the simplest: the number of additional kilograms each hectare produces each year for each crop.

This form of measurement makes it relatively simple to compare future demand growth rates from 2006 to 2050 with those from 1962 to 2006, which we call the "historical rates." To meet FAO's projected demand—unadjusted by us—without an increase in harvested area for each type of crop, cereal yields would only have to grow at 70 percent of their historical rates. However, soybean yields would have to grow 44 percent faster (Figure 23); cassava nearly three times faster; and vegetables, rapeseed, and sorghum roughly twice as fast.[139] Overall, using our adjustments to FAO projections, crop yields would have to grow roughly 32 percent faster from 2006 to 2050 than they did from 1962 to 2006 to avoid an increase in harvested area.[140]

In fact, as an average of all crops, FAO predicts that yields will grow in the next 44 years by almost exactly the same amount as they did in the past 44 years. This projection is not obvious because FAO projects that yields of cereals, which receive most attention, will grow at only 57 percent of their historical rates, and soybeans at 88 percent. But FAO projects that yields of most other major crops will grow much faster than their historical rates. The yields of pulses (dry beans and lentils) are projected to grow at 4 times their historical rates; and those of pota-

Figure 22 | **Compound growth and absolute growth produce varying estimates of future cereal yields (tons/ha/year)**




*Source:* WRI analysis based on FAO (2012a).

toes, cassava, and sugarcane are projected to grow at roughly twice their historical rates. Overall, the crops with lower and faster projected yield growth relative to the previous 44 years have the effect of balancing each other out so that FAO's projected growth in harvested area is almost exactly the level it would be if all crop yields were to grow over the next 44 years by their historical linear rates.[141]

IMAGE projects a need for even less additional cropland than FAO, at least in part because its cereal yields grow roughly 25 percent faster than FAO's yield growth. By contrast, GLOBIOM estimates more land use needs because yields overall grow at lower rates.

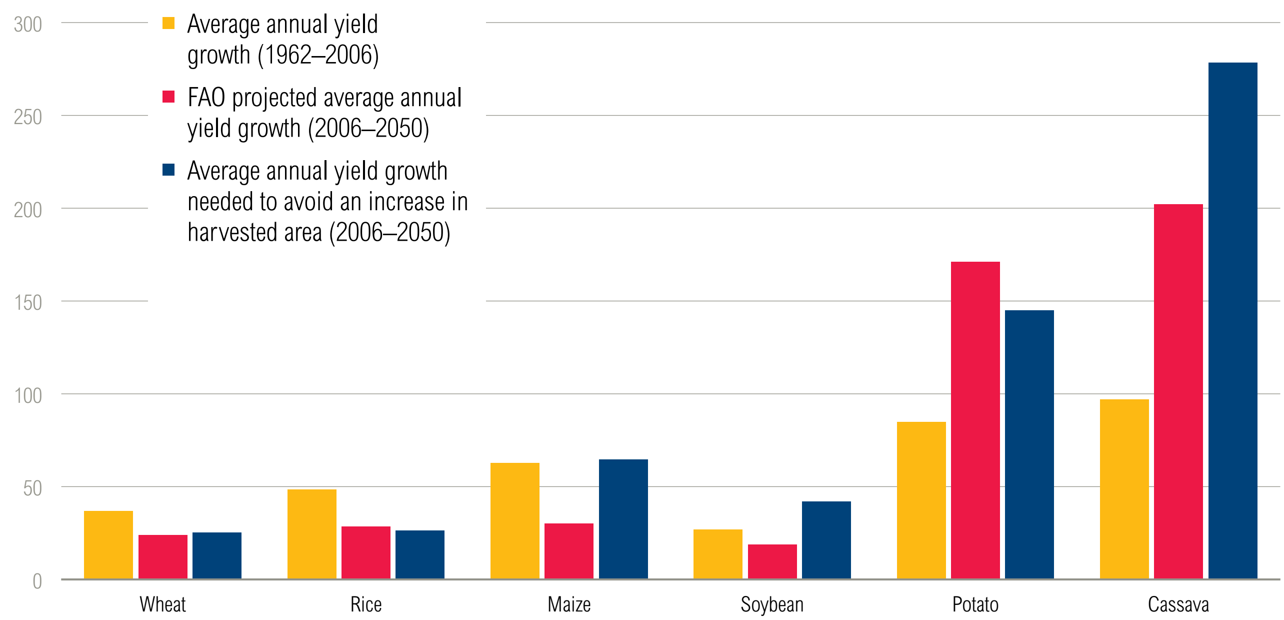
How yields evolve over the next 40 years is inherently uncertain and speculative. By our definition of BAU, we project yields based on their most likely development in the absence of new policies and initiatives, and by that standard, we consider both the FAO and IMAGE baseline estimates optimistic.

One reason for our skepticism of these baseline estimates is that no fundamentally new technologies appear capable of matching the three technologies that drove yield growth from 1962 to 2006:

- **Fertilizer.** Farmers worldwide used very little synthetic fertilizer in 1960. Today, most of the world fully exploits nitrogen fertilizer, and some countries overapply it. Only sub-Saharan Africa as a region uses little fertilizer.[142]

- **Irrigation.** The past 50 years saw a doubling of the area of irrigation, an increase of 160 Mha according to FAO,[143] and probably a doubling of water consumption by irrigation.[144] FAO estimates that irrigated land worldwide provides 44 percent of all food production, 47 percent of food production in developing countries, and 59 percent of the world's cereals.[145] One study estimates that irrigation increases world cereal production by 20 percent.[146] Yet, FAO projects an expansion of irrigation by only 20 Mha

Figure 23 | **Future crop yields overall will need to grow 32 percent faster than historical rates to avoid new land conversion (kg/ha/year)**




*Source:* Alexandratos and Bruinsma (2012), ACE and WRI analysis.

through 2050, mainly because there are few remaining additional areas that can be irrigated with available water.[147] Water is already overdrawn in many of the world's most productive areas, including the Indo-Gangetic plain of northern India, northeast China, the California Central Valley, and the Ogallala Aquifer region in the Great Plains of the United States.[148]

- **Scientifically bred seeds.** Fifty years ago, most of the world used seeds improved only by farmers, but in the past 50 years, most of the world adopted scientifically bred seeds. Adopters include the 12 major developed nations and East Asia, including China, which together contributed two-thirds or more of the world's cereals and oilseeds.[149] Although use of improved seeds remains low in Africa,[150] progress overall now rests largely on steady scientific improvements of the seeds that scientists have already improved.

Today, not only are all three technologies widespread—except in Africa—but boosting yields by increasing water, fertilizer, and other inputs at a similar scale would have high environmental impacts and fail to meet our environmental sustainability criteria. For example, the use of nitrogen, whether from synthetic fertilizer, manure, or nitrogen-fixing crops, has contributed to a global prevalence of "dead zones" in coastal waters, and also contributes large quantities of nitrous oxide emissions. Water withdrawals have left rivers dry and estuaries without freshwater flows, which has harsh consequences for communities, fish, and wildlife.

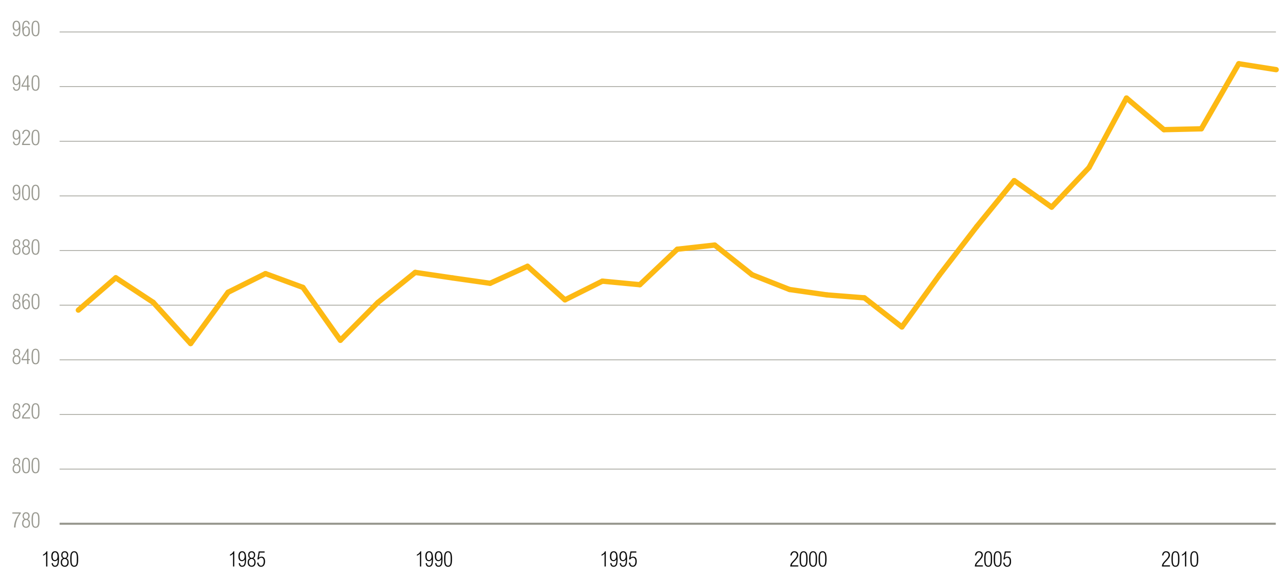
Yields are also likely to grow more slowly because of an increase in the share of global cropland coming from sub-Saharan Africa and other low-yield regions. To the extent production shifts from higher to lower yielding regions, that shift will lower average global yields even if yields are increasing in each region.

Recent evidence of expanding harvest area also supports a more pessimistic view. Although the area harvested of the 15 major crop categories barely changed from 1980 to 2000, it grew by almost 90 million hectares in the last 10 years (Figure 24). Perhaps 40 percent may be attributable to the area used for biofuels,[151] but the remainder implies that yield gains alone are not keeping up with increases in demand.

"Harvested area" refers to the number of hectares actually harvested each year, which is different from the area classified as cropland. This 90 Mha increase in harvested area is greater than increases in total cropland as reported by FAO, which increased only by 35 Mha from 2002 to 2011. The difference could result from an increase in areas cropped twice in the same year, or from a reduction in fallowing of existing cropland, both of which increase areas reported as harvested without expanding cropland. Indeed, some researchers cite the gap between the growth in harvested area and overall cropland as evidence that this has been happening.[152] Some increased use of cropland has probably been occurring, but as we discuss below, much of the gap between reported changes in harvested area and total cropland probably reflects only loose reporting of what constitutes cropland.

We believe all these factors make it imprudent to assume that, absent major new policies and initiatives, the expansion of cropland will decline in the next 44 years from its prior rates. If yields were to grow at an average of 80 percent of their historical pattern, harvested area would still expand by more than 200 Mha.[153] Such a baseline implies that the contribution of expanding cropland to greenhouse gas emissions from land use change is unlikely to decline.

Figure 24 | **Harvested area for 15 major crops has expanded by almost 100 million hectares in the past ten years (million hectares)**




*Source:* WRI analysis based on FAO (2012a).

*Note:* Data for 15 major crops includes: barley, cotton, groundnuts, maize, millet, oats, rapeseed, rice, rye, sorghum, soybeans, sugar beet, sugar cane, sunflower seed, and wheat.

## The effects of climate change on yields and land use

The effects of climate change on crop yields are uncertain but overall provide additional reasons for caution in estimating future yield growth. Average global surface temperature increased by 0.7° C from 1901 to 2000 and is projected to increase another 1.1° C to 6.4° C by the end of the 21st century.[154] The 2007 assessment of the Intergovernmental Panel on Climate Change (IPCC) summarized the prevailing view that climate change would not have adverse effects on global yields because beneficial impacts in northern latitudes would offset adverse impacts on yields in the global South, particularly in sub-Saharan Africa. Unfortunately, the science since the 2007 IPCC report has been almost entirely more pessimistic. Statistical studies have shown that just a few days of exceptionally high temperatures at the wrong time adversely affect yields of several major crops more than previously understood. Studies have also found that climate change is already adversely affecting overall yields in the northern hemisphere. Droughts and record high temperatures in Russia and the United States during 2011 and 2012 have begun to reveal the consequences of more frequent, highly adverse weather events, which previous analyses did not fully account for. Significant uncertainties remain about not only these effects but also the effects of climate change on regional rainfall patterns, which could be beneficial in some locations, but are more likely to have adverse consequences because of a shift from more frequent, gradual rainfall toward fewer, more intense storms.[155]

One study now estimates that by mid-century, global yields of wheat, maize, and soybeans could decline by 14–25 percent, 19–34 percent, and 15–30 percent, respectively, with a warming of 2.2° C to 3.2° C compared with pre-industrial temperatures.[156] With a one-meter rise in sea levels, almost 11 percent of South Asia's agricultural land is projected to be vulnerable to flooding.[157] By the end of the century, areas affected by drought disasters are projected to grow from 15 percent to approximately 44 percent of the planet. Regions facing the greatest increases include southern Africa, the United States, southern Europe, Brazil, and Southeast Asia.[158] And the evidence remains strong that climate change will have substantial adverse consequences on some of the hungriest parts of the world that need agricultural growth the most, particularly sub-Saharan Africa.[159]

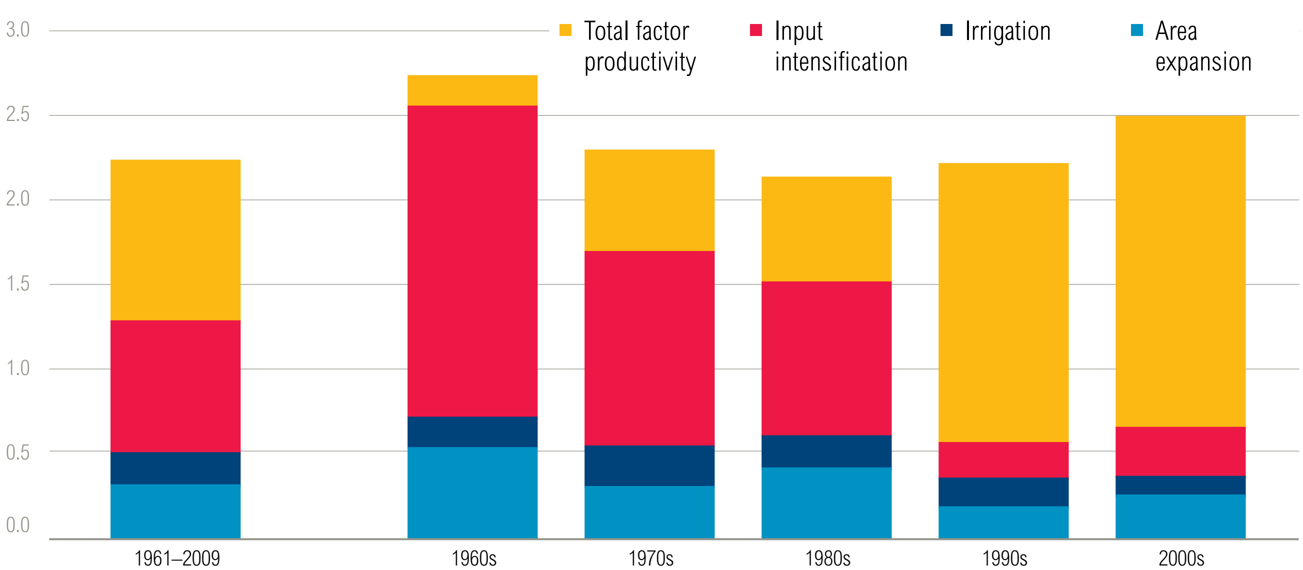
The effects of climate change provide another reason to project that emissions from land use change will remain at least at constant levels absent major new initiatives.

## Increasing Yields on Existing Croplands

This assessment of future cropland needs, although cautious, highlights the importance of boosting crop yields. If the world could boost overall yields from 2006 to 2050 at a rate one-third faster than it boosted yields from 1962 to 2006, those gains could by themselves fill the food gap without net agricultural expansion or reduction in food consumption. Without the same potential to increase inputs, the world instead has to use those inputs more effectively. Fortunately, like the manufacturing and service sectors, agriculture has better information technology, machinery, and transportation systems than in the past. It also has better tools for future plant breeding, capacity to evaluate soils, and ability to predict weather, which is critical to planting decisions. The world also has the capacity to pay more attention to those farms that are lagging behind. In short, the world has the capacity to farm smarter and more efficiently, which are the core qualities of what many are now calling "sustainable intensification."

Over the past couple of decades, the evidence suggests that smarter farming has in fact been offsetting a decline in the growth rate of inputs enough to keep the value of agricultural economic output increasing at historical rates. Since 1960, the annual growth rate of agricultural production, as measured by economic output, has remained consistent. (The increase in economic output is not exactly the same as an increase in yield—as the former gives greater weight than the latter to the growth of high-value agricultural products, such as milk, meat, fruits and vegetables—but the economic measure recognizes the full scope of production increases.)[160] Yet, the role of increased inputs and land in this growth has declined from 95 percent in the 1960s to only 25 percent in the 2000s.[161] Instead, 75 percent of the gain in output in the 1990s and 2000s resulted from improvements in total factor productivity, which means improved technology or better use of existing technology (Figure 25).[162] Much of the gain has resulted from the spread of advanced farming technologies, particularly to China, Brazil, and

Figure 25 | **The primary source of agricultural growth has shifted from input increases to efficiency gains (rate of output growth, % per year)**




*Source:* Fuglie (2012).

Argentina. Although these farming improvements have not been sufficient to eliminate agricultural land expansion altogether, they suggest the potential power of farming advances.

We discuss four menu items to increase output on existing croplands by farming smarter: improved crop breeding, "leaving no farmer behind," planting existing cropland more frequently, and improving soil and water management.

## MENU ITEM | Boost yields through attentive crop breeding

Although improved management plays an important role in boosting yields through such means as better fertilizing, watering, seed selection and weed and pest control, crop breeding also is critical. Gains in crop breeding occur in part through the steady annual selection and adoption of higher yielding seeds and in part through the development of more fundamentally new varieties. Improved yields result in part from growth in physical yield potential—the maximum production of the edible parts of plants under ideal conditions in a particular climate. Two factors have fueled the growth in yield potential: (1) the percentage of the energy the plant obtains from the sun that goes into those edible parts, which is known as the "harvest index;" and (2) the ability to grow plants more densely, and therefore to produce more plants on the same land.[163] Improved yields through breeding also result from improved plant adaptation to local conditions to realize more of this maximum potential. Those conditions include weather characteristics, particular latitudes, lengths of growing periods, and rainfall patterns. They also include adaptations to local soil characteristics and pests.

New seed varieties emerge from an essentially two-step process: they are invented at a central breeding institution and are then adapted to local needs. Future yield gains may occur through improvements at either step.

### Genetically modified crops: subject of great debate

The benefits and costs of genetically modified (GM) crops attract enormous levels of public attention and policy debate. As the term is typically used, genetic modification differs from conventional plant breeding because it involves the insertion of specific genes into the genes of a target plant, often from a separate species. Although plant scientists have bred crops with a wide variety of GM traits, two have dominated the actual market for GM crops. One is resistance to a particular herbicide, which at this time is overwhelmingly glyphosate (most commonly sold under the trademark "Roundup"). This trait allows farmers to spray a single herbicide—which was originally effective against virtually all weeds—directly over crops that would otherwise be affected. The other major GM trait involves insertion of a gene that allows plants to make a Bt toxin, a natural insecticide, which is particularly effective against worms and caterpillars. Bt traits are used

particularly in maize and cotton. Farmers now plant GM crops on 170 million hectares annually, 90 percent of which are in the United States, Canada, Brazil, Argentina, and India.[164]

The debate over genetic modification tends to focus on four issues: food safety, toxicity and pest problems, effects on crop yields, and shift of profit to major corporations. We discuss each of these concerns below.

### FOOD SAFETY

Much of the opposition to GM crops arises from a fear that they are not safe to consume. At this time, there is no evidence that GM crops have actually caused any human health harm.[165] The vast number of studies has found no adverse health effects,[166] and even GM critics mainly argue that the risks have been insufficiently studied.[167] The most alarming study of GM crops claimed to find a large increase in rat cancers. However, the sample involved only 10 rats of each sex, and food safety institutes criticized the study as having a high likelihood of random error.[168]

Any breeding has some potential to create unintended health consequences. The U.S. National Research Council has agreed that genetic modifications using genes from diverse species poses a greater risk of unexpected effects than conventional cross-breeding of same-species varieties.[169] That greater risk justifies requiring safety studies, and there is room for reasonable debate about the proper scope of such studies. But conventional breeding can also result in unintended health effects.[170] Indeed, conventional breeding includes methods of encouraging and experimenting with mutations in existing crops whose potential for unintended consequences is close to that of genetic engineering. Genetic engineering can also help breed crops with enhanced nutritional benefits. For example, genetically engineered golden rice is high in vitamin A, which could help to remedy vitamin A deficiencies that cause blindness in many poor countries.[171] Overall, there is an overwhelming scientific consensus that while GM crops should undergo safety screening, food safety provides no justification for rejecting genetic engineering outright.[172]

### TOXICITY AND INADVERTENT PEST PROBLEMS

Because both glyphosate and Bt are less toxic than other herbicides and pesticides, researchers have generally made the case that their use has led to a decline in the overall toxicity of pesticides in the case of glyphosate and a decline in both toxicity and volume of pesticides in the case of Bt crops.[173] There are some contrary studies.[174]

Measured by sheer volume rather than toxicity, the quantity of pesticide used in the United States increased gradually from 1996 and then jumped in 2011.[175] The overall increase in pesticide use is important because not all health concerns are related to toxicity. In particular, glyphosate is a

hormone disruptor, like many other herbicides, and its widespread use in high volumes is a concern even if its acute and chronic toxicity is lower than other pesticides.[176]

In contrast, Bt crops appear to have reduced use of pesticides, particularly in China and India.[177] There is some disagreement regarding the quantity of that reduction. In some places, Bt crops have led to an increase in "secondary" pests that are not the primary target of pest spraying. Reducing the secondary pests, in turn, requires more pesticide control. But studies tend to show that Bt crops can also contribute to reductions in secondary pests,[178] and that Bt crops can even promote beneficial insects that reduce pests on neighboring maize, peanut, and soybean fields.[179] However, one prominent critic points out that Bt crops express Bt proteins throughout the entire crop, not merely the roots that are most vulnerable to pests, and that if all this Bt is counted as a pesticide, the quantity of pesticides does not decrease.[180] That argument merits some concern, although such pesticides incorporated into crops are unlikely to be as problematic as sprays, and Bt has relatively low toxicity compared to other pesticides.

Much of the environmental criticism of these particular GM crops acknowledges toxicity advantages in the short term, but argues they may lead to greater toxicity in the long term. The increased reliance on individual pesticides can lead to more rapid development of resistance by weeds or insects, which could eliminate the usefulness of less toxic pesticides such as glyphosate and Bt. To date, there are examples of infestations by insects that are resistant to one Bt protein, but no Bt resistance to crops with a broader range of Bt proteins has emerged. Breeding multiple Bt proteins into crops should help reduce the likelihood of resistance because even genetic mutations that lead to resistance to one Bt protein will not allow insects to outcompete nonresistant species.[181] In contrast, resistance has been developing rapidly to glyphosate and has now spread to 24 different weeds.[182] In some areas, glyphosate-resistant weeds have become major and expensive problems,[183] and trying to overwhelm this resistance has led to a large rise in the total quantity of glyphosate applied.[184] In part because of this resistance, chemical companies are now trying to add resistant traits in crops to more toxic pesticides, such as 2,4-D, which would be applied along with glyphosate and would reduce if not eliminate the toxicity benefit of using glyphosate-resistant crops.

The focus on breeding resistance to other pesticides also highlights that nothing inherent in GM technology should lead to lower pesticide toxicity. Breeding probably originally focused on glyphosate in part because its lower toxicity was likely to lead to its greater use, but GM technology can be used as well for more toxic pesticides. GM technology is thus a tool whose merits depend on how it is used.

### YIELDS

There is debate about whether glyphosate-resistant crops have led to yield gains. In the short run, the introduction of a new gene leads to "yield drag," because conventional versions of those crops continue to improve during the time it takes breeders to integrate the new gene into local crops. The U.S. National Research Council concluded that this drag effect eventually disappears for that particular gene,[185] but the insertion of new genes will repeat the drag effect in the future. On the other hand, the easier management of weeds makes it possible for farmers to increase yields in real world situations. In the United States, the net effect on yields of glyphosate-resistance has probably been modest, although the reduction in farm labor and management intensity has been large.[186] By contrast, there is evidence that farmers in developing countries, who are less able to control weeds in other ways, have been able to use this trait to boost yields. The precise benefits are hard to calculate. Comparisons of yields by those who adopt and do not adopt GM crops are confounded by the fact that early adopters tend to be higher yielding farmers.[187] Studies based on country comparisons tend to ignore the fact that those countries adopting GM crops are countries that already had high and rising yields.[188] Yet, reducing production costs may also indirectly lead to yield gains by making agricultural investment more profitable.

The same measurement challenges apply to Bt maize and cotton, but there is stronger evidence of their contributions to yields in part because it is hard to spray pesticides on crops to control the worms attacking roots. Even in agriculturally advanced countries such as the United States, the integration of Bt into the crop roots appears to promote better growth and has led to 5–10 percent yield gains for cotton[189] and perhaps smaller gains for maize,[190] although the gains depend on the scope of the pest problems.

In warmer developing countries, where pest pressures are naturally greater and pesticide use is otherwise less developed, Bt offers built-in control of many worms and insects. India experienced yield gains in cotton of 56 percent between 2002 and 2011, which corresponded overall to the introduction of Bt cotton. Doubters properly point out that nearly all of this rise occurred from 2002–05, when official Bt cotton adoption rates were only 6 percent.[191] Yet other researchers have pointed out that even in this period some farmers were already adopting the seeds unofficially, suggesting that the 6 percent adoption rate figure was an underestimate and suggesting a significant role of Bt cotton in yield gains.[192] Overall, the evidence tends to justify claims that Bt cotton helped to significantly increase yields, although other factors played an even larger role in the yield gains.[193]

Genetic engineering has also helped some less widely produced crops resist pests. For example, papaya faced a virulent virus in Hawaii but was protected by insertion of genes from the virus into the papaya itself, generating a kind of plant immune response.[194] This variety has not spread much to the developing world because of challenges from NGOs.[195] But Japan, which long resisted Hawaii's genetically modified papaya, has now lifted its restriction.

#### SHIFT OF PROFIT TO MAJOR CORPORATIONS

The last major concern with genetic engineering is expense. Farmers must buy new seeds annually, instead of harvesting their own seeds, and GM seeds cost more. The result is that the farmer must surrender more of the revenues from farming. The same is true of hybrid seeds, which dominate the world's maize production; some farmers resist hybrid seeds because of their expense. On the other hand, farmers would not be buying hybrid or GM seeds unless the payoff exceeded the cost—suggesting that boosts in yield or reduction in other costs justify the seed costs. Many studies have found benefits of GM seeds for small farmers.[196]

Increases in seed costs have the potential to increase pressures on small farmers more than large farmers because small farmers are often less able to raise capital. Higher input costs also increase the risks associated with bad weather and crop failure. Many small farmers are less able than larger farmers to balance these added losses in bad years with the greater benefits in good and average years, even though small farms are as or more productive overall as large farms in many farming systems.[197] In this regard, GM seeds present the same problems as any other increase in input costs due to technological change. If public researchers were to develop GM seeds, the concern about losing much of the profits from productivity gains to large seed companies would be lower. And although annual seed purchases would probably still be necessary, the seed costs would not include payments to a private patent holder.

### What role for genetically modified crops?

To date, GM crops' contribution to yield gains stems overwhelmingly from improved pest resistance, particularly through the Bt gene. In the short term, much of the potential yield benefit from genetic engineering lies in pest resistance for additional crops. Increased pest resistance does not necessarily involve breeding in pesticide resistance or natural pesticides. It might focus on other traits that make specific crops resistant to particular pests. Genetically modified cowpeas and plantains provide examples that could be useful for Africa.[198]

GM technology may also contribute to yields through improved drought resistance. Improving drought resistance, however, is complicated because of the large number of genes involved. Traits that lead to more resistance to some kinds of droughts will increase damage in other kinds of droughts and could hold down yields in wet years. The challenge, therefore, is finding the right mix that generates overall net gains across different years.[199] At this point, it is too soon to determine if drought-resistant crop varieties emerging in the United States will contribute to yield gains over multiple years, but the range of tools that could become available through different GM techniques offers hope.

Much of the interest in genetic engineering lies in the vast improvement in genetic techniques. To date, most genetic engineering is accomplished through a kind of "gene gun" that inserts a gene into existing DNA at unknown locations and in unknown ways. The current system relies on large-scale trial and error. But a variety of new techniques allow the precise placement or replacement of existing genes in particular locations, which holds great promise when combined with increased knowledge of what the different genes in a plant do.[200] Other techniques may permit the moving of genes around within a plant, or may change plants by suppressing the expression of some genes, therefore avoiding common consumer concerns about GM plants that contain foreign genes.

These techniques should not only make it easier to breed for pest resistance, but they could also lead to more fundamental improvements. One recent paper cites the potential to increase traits that resist aluminum toxicity or high salt concentrations, and that increase the plant's uptake of phosphorus and nitrogen.[201] Some researchers are trying to develop cereals that fix their own nitrogen, like soybeans and other pulses. Nitrogen-fixing cereals would probably assist production in some regions, although plants typically extract an energy cost for fixing their own nitrogen, which may hold down yields.[202] Researchers at the International Rice Research Institute are attempting to develop a C4 rice variety—a rice that would share the different photosynthetic chemistry of maize and sugarcane and generate higher growth in a number of conditions.[203] There are some even more ambitious efforts to reengineer some fundamental properties of photosynthesis to increase its rates. These changes could have dramatic benefits for yield growth, but even if successful, will almost certainly take decades.[204]

### The importance of conventional breeding aided by genomics

The most significant concern with genetic engineering as an overall technique for agricultural improvement is that its potential benefits are often overemphasized and could lead to distortions of research priorities. Whatever its benefits, genetic engineering is almost certainly less important to future yield gains than conventional breeding. GM technology generally works for traits that are controlled by a single gene, while most traits that lead to higher yields result from multiple genes.[205] In agriculturally advanced countries, the annual selection of the most favorable seeds from previous year trials supports the steady advance of yields. The major research breakthroughs that advanced yields in Brazil involved improvements through conventional breeding techniques—to soybeans, maize, and *Brachiaria* grasses for pastures—all of which can now thrive despite the higher aluminum in Brazil's more acidic soils.[206]

Fortunately, the improvement in genomics (DNA analysis) has also created many opportunities to improve conventional plant breeding. Because of genomics, it is now possible to identify more easily and cheaply the specific combinations of genes that are associated with desirable traits and to determine whether they are present in the offspring of even conventional breeding programs. The advance in genomics should make it possible to identify gene combinations that result in yield gains whose causes are not immediately obvious, and then to focus on their spread. This technology should also speed up breeding by making it possible to determine if particular cross-bred crops contain the desirable genes before the plant is fully grown and tested.[207] Genomics may also permit advances in fundamental science that could lead eventually to other improvements, including better understanding of the basic mechanisms by which plants resist pests and of the microbial interactions between plants and soils. These advances in genomics provide powerful arguments for increases in breeding budgets.

These advances also make a strong case for increased breeding attention to so-called orphan crops in developing countries.[208] Nearly all crops in these countries other than major grains and oilseeds are considered "orphan crops" because they receive less research attention. One 2004 article observed that 25 orphan crops in developing countries occupied 240 million hectares.[209] For example, although maize area in sub-Saharan Africa has been rapidly growing, in 2011 sorghum and millet still occupied roughly the same area as maize and wheat. Nevertheless, sorghum and millet breeding improvements receive a small fraction of the research funding for grain crops.[210] Genomic advances should make it easier to advance breeding quickly in these less-studied crops through the improved understanding of the gene combinations that have led to yield gains of the more studied crops. Improved breeding of orphan crops in many developing countries will require substantial investments in research, equipment, and training.[211]

The FAO projections of food demand discussed previously provide another reason to focus on orphan crops. Demand for pulses, potatoes, oil seeds, and fruits and vegetables is projected to grow more rapidly than demand for cereals, and FAO land use projections rely on greatly accelerated yield growth for many of these secondary crops. A new research initiative on grain legumes by a partnership led by the CGIAR provides a small but important step toward filling this need.[212]

Recent analysis of agricultural growth also supports the longstanding view that investments in agricultural research and development have high economic returns, with estimates commonly in the range of annual returns of 40 percent.[213] Although publicly funded agricultural research in the United States has declined,[214] it has been growing in middle-income countries such as Brazil, and in fact grew worldwide from $26.1 billion in 2000 to $31.7 billion in 2008.[215] Public funding for agricultural research and development in China grew almost four-fold between 1986 and 2007.[216] Fuglie (2012) shows a strong correlation between a country's growth in agricultural productivity and the combined investment in both agricultural research and development and extension services.[217] Extension services are responsible for disseminating research and helping farmers with their individual technical challenges. Investments only in research or only in extension result in modest gains, but putting the two together appears to lead to high rates of growth in productivity.

Overall, there is a good technical case for genetic engineering as one of the tools of improved breeding, but that should not obscure the even stronger case for increased investments in genomics and conventional breeding through publicly funded research and extension services.

### MENU ITEM | Boost yields by "leaving no farmer behind"

Although gaps between technical yield potential and actual yields exist everywhere, a common sense assumption is that these gaps are greatest in areas where agricultural technology is less advanced, particularly sub-Saharan Africa and other parts of the developing world. One cause of yield gaps in these regions is the lack of resources available to women farmers, which causes their yields to be lower than those of men (Box 6). Closing this gender gap in agriculture has great potential to reduce poverty and hunger directly. More broadly, bringing more farmers up to standard farming efficiencies should provide an effective way of closing yield gaps. Although the existence of yield gaps indicates that many farmers face a variety of economic or social obstacles not faced by other farmers, the fact that millions of farmers in a variety of settings have achieved higher yields on comparable land implies that many improvements should be both technically and economically feasible. In effect, these gaps call for a "no farmer left behind" strategy.

But what and where is the potential? Researchers have offered a variety of answers, which result not just from different methods of estimating yield gaps but also from different ways of defining them. Depending on the study, yield gaps are defined as the difference between actual yields and any of the following: the highest yields of that crop anywhere, the highest yields achieved by farmers in the region, the highest yields achieved by researchers in the region, the highest yields predicted by any of a number of different crop models, or the yields achieved in general by good farmers under growing conditions considered roughly equivalent. Each of these methods has strengths and weaknesses.[218]

One particularly well-known paper in *Nature* by Foley et al. (2011) found that "bringing yields to within 95 percent of their potential" for the 16 major food and feed crops would increase production 58 percent. Closing these yield gaps would be enough to close the bulk of our projected food gap by 2050, although the crop mixture does not perfectly match the FAO projections. Unfortunately, according to the paper, the highest estimated yield gaps on an absolute caloric basis (more than 4 million kcal/ha/yr) exist in northern India, northeastern China, and even parts of the United States grain belt—regions already intensively managed. The former Soviet Union provides the other area with large absolute yield gaps, and the only one where farming falls far short of technological potential according to common understanding. According to this study, although sub-Saharan Africa's yield gaps are high on a percentage basis, only southern Nigeria and Zimbabwe show up on the map with large yield gaps as measured in calories per hectare,

## BOX 6 | EMPOWERING WOMEN IN AGRICULTURE FOR IMPROVED YIELDS AND FOOD SECURITY

Women farmers produce half of the world's food, and between 60–80 percent of food crops in developing countries (FAO n.d.). However, on average, farms operated by women have lower yields than those operated by men, even when men and women come from the same household and cultivate the same crops (World Bank 2011).

Inequitable access to inputs and property explain much of this gap. For example, women typically have less access than men to fertilizer and improved seeds, to finance, and to market information. They have less ability to command labor, both from unremunerated family members and other members of the community (UN 2012). In some developing countries, women also may have lower levels of education, constraints on mobility, and high additional time commitments for child-rearing, gathering of firewood and water, and cooking (World Bank, FAO, and IFAD 2009).

Perhaps most difficult to rectify is women farmers' lack of property rights, which reinforces their limited access to inputs and credit because credit often requires collateral such as land. Although women represent an estimated 41 percent of the world's agricultural labor force, they control far less land: in Kenya, for instance, they are only 5 percent of the nation's registered landholders (World Bank 2011).

Studies have estimated that rectifying these imbalances can increase yields. The World Bank has estimated that if women farmers were to have the same access as men to fertilizers and other inputs, maize yields would increase by 11–16 percent in Malawi, by 17 percent in Ghana (World Bank 2011), and by 20 percent in Kenya (World Bank, FAO, and IFAD 2009). Overall, ensuring women's equal access to productive resources could raise total agricultural output in developing countries by 2.5 to 4 percent (UN 2012).

These gains in turn could have disproportionate benefits for food security because women are more likely to devote their income to food and children's needs than men (World Bank, FAO, and IFAD 2009). IFPRI has estimated that improvements in women's status explain as much as 55 percent of the reduction in hunger from 1970 to 1995. Progress in women's education can explain 43 percent of gains in food security, 26 percent of gains in increased food availability, and 19 percent of gains in health advances (IFPRI 2000). In the same vein, FAO estimates that providing women with equal access to resources could reduce world hunger by 12–17 percent (FAO 2011a).

while yield gaps in most of the region are less than 1 million kcal/ha/yr. These results are discouraging, because high crop prices, government support, and infrastructure already provide farmers in the high yield-gap regions of the United States, China, and India high incentives to boost yields.

In contrast, a global yield gap study by Neumann et al. (2010b) resulted in quite a different map showing, for example, much larger maize yield gaps in Africa (5–9 t/ha/yr) and much smaller gaps in the United States (less than 2 t/ha/yr in most areas).[219] Different methods lead to greatly different results at the global level.

There is a conceptual problem with all yield-gap analyses that is particularly problematic for global studies. In effect, any yield-gap analysis uses some kind of a model to predict what yields should be across broadly similar areas, assuming the same type of excellent management. Yield-gap analyses then assume that any lower yield results from poorer management. In fact, model predictions are imperfect because of data error, because they cannot capture all the physical factors that drive yields, and because we do not even know how all those factors influence yields. These imperfections result in an inherent tendency to exaggerate yield gaps and an inability to know precisely the extent to which lower yields—that is, the "yield gap"—result from management limitations rather than data or model error. Global estimates will have the largest errors because their models must be relatively crude and because the data errors at the global level are high. As Neumann et al. (2010b) forthrightly acknowledge, the inaccuracies in global data "might even outrange the yield gap itself."

Yield-gap analysis becomes more reliable the more it is based on local data about soils and climate and locally verified crop models.[220] Such a rigorous local approach can potentially not only identify yield gaps, but also tease out the key factors keeping yields low that can be modified. This logic provides a strong case for the Global Yield Gap Atlas project.[221] Led by agronomists at the University of Nebraska and Wageningen University, the project is pursuing such local yield-gap analyses worldwide. It should be a global research priority to identify the best ways of helping farmers everywhere to catch up.

No one doubts the existence of sizable yield gaps or the importance of closing them to achieve a sustainable food future. However, the causes of and potential solutions to those gaps—as well as the scale of the opportunity these solutions offer—remain to be properly studied.

### MENU ITEM | Boost output per hectare by planting existing cropland more frequently

One way to produce more food on existing cropland is to plant and harvest crops on that land more frequently. What is a likely scenario, what are the prospects for doing better, and what are the implications for greenhouse gas emissions?

The ratio of the quantity of crop harvests in a year—the harvested area—to the quantity of arable land is known as the "cropping intensity." Two factors influence that ratio in different directions. First, not all cropland is harvested each year. Lands identified as fallow imply that cropland is being rested, which results in a cropping intensity of less than one. But in some warm climates with irrigation or sufficient rainfall throughout the year, farmers plant and harvest two crops a year, and in a few locations three, which increases cropping intensity. In Bangladesh, for example, farmers harvest on average 1.56 crops each year per hectare of cropland.[222]

FAO projects an increase in the harvested area by 2050 of 131 million hectares, but it projects that cropland area will only increase by 69 million hectares. An increase in cropping intensity explains the 62 Mha difference,[223] and that increase helps to explain the difference in projections of cropland expansion between FAO and GLOBIOM. FAO projects that irrigated lands will provide roughly two-thirds of this cropping intensity gain, presumably from an increase in doublecropping.[224] These estimates are based on the judgments of regional experts, but there is no documentation to evaluate them further.

IIASA estimates that the potential for increasing doublecropping—even on rainfed lands—is large and that half of all land suitable for growing cereals could technically support two crops.[225] This figure counts both existing cropland and potential cropland, including forests. Yet farmers probably plant two crops a year on only 5 percent of rainfed area.[226] Unless farmers are massively missing opportunities, the realistic economic prospects for expanding doublecropping on rainfed lands must therefore be far more limited than those projected by IIASA.

The alternative mechanism for increasing cropping intensity involves leaving land fallow less often. Adjusting for areas that are double-cropped, about 400 million hectares of cropland were not harvested in 2009, according to FAO data.[227] This amount roughly matches the 450 million hectare estimate based on 2000 data from a paper by Siebert et al. (2010a) that attempted to analyze cropping intensity globally.[228] Siebert's data suggest great potential to produce more food on existing cropland, but a closer look is more discouraging:

- **Some cropland is already planted and used but left out of FAO data on harvested area.** In the United States, roughly 15 percent of all cropland—more than 20 Mha—produces hay, which is often highly productive and lucrative, and another 5 percent is typically used for pasture. FAO does not gather data on hay or cropland used for pasture, and the global portion of cropland used in this way is unknown.

- **Much fallow land is dry.** The Siebert study indicates that much cropland lies in exceptionally dry environments, where rainfall does not permit production of crops each year.

- **Much land called "cropland" is actually abandoned.** To meet FAO's definition, any "cropland" must have been cropped within the past five years. But even the data for U.S. cropland includes lands enrolled in the U.S. Conservation Reserve Program, and most of these lands have been planted with grasses or trees for more than five years.[229] Cropland also appears to include large areas abandoned from agriculture in the former Soviet Union.[230] Unlike truly occasional fallow land, abandoned land reverts to forest or grassland, which sequesters abundant carbon and provides other ecosystem services. Using this land may be preferable to plowing up the world's remaining intact ecosystems, but it still comes at substantial environmental cost.

More broadly, FAO data for reported cropland can be unreliable. For example, between 2001 and 2008, FAO reported a decrease in Indian "temporary fallow" cropland of 92 Mha, even though there was no corresponding decline in cropland or increase in harvested area. That change probably reflected a realization that land once categorized as arable was truly abandoned. These judgments can be difficult when it comes to shifting agricultural systems, since lands lie in various stages of vegetative regrowth.[231]

- **Planting fallow land may have substantial environmental costs.** According to the Siebert paper, Africa and parts of Southeast Asia contain a great deal of fallow land reported to FAO. But much of that land is probably "long-term fallow" land rotating in and out of agriculture only over many years. In these landscapes, the fallow land on average stores substantial carbon and provides other ecosystem services. Harvesting more of those "croplands" each year would increase greenhouse gas emissions and cause a decline in ecosystem services, even if doing so only technically represents an increase in cropping intensity and not an increase in cropland area.

Overall, the data limitations bar any confident assessment of the potential or likelihood of increased cropping intensity or of the environmental implications of such an increase. Increases in doublecropping and reductions in short-term fallow lands probably provide an important mechanism for holding down land use change. In some long-term fallow regions, more intense cropping of regularly cropped land might allow permanent regeneration of forests on other shifting cropland. But where and how this intensification occurs will determine its environmental merits. Although we cannot judge the scale of this menu item, it merits a more careful analysis. Such an analysis should assess the technical and practical potential to plant land more frequently based on good land use data from high-resolution imagery and corresponding field analysis.

### MENU ITEM | Boost yields through improved soil and water management (especially in Africa)

Land degradation drags down production in many regions, and nowhere more so than in Africa, where yield gains are particularly needed (Box 7). Forms of degradation include deforestation and loss of vegetative cover, soil erosion, nutrient loss, and loss of soil organic matter. Nutrients are lost as the annual removal of nitrogen, phosphorus, and potassium by crops exceeds the annual additions.[232] More rainfall runs off degraded than good cropland, which leads to erosion and loss of organic matter, lower rates of infiltration, and water stress. Losses of organic matter, due in part to failure to replenish soils with sufficient plant material, reduce the capacity of soils to hold water and to hold and exchange nutrients with plants.[233] Crops on soils with low organic matter have lower fertilizer-use efficiencies, which in Africa can make the use of fertilizers economically unattractive.[234] Adopting soil and water conservation practices to reverse this degradation therefore has potential to boost yields.

A number of on-farm soil and water conservation practices can help address these challenges (Box 8). Although these long-known practices are being implemented to varying degrees around the world, two in particular appear to have potential for take-off in Africa: agroforestry and water harvesting. These practices not only can boost yields, but they can also generate a range of economic and ecosystem benefits.

## BOX 7 | THE IMPORTANCE OF BOOSTING YIELDS IN SUB-SAHARAN AFRICA

Although yield growth anywhere will contribute to a sustainable food future, yield growth in sub-Saharan Africa is particularly important. Nearly all the growth in food demand by 2050 will occur in the developing world, and the largest demand growth will occur in sub-Saharan Africa. The region today consumes 9 percent of world calories annually, but the region's growth in demand will account for 37 percent of all projected new calories by 2050.

Because the region is poor and depends heavily on importing staples, local yield growth has particular significance for reducing hunger. It also has the potential to reduce land expansion. Because yields in sub-Saharan Africa are low–cereal yields average roughly one-half of global yields–increasing food production in the region could result in greater expansion of crop area than increasing food production elsewhere in the world.

To illustrate the importance of the region's yields to future land use, if sub-Saharan Africa were to cut in half its dependence on imports for staple foods yet meet FAO's food demand projections, we calculate that the region would have to triple cereal yields by 2050 to avoid expanding agriculture onto new land. This required annual yield growth–every year an additional 59 kg/ha/year—exceeds the world's average annual cereal yield growth over the past 50 years. It would rival yield growth in China over the past 45 years, but China's land is far wetter and more fertile.

Projecting Africa's demand for land depends both on the continent's yield growth and on how much it relies on imports for staple crops. For decades, yield growth in the region was stagnant, but yields have started to grow in the past five years. No one can confidently project what either its yield growth or import reliance will be. Much of the difference between the expansion estimates of GLOBIOM and FAO lie in how much land expansion they predict in Africa: 183 Mha by GLOBIOM and 51 Mha by FAO. Overall, how much agricultural land expands in the world will largely depend on how much it needs to expand in sub-Saharan Africa, and that makes the boosting of the region's yields of special importance, not only for food security, but also for carbon emissions and ecosystem health.

But closing yield gaps is not necessarily easy. Farming in sub-Saharan Africa in particular is limited by poor infrastructure and soil conditions. High rainfall variability also makes it less economically attractive to use high yielding technology. Although farmers could increase yields by using more inputs such as fertilizer to take advantage of potentially good yields in wet years, much of that fertilizer will go to waste in years when rainfall is low. To employ these inputs amid rainfall variability, farmers must also have greater capacity to smooth income over multiple years–precisely the greatest challenge for small farmers. Restoring degraded soils in Africa is one way of boosting yields.

### Agroforestry

Agroforestry involves the integration of trees and shrubs on land with crop or animal production. Farmers practice agroforestry in different ways in many parts of the globe, including Latin America, Asia, and Africa.

For the drier regions of Africa, the experience in Niger profiles the potential benefits of agroforestry. Over the past several decades, farmers in Niger have managed the natural regeneration of native trees growing in farm fields across approximately 5 Mha. A native acacia, *Faidherbia albida*, is particularly popular with farmers because it fixes nitrogen in the soil, protects fields from wind and water erosion, and drops its leaves before the start of the growing season, which both releases nitrogen and contributes soil organic matter.

Similar practices have begun to spread to other countries. In the Seno Plains of Mali, farmers have expanded agroforestry practices over 450,000 hectares.[235] Kenya, Zambia, and Malawi are increasing the protection of trees on farms and increasing adoption of intercropping of nitrogen-fixing species, including *Faidherbia*.[236] Interest is also growing in other areas of the world in the intercropping of shrubs like *Leucaena*, the leaves of which provide high-protein forage.

A number of recent studies indicate that agroforestry can increase crop yields. Trial sites under *Faidherbia albida* canopies in Zambia yielded 88–190 percent more maize than sites outside of canopies (Figure 26). In the Kantché district in southern Niger, a region with high levels of on-farm tree densities, farmers have produced grain surpluses every year since 2007, even in the below-average rainfall year of 2011.[237]

Farmers in the Sahel often encourage the regeneration of other trees such as baobab, shea nut, desert date, and néré to generate additional outputs, including fruit, medicines, and fiber. Seed pods and leaves serve as fodder for livestock. Leaves of one mature baobab can vary in value from $28 to $70, an amount sufficient to buy 70–175 kg of grain in the market.[238] Large branches supply poles for home construction or can be sold in local markets for additional income. Branch trimmings provide firewood. In Niger, studies compared responses of villages with and without investments in managing on-farm trees during the 2004–05 drought, and found that those with more trees on their farms were better able to cope because they had tree products generating income to buy grains.[239]

## BOX 8 | MAJOR TYPES OF SOIL AND WATER MANAGEMENT PRACTICES

The World Overview of Conservation Approaches and Technologies publication—*WOCAT 2007: Where the Land is Greener*—identified seven major types of soil and water management practices. This global survey and analysis of what works, where, and why generated 42 case studies on the costs, benefits, and impacts associated with specific applications of the following practices:

1. **Conservation agriculture** – Promoting minimal soil disturbance from tillage (e.g., no-till, low-till); a balanced application of chemical inputs (only the amount required for improved soil quality and healthy crop and animal production); and careful management of residues and wastes.

2. **Manure and composting** – Enriching and replenishing the nutrient content of cultivated soils by the addition of livestock manure, decomposed crop residues, and other organic wastes.

3. **Vegetative strips** – Planting multipurpose vegetation barriers or buffers along contours in fields to help control erosion and reduce the flow of sediment, organic matter, and nutrients off farms and the flow of pollutants into adjacent water bodies, while increasing production of fodder and thatch.

4. **Agroforestry** – Incorporating the cultivation and conservation of trees in farm fields or growing harvestable trees or shrubs among or around crops or on pasture.

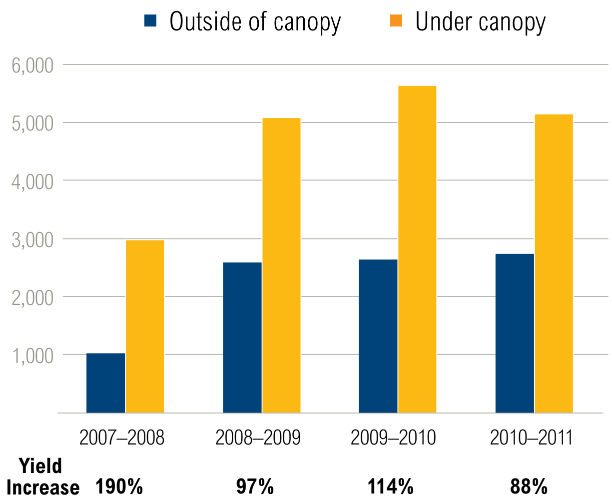
5. **Water harvesting** – Implementing a variety of techniques—such as planting pits, half-moon-shaped earthen bunds, stone lines, and ridge tillage along contours—in order to collect and concentrate rainfall runoff to improve soil moisture, plant growth, and crop production.

6. **Gully rehabilitation** – Placing barriers of stone, earth, or vegetation across gullies to control runoff and reduce erosion.

7. **Terraces** – Constructing earthen embankments across fields to reduce erosion and retain runoff to conserve soil nutrients and moisture.

Source: Hanspeter and Critchley, eds. (2007).

Figure 26 | **Maize yields in Zambia are higher under *Faidherbia* trees (kilograms per hectare)**




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

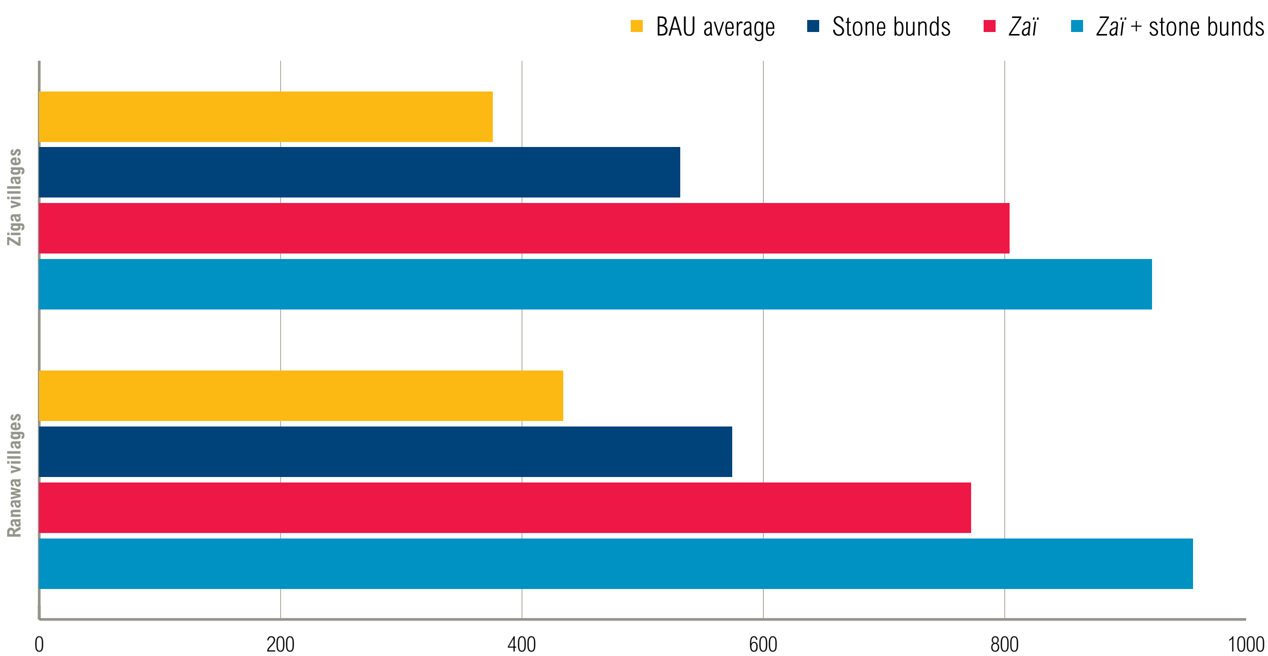
*Source:* Shitumbanuma (2012).

### Water harvesting

In dry areas, a variety of low-cost, simple water management practices can capture and collect rainfall before it runs off farm fields. Without attention to soil and water conservation and erosion control, rainfall runoff on unprotected fields is estimated to average 25–50 percent. In Mali, 70–80 percent of rainfall can be lost to runoff, taking with it 40 percent of the nutrients applied to soil through organic and mineral sources of fertilizer.[240] A variety of structures can serve to capture the water—including planting pits (called *zaï* in Burkina Faso), half-moon-shaped earthen bunds, stone or earth barriers, and trenches across slopes. In the Tahoua Region in Niger and the Central Plateau of Burkina Faso, farmers have employed water-harvesting techniques on 500,000 hectares since the late 1980s.

Water harvesting helps to buffer farmers from the effects of erratic and reduced rainfall and thereby increases crop yields.[241] In the Sahel, tilled ridges–giving a surface storage of 20-30 mm–can prevent much runoff and capture scarce rainfall in a dry year. This practice allows earlier sowing and prolongs the

Figure 27 | **A combination of water harvesting practices increases grain yields more than one practice (kilograms per hectare)**




*Source:* Sawadogo (2008).

*Note:* These two groups of villages are located on the northern central plateau of Burkina Faso. "BAU" = business as usual.

vegetative growth by as much as 20 days, which can increase the millet yield by 40 percent.[242] Combining techniques on the same farm can increase yields more than one technique on its own (Figure 27).[243] Field observations and farmer testimonies indicate that water harvesting also has contributed to increased water levels in nearby wells and to an expansion of small-scale dry season irrigated vegetable gardens.[244] One study in Zimbabwe found that water harvesting, combined with conservation agriculture, increased farmer gross margins per hectare four-to-seven-fold, and returns on labor two-to-three-fold compared to standard practices.[245]

### Complementary approaches

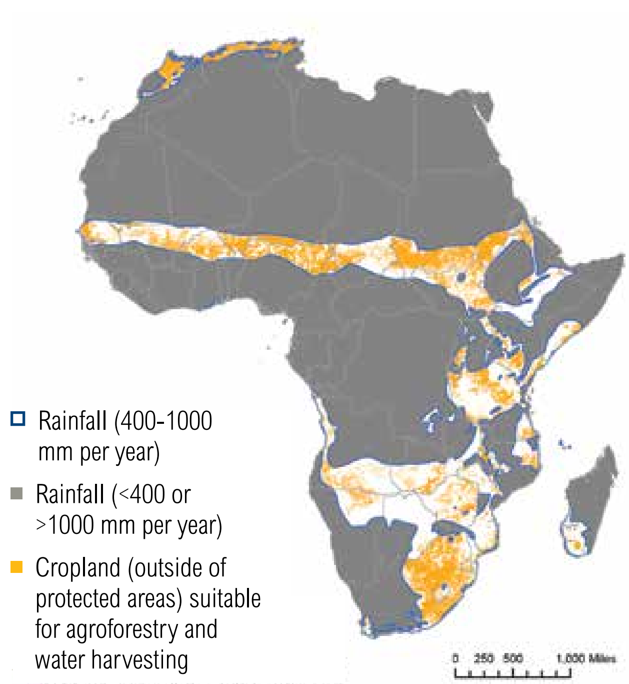
As studies have shown, soil and water management practices can be conducted either in isolation, together, or in conjunction with conventional technology solutions such as fertilizers and improved seed varieties. Microdosing provides an example of a complementary practice and involves the application of often just a capful of fertilizer directly to crop seeds or young shoots at planting time or when the rains fall.[246] Microdosing enables expensive fertilizer to go as far as possible with the least amount of waste. Approximately 473,000 smallholder farmers in Mali, Burkina Faso, and Niger have now employed the technique and have experienced increases in sorghum and millet yields of 44–120 percent, along with increases in family incomes of 50–130 percent.[247]

Field results indicate that combining water harvesting, agroforestry, and microdosing has significant promise.[248] Water harvesting helps improve soil moisture and recharge groundwater. Agroforestry increases soil nitrogen, organic matter, and moisture. Fertilizer microdosing adds phosphorus and potassium where soils lack those elements. When conducted in sequence, water harvesting and agroforestry prepare the soil for the fertilizer, maximizing fertilizer-use efficiency.[249]

### The potential for scaling

The potential for expanding these and related soil and water management practices is vast. Within sub-Saharan Africa, agroforestry and water harvesting could potentially be implemented on more than

Figure 28 | **Agroforestry and water harvesting could be scaled up on more than 300 million hectares in sub-Saharan Africa**




*Source:* WRI analysis based on IUCN and UNEP (2013), Fritz and See (2013), and FAO and UNEP (1986).

300 million hectares. Figure 28 shows areas with suitable rainfall levels—400–1,000 mm per year—and suitable soil conditions for agroforestry, while excluding protected areas, existing dense forests, and other natural ecosystems, cities, and villages. If improved soil and water management practices were implemented on just 25 percent of this cropland and increased crop yields by an average of 50 percent, farmers would produce on the order of 22 million more tons of food per year, equivalent to about 64 trillion kcal.[250] Although this increase is not large in a global context, it could increase calorie availability by 615 kcal per person per day for the approximately 285 million people who live in these regions.

### BOX 9 | WHAT ARE "LOW-CARBON DEGRADED LANDS"?

Low-carbon degraded lands are areas where natural vegetation has been cleared in the past, where there is limited human use, and where carbon stocks and biodiversity levels are both low today and likely to remain low in the future. "Degraded" in this sense does not imply that the land necessarily has poor soil quality. These lands are "low cost" only in the sense that the economic and environmental costs of converting them to agriculture are low. Yet even these areas are not necessarily devoid of people who use or claim the land, so social safeguards are important when considering conversion of these lands into agriculture.

## Minimizing the Consequences of Cropland Expansion

Our analysis suggests it will be difficult to boost yields sufficiently to avoid any net expansion of cropland globally. Even if it does sufficiently boost yields, there will be powerful forces to expand cropland in some locations. This reality calls for strategies to direct any cropland expansion into areas with only modest environmental and economic costs.

### MENU ITEM | Expand onto low-carbon degraded lands

Expansion onto "low-carbon degraded lands" (Box 9), if done right, could avoid conversion of natural ecosystems and carbon emissions, while boosting income and job growth by increasing agricultural output from currently underproductive areas. A critical question is what land should qualify. Some researchers have used vague and inappropriate definitions when claiming that vast areas of low-carbon degraded land exist. Nevertheless, attractive candidates with meaningful potential do exist.

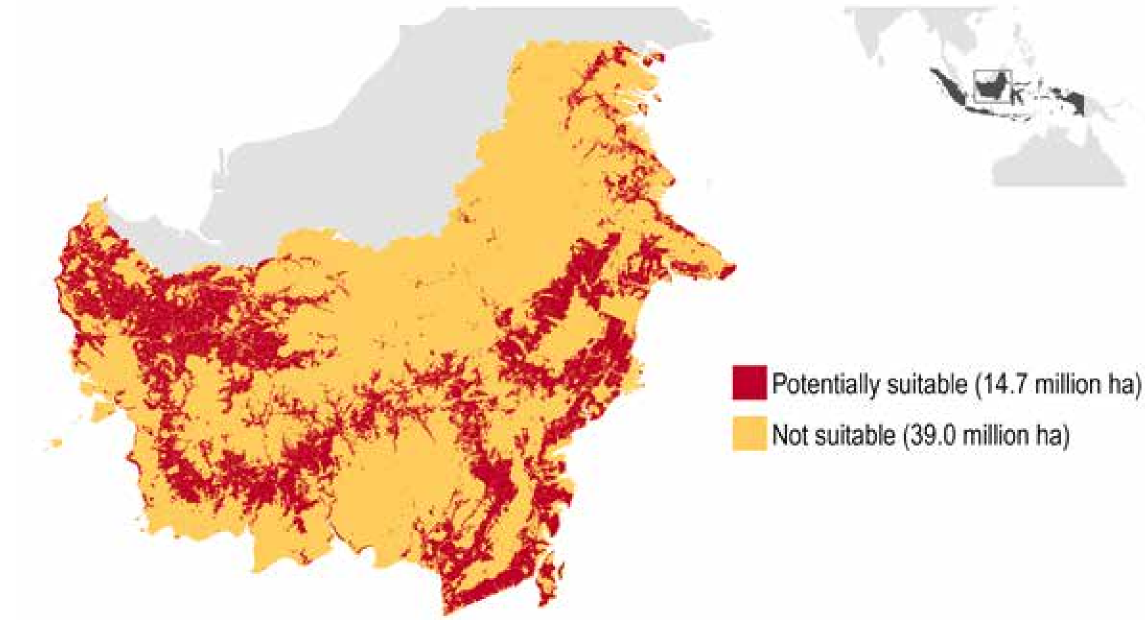
#### Attractive candidate

The *Imperata* grasslands (*Imperata cylindrica*) of Indonesia provide probably the prime example of low-carbon degraded land suitable for agriculture expansion. Also called "alang-alang," these invasive grasses often dominate landscapes after forests are cleared. These grasslands have low carbon content—less than 20 tons of carbon per hectare (tC/ha) compared to more than 100 tC/ha in secondary forests and more than 200 tC/ha in the primary forests of Sumatra and Kalimantan, Indonesia.[251] They also tend to prevent the return of a natural forest because they frequently burn and exude chemicals that inhibit competing plant growth. As a result, the potential future carbon storage of *Imperata* grasslands is also low.

The economic returns of *Imperata* are low, too. Because annual crop production on these grasslands is difficult and costly,[252] these lands are generally only used for thatch or for non-intensive grazing. Nonetheless, converted *Imperata* grasslands can support sustainable and economically viable tree crops, for instance oil palm. The return on investment from establishing oil palm on converted *Imperata* grasslands can be favorable when compared with the return on investment of establishing oil palm on recently cleared forests.[253]

Use of *Imperata* grasslands to produce palm oil is important, because the demand for palm oil is growing rapidly and alternative plantation sites have very high environmental value. The oil palm tree is the world's most productive source of vegetable oil, with average global yields of 3.7 tons of oil per hectare, or 10 times the yield per hectare of soybeans.[254] In 2011, oil palm provided 32 percent of the world's vegetable oil production,[255] beating out soybeans as the world's dominant vegetable oil crop. Experts predict that oil palm will fill an even larger percentage of future demand because of its

Figure 29 | **More than 14 million hectares of low-carbon degraded lands in Kalimantan (Indonesia) are potentially suitable for oil palm**




*Source:* Gingold et al. (2012).

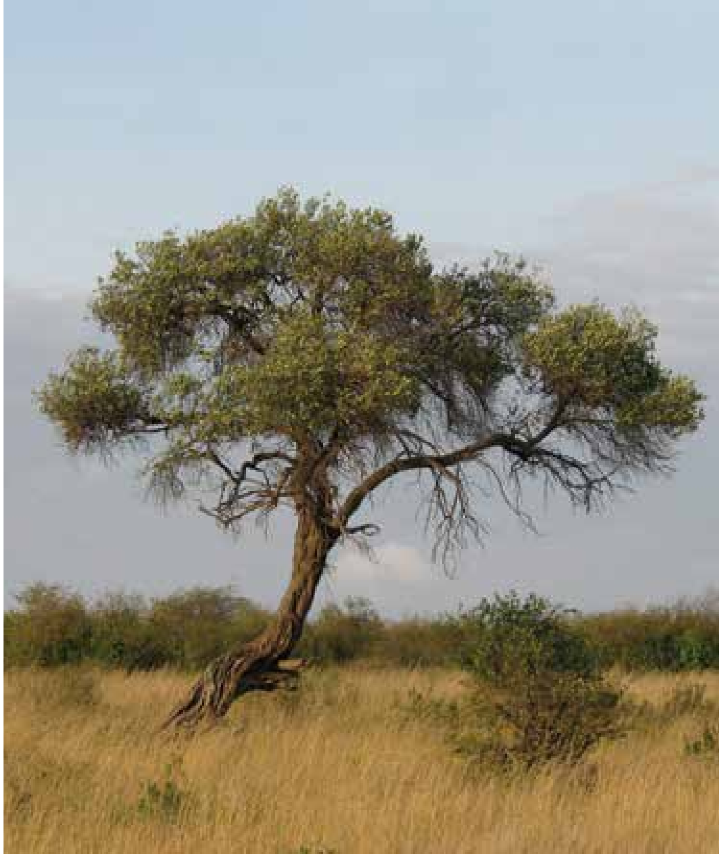
high productivity. One estimate projects a need for at least an additional 12 Mha of oil palm plantations globally by 2050 to meet worldwide demand—and potentially far more.[256]

Historically, expansion of oil palm has come at the heavy expense of carbon-rich natural forests and peatlands. Converting peatlands to oil palm requires drainage, which allows oxygen to penetrate and decompose the vast stores of carbon laid down over thousands of years. The release of carbon continues for decades. One paper estimates the peat deposits in Indonesia and Malaysia contain carbon equal to nine years of the world's global emissions from fossil fuel use.[257] According to the best information available, this peat oxidation would release an extraordinary 4,300 tons of $CO_2$e per hectare over 50 years, which is on the order of eight times the likely emission from the burning of even the densest tropical forest cover.[258]

Oil palm in Indonesia has now expanded into 2.1 million hectares of peatlands.[259] Based on patterns of expansion and maps of concessions, this area will probably double to 4.1 million hectares by 2020, and could plausibly even triple by that date.[260] Yet, in 2010, the ongoing degradation of peatland in Southeast Asia alone was responsible for roughly 2.5 percent of annual, global greenhouse gas emissions from all human sources, or roughly one quarter of all emissions from land use change.[261] By simple arithmetic, doubling or tripling the area of drained peatland could therefore double or triple their emissions to 5–7.5 percent of all global emissions. As these emissions continue for decades, such an increase would lock in annual emissions from degrading peat alone at half or more of today's total global emissions from land use change. Finding alternatives to natural forests and peatlands is therefore urgent.

The use of *Imperata* grasslands could provide vegetable oil and economic opportunities while avoiding forest and peatland conversion and associated greenhouse gas emissions. But are there enough of these grasslands? One study estimates a need for 3 to 7 million hectares of additional oil palm plantations in Indonesia between 2010 and 2020.[262] Estimates of *Imperata* grassland area in Indonesia range from 3.5 Mha[263] to 8 Mha[264] to even 20 Mha.[265] An analysis by WRI and partners suggests that more than 14 million hectares of low-carbon degraded land in

Indonesia's Kalimantan region of Borneo may be suitable for palm oil production, although not all are *Imperata* grasslands (Figure 29).[266] Not all of these hectares will become plantations, nor should they; people living near some degraded areas may not want oil palm plantations and some areas may be better suited for forest regeneration.[267] Yet at least for some years, *Imperata* grasslands appear technically capable of meeting growing oil palm needs.



### Unattractive candidates

Unlike the *Imperata* grasslands, many areas sometimes called "degraded land"—or treated as a low environmental cost "land reserve"—cannot in fact be used for new croplands without serious costs to climate, ecosystems, and/or water. In other cases, these degraded lands already support agricultural production, overstating the opportunity. Examples include:

- **Wet tropical savannas.** A number of studies identifying potential lands for food and bioenergy expansion start with an assessment of lands physically suitable for food or bioenergy crops and then screen out certain land use types. These studies typically exclude existing cropland and intensively managed grasslands, denser forests, protected areas, and urban land. The remainder is treated as a land reserve with low environmental value.[268] Many of these remaining lands are wet tropical savannas in Africa and South America. However, wet tropical savannas store large quantities of carbon, have high levels of biodiversity including the great mammals of Africa, and provide important watershed functions.[269] They are anything but of low environmental value. Furthermore, many of these lands are used by local people for other uses such as small-scale livestock grazing, wild game hunting, and traditional cultural uses.

- **Physically degraded land.** FAO published the GLASOD map of land that is physically degraded based on local expert estimates using broad, narrative criteria. However, these maps were based on limited information and do not necessarily identify lands that are not already productive. They also refer primarily to lands that are already in agricultural production and thus identify areas in need of soil quality improvement, not areas with potential conversion to agriculture.[270]

- **Abandoned farmland.** Some papers treat abandoned farmland as an essentially free land reserve.[271] But abandoned farmland in areas capable of supporting trees will typically revert to forest, and thereby not only provide wildlife habitat but also combat climate change by absorbing atmospheric carbon dioxide. The most oft-cited study estimating the amount of global abandoned land that has not yet reverted to forest primarily identifies dry, abandoned grazing land that would be practically unsuitable for food or bioenergy.[272] Abandoned farmland, in fact, plays an important role in global land use shifts. As the FAO recently showed, as farmers around the world are clearing more land for agriculture, large areas of abandoned land are reverting back into forest.[273]

- **Secondary forests.** Some proposals to focus agricultural expansion on low-cost lands treat secondary forests as appropriate.[274] While such forests tend to store less carbon and support less species diversity than primary forests, they do still perform both of these functions.[275] In Europe and the United States, secondary forests constitute nearly all the remaining forests. The regrowth of secondary forests sequesters carbon and plays a large role in holding down climate change.[276]

A failure to appreciate the dynamic nature of land use leads some people to mistakenly view these unattractive candidates as attractive. Changes in the total quantities of forest and grassland obscure the large volume of land transitioning from one land use to another. Whether a tract of land is considered "low carbon" should reflect not only the amount of carbon it currently stores, but also the amount it is likely to sequester in the future if left alone. Calculations must also consider the potential benefits of crop conversion, including likely yields. Even if conversion of a tract of degraded land resulted in only small quantities of carbon emissions, this approach would not contribute much to a sustainable food future if crop yields on that land were also likely to be low.

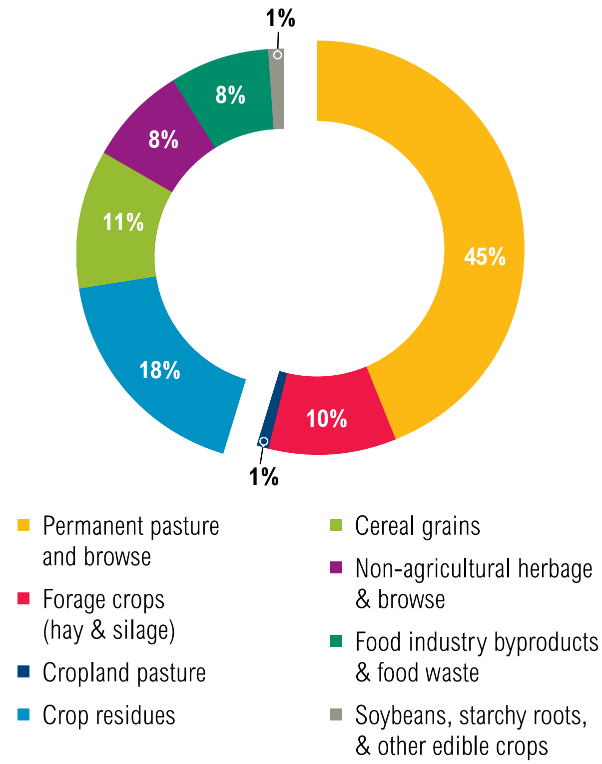
## The Pasture Challenge

Pasture expansion into forests and native savannas has probably led to more land use change and greenhouse gas emissions than cropland expansion over at least the past two decades.[277] Overall, the world contains two to three times as much grazing land as cropland, depending on the criteria used to identify grazing land.[278] Turning forest into grazing land has been the dominant cause of forest loss in Latin America over the past several decades.[279] Grasses contribute a majority of all global animal feed calories—56 percent by one calculation (Figure 30).[280] Although pasture yields receive a fraction of the attention devoted to cropland, increasing those yields will be critical to protecting ecosystems and minimizing greenhouse gas emissions from land use change.

### Scope of the challenge

Between 2006 and 2050, FAO projects a roughly 80 percent increase in the demand for beef, mutton, and goat, and a 70 percent increase in demand for dairy. This increase does not reflect our population and food availability adjustments, which raise the figures modestly to 90 percent (beef) and 80 percent (dairy). At the same time, FAO projects a smaller percentage rise in the use of crops as feeds to generate those animal products.[281] Even though FAO assumes continuing improvements in feeding efficiency within livestock production systems, it projects overall efficiency will decline due to a shift in production from developed to developing countries, where reliance on crops for feed and overall

Figure 30 | **Grasses provide more than half of all animal feed (percent, 100% = 6,724 Tg dry matter per year, 2010)**




*Note:* Soybean and other oil meals are included in "Food industry byproducts" while whole soybeans are included in "Soybeans, starchy roots and other edible crops." Data represent means between 1992–94 and 2030.

*Source:* Wirsenius et al. (2010).

feeding efficiencies are lower. Although FAO does not explicitly project changes in pasture area, the implication is that the yields of both meat and dairy from pasturelands must also increase by 80–90 percent to avoid further pasture expansion. Mathematically, if average pasture yields did not increase at all, producing that much more dairy and meat would require the conversion of the bulk of the world's remaining tropical forests and savannas.[282]

To put the challenge in perspective, FAO projects a higher annual growth of milk and ruminant meat going forward than in the past. The annual absolute projected increase in calories per year from 2006 to 2050 from both milk and ruminant meat exceeds the rate of the previous 44 years by 40 percent. This previous period already experienced what scholars have called a "livestock revolution," with many increased feeding efficiencies in raising livestock—as well as associated environmental challenges from such changes as the concentration of wastes by feedlots. Yet pasture areas expanded as well, according to FAO data, increasing by 270 million hectares from 1961 to 2009.[283] To avoid further expansion, the yields of milk and meat from pasture must increase at much faster rates. And to avoid emissions from land use change and impacts on ecosystems, this increase in yields must not result from a shift in pasture away from dry lands and into tropical forests and wetter savannas—but such shifts appear to be occurring.[284]

Despite this challenge, the OECD study using the IMAGE model projects that pasture area will modestly decline by 50 Mha from 2010 to 2050. This study also projects a 70 percent rise in beef production in this period, a 37 percent increase in dairy production (which is more modest than the FAO projection), and a more than 70 percent increase in production of sheep and goats. Like the FAO analysis, IMAGE projects that the role of crops as feed for ruminants will actually modestly decline. In IMAGE, the growth of dairy production is entirely due to an increase in the quantity of grasses and crop residues, and scavenged feed. Shifts of dairy production into less intensive regions cause dairy production overall to become modestly less efficient at turning feed into milk. In the case of beef, the growth in consumption of grass is proportionate to the growth in total feeds by 2050 and contributes 70 percent of the production increase, while 30 percent is due to improvements in the efficiency with which cattle process grasses and other feeds into meat.[285] Overall, IMAGE's projection of a modest global decline in pasture area relies on very large global increases in the quantity of meat and milk generated by each hectare of grazing land.

In some countries, the expectation is not only that pasture area will cease to expand, but that it will contract and thereby free up wetter grazing lands for cropping, for plantation forests, or for the restoration of natural habitats. Brazil's national climate plan relies on such gains in pasture productivity and intensive forest management to accommodate ongoing expansion of cropland while eliminating deforestation.[286] If pasture yield increases are to not only meet the projected growth in demand for pasture-based milk and meat, but also free up land for additional cropping, the yields would have to grow even more than 80–90 percent.

Yet if grazing land yields do not grow as much as assumed by IMAGE, demand for pasture area will increase greatly. For example, GLOBIOM estimated 121 million more hectares of pasture by 2050—despite projecting a 60 percent increase in the world's grazing livestock per hectare. Although Wirsenius et al. (2010) uses a different period and is not directly analogous, it estimated a 151 Mha increase in grazing land over a 37-year period after 1990. It did so despite assuming almost a 50 percent increase in grasses consumed per hectare globally, along with a 7 percent average global increase in the efficiency of converting those grasses to meat and milk.[287]

Overall, we consider the predictions of the IMAGE model too optimistic for a business as usual scenario as we define it. Despite technical potential to increase grazing efficiency, there are also major challenges. We believe there are no general grounds for projecting that pasture will expand at less than historical rates without major policy changes.

## MENU ITEM | Increase productivity of pasture and grazing lands

Our analysis highlights the importance of increasing pasture yields. The basic types of tools for doing so are well-known:

- Plant pastures with improved grasses and legumes, and fertilize them to produce larger and more digestible forage.
- Selectively use more grains and high protein oilseed meals as a grass supplement, particularly during the inevitable dry or cold seasons when grass production drops off. Helping to maintain growth during dry periods disproportionately contributes to a net gain in meat or milk.
- Improve health care for cattle, goats, and sheep—and improve breeds so that the animals produce more meat and milk from the same amount of feed.
- Graze animals more efficiently by rotating them quickly among parts of a field, often by moving electrical fences. Overall, this approach

leads animals to consume more of the available forage while it is more nutritious, and tends to maximize grass growth by keeping grasses at optimal growing heights. In some areas, improvements can occur just by mixing cattle with sheep or goats, which graze differently and improve the efficient use of the whole pasture. Mixing species can also address pest problems, such as those from worms.[288]

- In tropical areas, add shade trees and nitrogen-fixing shrubs to reduce animal stress, maintain moisture levels, add protein to animal diets, and fertilize the grasses.

The world's wetter grazing lands hold the greatest potential for yield improvement. Wetter pastures include pastures carved out of native forest, which includes nearly all the pastures of western Europe, the eastern United States, and the Amazon. This category also includes pastures created out of wetter savannas and low woodlands, like the Cerrado of Brazil. In contrast, although some of the world's drier grazing lands are overgrazed—western China is a prominent example[289]—many traditional pastoralists have already achieved high levels of grazing efficiency, sometimes through subtle estimates of the location and availability of forage that scientists cannot match.[290] There is little evidence of a potential for large yield gains on these drier lands.

Thanks to its high rainfall and present low production efficiencies on at least 175 million hectares of pasture, Brazil probably has the largest potential to intensify its grazing land. Improvements in the state of São Paulo and more modest increases nationwide have already demonstrated Brazil's high potential to increase grazing land efficiency.[291] An analysis led by Bernardo Strassburg of the International Institute for Sustainability estimates that beef production on existing grazing land is only at roughly one-third of capacity in Brazil.[292] This study estimates that Brazil can increase its exports of beef by 50 percent over the next 30 years by increasing pasture productivity from one-third of potential to one-half of potential. This estimate assumes only basic methods of intensification, such as improved fertilization and rotational grazing.

Silvopastoral systems can achieve even higher levels of pasture productivity. These systems combine forage grasses with trees and sometimes shrubs. As

practiced with particular intensity on 4,000 hectares in one region of Colombia, an intensive silvopastoral system includes five separate layers of vegetation: a layer of mixed grass, a layer of shrubs, and three layers of trees. According to researchers at CIPAV,[293] shrubs that provide abundant, high protein fodder and fix nitrogen for the grasses particularly enhance production of meat or milk. The trees also increase humidity under the canopy, which promotes grass growth, and tree shade reduces heat stress on animals. Compared to extensive grazing, silvopastoral systems can generate more than 10 times the milk per hectare and better resist drought. Production can even be 70 percent higher than otherwise well-managed and fertilized pasture. Silvopastoral areas also have enhanced carbon stocks and enhanced biodiversity, including a reported 71 percent increase in bird abundance and diversity. However, although silvopastoralism is highly profitable, it requires a relatively high up-front investment and far more complicated management.

Although the technical potential to improve many pastures is clear, the realistic global potential is not. For example, even though Brazil is the world's second largest beef producer, doubling its production on existing grazing land would close less than a quarter of the projected gap in pasture-based production between 2006 and 2050.[294]

Furthermore, not all pasture intensification measures meet our sustainability criteria. Large areas of the Brazilian Cerrado have been planted with improved *Brachiaria*, an African grass, and have little remaining native vegetation. These pastures can be intensified with limited environmental cost. But Brazil continues to clear the trees, shrubs, and grasses of the Cerrado to plant *Brachiaria*. Doing so has high costs in both carbon and biodiversity as the Cerrado is one of the most biologically diverse ecosystems on the planet.[295] In recent years, occasional examples of Brazilian-style improved ranching have started to transform the wet savannas of Africa. Although *Brachiaria* grasses are native to Africa, such efforts will have similar effects on biodiversity and carbon as in the Cerrado. To protect carbon and biodiversity, ranching intensification should focus on the areas that have already lost their native vegetation.

## Requirements for Moving Forward

Although pasture intensification can reduce pressures on forest expansion, farmers will probably not fully realize intensification potential unless governments also take steps to stop expansion of pasture into forests. Between 2000 and 2006, cattle density in the Brazilian Amazon increased from 0.74 to 1.17 animal units per hectare, but pasture area still increased from 49 to 61 Mha.[296] Pasture area south of the Amazon may have declined and offset some or all of pasture expansion in the Amazon, but the statistics are unclear.[297] What is clear is that shifts in grazing area have led to large additional $CO_2$ emissions and conversion of natural ecosystems. One recent paper estimated that 17–80 percent of the Amazon would be profitable to convert to grazing if the land could be obtained at no cost from governments—with the percentage depending on beef prices.[298] The overall inference is that even if increased demand for meat leads to some pasture intensification, it will also likely lead to continued clearing of forest until such time as governments put in place, and enforce, policies that prevent further deforestation.

On the other hand, the potential to intensify pasture and free up land for cropping and forest restoration has helped to persuade the Brazilian government to enforce legal policies to protect forests.[299] As a result, Brazil has vastly decreased its rates of forest loss since 2007.[300] This experience suggests that improved understanding of the potential to intensify pasture can help to encourage forest protection efforts. Yet there are large information gaps.

First, despite positive experience, the evidence for intensification potential and methods is uneven across the tropics and temperate zones. For example, substantial potential may exist in the southeastern United States, but analysis is lacking. Improved global estimates of intensification potential could help motivate additional efforts.

Second, even though the basic means of pasture intensification are known, knowledge of the details varies. For example, even though *Leucaena* shrubs provided a pivotal breakthrough in Colombia's intensive silvopastoral systems, *Leucaena* does not grow well on highly acidic soils. For Colombia's silvopastoral system to work in these soils, *Leucaena* will need to adapt or an alternative must be found.

Many pasture management principles result from extrapolations of nutritional studies conducted in controlled conditions in stalls far from the pastures, even though cut and grazed forage may differ substantially in nutrient quality. Fortunately, advances in GPS technology make it easier to better analyze the management and consumption of existing natural grasslands[301] so forage can be exploited at the optimum state of maturity.[302]

Third, the economics of intensification are complicated, variable, and poorly understood. Analysis by the Brazilian agricultural research agency, Embrapa, has at times shown that expanding pasture into forest is cheaper than rehabilitating pasture.[303] One study in the early 2000s showed that a modest form of intensification, fertilizing degraded pasture, was cost-effective in the western Amazon, but that a more intensive form, using some supplemental feeds, was not.[304] A more recent study of Mato Grosso estimated that extensive cattle raising in itself is not profitable but can become profitable with better management.[305] Brazil has set aside a large sum of money for low-cost loans to improve pasture, which originally had few takers but is now coming into use.[306]

A future installment will explore increasing pasture productivity in greater detail as well as the policy options to advance it.

## The Challenge of Shifting Agricultural Land

Boosting crop and pasture yields enough to supply all food on existing agricultural land is necessary to preserve forests and sustain their ecosystem services, but it is not sufficient. A variety of studies have shown that boosting either crop or pasture yields in an individual country may actually lead to increases in agricultural land area in that country.[307]

One potential explanation is that boosting yields can help lower prices, and people may respond by consuming more food. If consumption increases by a larger percentage than yields, agriculture will expand into new lands. However, people only modestly increase their consumption of crops when prices decline, so yield gains should nearly always save land globally. But the land savings may be less for improvements in yields of beef and other meats because consumption of meat responds more to price than crops.[308]

The more important and environmentally challenging explanation is that yield gains may still encourage loss of forests and savannas locally even if they spare land globally. Yield gains can help lower production costs sufficiently to make it possible to increase production for export, and producers may then convert more land to do so. This pattern has led to expansion of soybeans, maize, and beef in Brazil and Argentina, and spurred expansion of oil palm in Indonesia and Malaysia. In these situations, the local land expansion associated with yield gains provide economic benefits, but at considerable environmental costs.

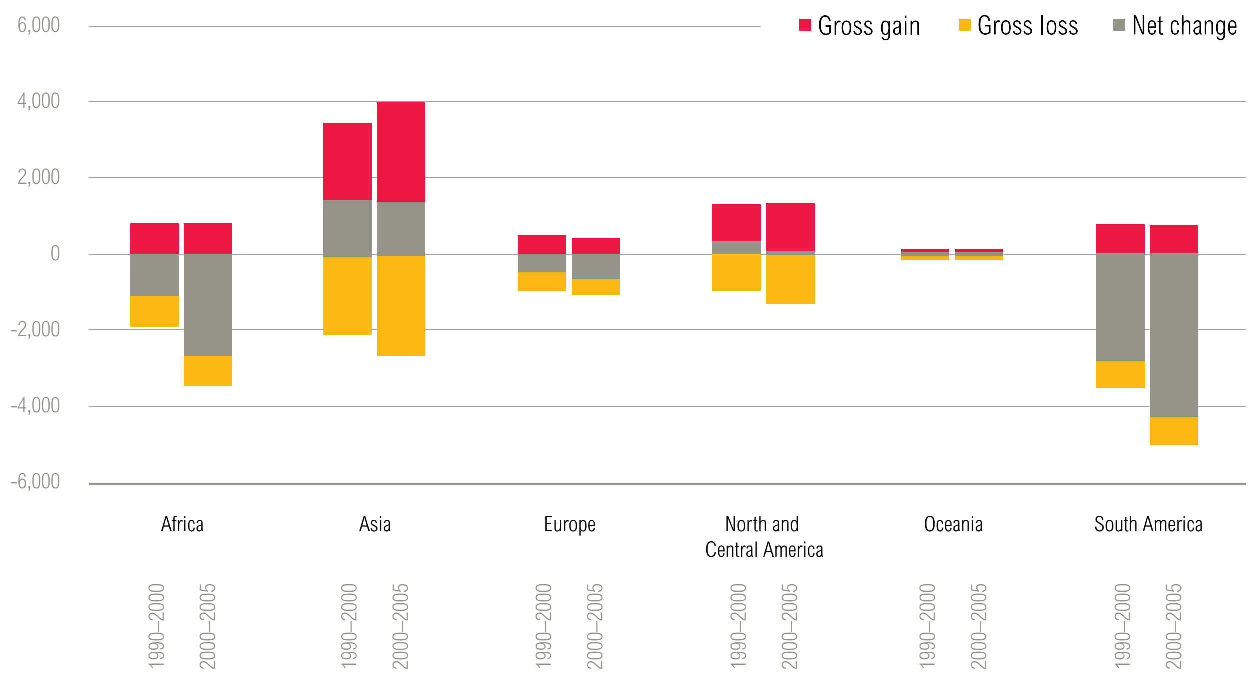
### MENU ITEM | Avoid or better manage shifts in agricultural land

The local expansion of land that can result from yield gains is part of the broader shifting of agricultural land from one region to another. Between 1962 and 2006, even as cropland expanded by 275 million hectares in developing countries, it declined by 54 million hectares in developed countries.[309] By 2050, FAO projects that cropland area will decline another 38 Mha in developed countries even as it expands by 107 Mha in developing countries.[310]

As new satellite studies show, agricultural land also shifts within regions. Figure 31 shows a recent analysis by FAO based on satellite imagery of forest losses and gains in Latin America and Africa from 1990 to 2005. It found net losses were still substantially smaller than gross losses, which implies an important shift of agricultural land.[311] Asia too had large gross losses, particularly of native wet tropical forests, while it had forest gains overall, largely due to planted forests in China and Vietnam. Another recent study of deforestation in Latin America from 2001–10 found that gross deforestation exceeded net deforestation by three to one.[312]

These agricultural land shifts have important implications for carbon storage and other ecosystem services. In part, they show that abandoned lands are an important resource because many regenerate as forests, providing carbon gains and often biodiversity benefits. Policy could help by expediting the regeneration of abandoned lands in native vegetation.

Figure 31 | **Gross forest losses are far greater than net forest losses because agricultural lands are shifting (thousands of hectares per year)**




*Source:* FAO (2012e).

Yet plowing up of native forests in the tropics generally causes more carbon loss and has greater impacts on biodiversity than the reforestation of land elsewhere. The carbon loss is immediate, while reforestation occurs more slowly. Both because of lower yields and higher density of forest carbon in the tropics than the temperate zone, the losses of carbon tend to be higher in tropical areas for each ton of crops than in temperate zones.[313] And biodiversity is exceptionally high in tropical forests and savannas, particularly in native forests.[314]

The goal should be to boost yields of cropland and pasture to make it possible to spare land globally and to meet the growing food demands of developing countries, and at the same time to avoid land shifting into carbon-rich and biodiverse habitats. A range of government policies can influence these developments, including the location of roads and other infrastructure, and the incentives or restrictions on land clearing. Different types of agricultural improvement are likely to have different consequences for local land expansion. Overall, policy must find a way not merely to avoid net expansion of cropland, but also to avoid shifts of cropland into high-carbon and valuable ecosystems.

Chapter 5

# INCREASING PRODUCTION WHILE LOWERING GREENHOUSE GAS EMISSIONS

The food gap between 2006 and 2050 is not the only gap of concern. Another gap exists between the expected greenhouse gas emissions from agricultural production in 2050 and those that would be necessary for agriculture to contribute a reasonable share of greenhouse gas emissions mitigation. For the food gap, the focus is on increasing food availability and sustainably reducing demand. For the emissions gap, the focus is on decreasing emissions associated with food production. This chapter explores the potential for closing that "mitigation gap."

## Scope of the Agricultural Greenhouse Gas Emissions Mitigation Gap

Although emissions estimates are rough, producing agricultural crops and livestock probably generated around 13 percent of net worldwide greenhouse gas emissions in 2010, or 6.5 gigatons of carbon dioxide equivalent (Gt $CO_2e$).[315] That amount excludes emissions from land use change. Roughly 70 percent of these agricultural production emissions occur in the developing world, and more than 80 percent are likely to occur there by 2050.[316] These emissions result primarily from methane and nitrous oxide from five basic sources:

- Ruminant livestock, which generate methane in their stomachs (enteric fermentation) and both methane and nitrous oxide from wastes they deposit on pastures.
- Manure managed in storage facilities and barns (as opposed to deposited on pastures), primarily from pigs, dairy, and some beef feedlots.
- Rice paddies, which release both methane and nitrous oxide.
- Croplands and grasslands, which release nitrous oxide from the interactions of soil bacteria with nitrogen, which may originate from fertilizer, manure, or from the fixation of nitrogen by crops.
- Methane and nitrous oxide from burning crop residues.

Energy use is a large source of emissions throughout the overall food system, including processing, transportation, and retail, but it is a smaller source of emissions from the actual production of crops and livestock products. According to a recent FAO estimate, energy use during production contributes slightly more than 1 Gt of $CO_2e$ emissions.[317] These emissions mostly result from on-farm energy fuel use, as well as from manufacturing of farm tractors, irrigation pumps, other machinery, and key inputs such as fertilizer.

Although many estimates of agricultural emissions include the methane and nitrous oxide from regular burning of savannas to stimulate grass production, we do not include them here. Savannas burn naturally, and there is little evidence that burning by people increases these emissions in general.

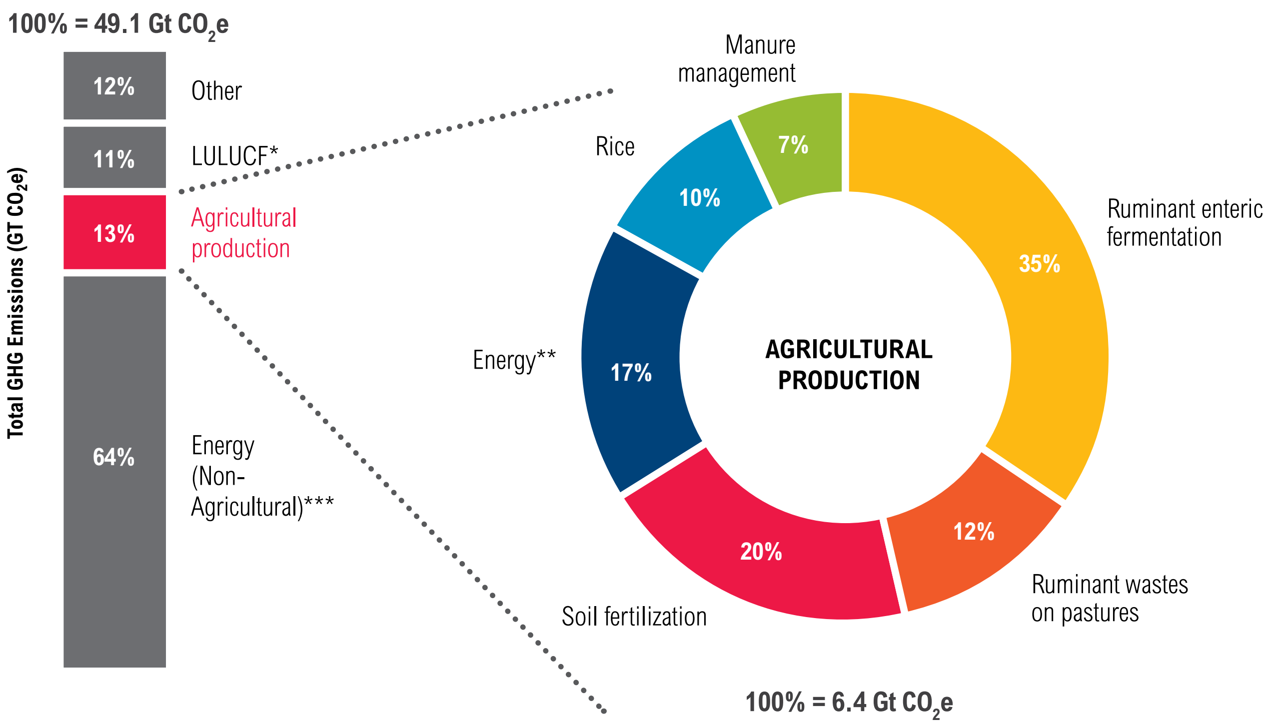
Figure 32 provides a breakdown of global greenhouse gas emissions overall, and from direct agricultural production by major source in particular. Some other estimates are higher.[318] Ruminants deserve particular attention. Many reports present the emissions from their wastes deposited on grazing land in a broader category of "agricultural soils."[319] But combining ruminant wastes and enteric fermentation into a broad category for ruminants shows that they contribute roughly half of global agricultural production emissions.

How might agricultural production emissions change between now and 2050? Any estimate must be extremely rough in light of the many scientific uncertainties about present production emissions, and the many possible paths that production increases could take to 2050. Starting from emissions of roughly 6.5 Gt of $CO_2e$ per year in 2010, we estimate that increased crop and livestock production could easily bring the total to 9.5 Gt of $CO_2e$ per year in 2050 under business as usual. This emissions level assumes a 14 percent reduction in emissions per calorie of crops and a 19 percent reduction in emissions per ton of milk and meat.[320] Although fertilizer use efficiency is growing in the United States and Europe, fertilizer use efficiency is likely to decline over coming decades in countries that currently use little fertilizer because as more fertilizer is applied, more will escape.[321] In addition, although rice area is unlikely to expand and its emissions mostly depend on the area of production, a recent paper estimates that rice emissions will actually rise substantially due to warming temperatures.[322]

The significance of this emissions growth has received inadequate attention. If agriculture-related emissions from land use change remain unchanged at roughly 5.5 Gt of $CO_2e$ per year through 2050, and if agriculture production emissions grow to 9.5 Gt of $CO_2e$ per year by 2050, then the combined emissions will reach about 15 Gt by 2050. Such emission levels would seriously undermine climate goals.

The OECD business-as-usual scenario projects that emissions from human activities other than agriculture and land use change would reach roughly 70 Gt

Figure 32 | **Ruminants contributed nearly half of global greenhouse gas emissions from agricultural production in 2010**




*Notes:* Numbers may not sum to 100 due to rounding.

* LULUCF = Land Use, Land Use Change, and Forestry.

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

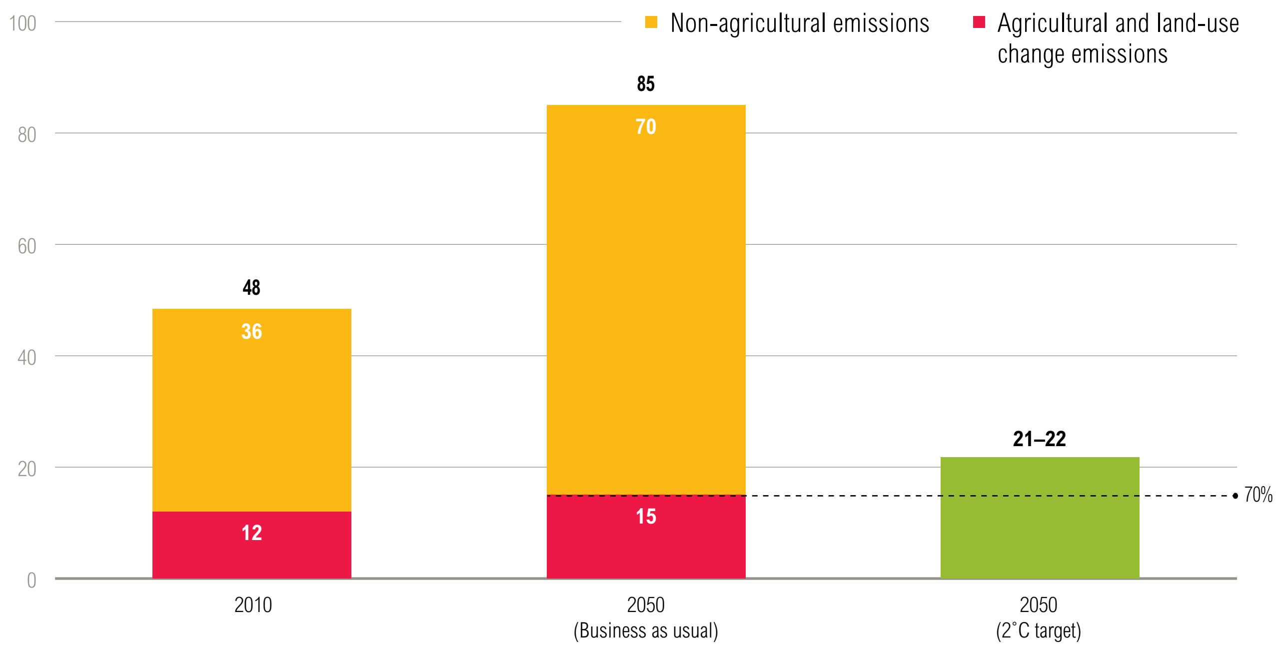
*** Excludes emissions from agricultural energy sources described above.

*Source:* WRI analysis based on UNEP (2012), FAO (2012e), EIA (2012), IEA (2012), and Houghton (2008) with adjustments.

per year by 2050.[323] Although stabilizing the climate could take a variety of pathways, most countries at the 2009 UNFCCC COP 15 in Copenhagen endorsed a goal of limiting global warming to 2° Celsius. Analyses of how to attain this goal on average project that total global greenhouse gas emissions around 2050 must be around 21-22 Gt of $CO_2e$, with sharp reductions thereafter.[324] By our estimate, absent any change in its trajectory, under BAU, agriculture would therefore contribute roughly 70 percent of the total annual emissions in 2050 that are consistent with a 2° Celsius warmer world (Figure 33).

If agriculture were to reduce its share of emissions proportionate with other sources to reach a 21-22 Gt target by 2050, total emissions from agriculture and land use change would have to come down from 12 Gt of $CO_2e$ per year in 2010 to 4 Gt per year in 2050. Even if emissions from land use change were to disappear by then, the needed emissions reductions from agriculture production under our BAU would still be on the order of 5.5 Gt, or almost 60 percent. Reducing agricultural production emissions to that level by 2050 will be incredibly challenging. The rest of this chapter explores some options discussed in the literature and the promise that we believe each option holds.

Figure 33 | **"Business as usual" agriculture emissions would comprise 70 percent of allowable emissions in 2050 to achieve a 2°C warmer world (Gt $CO_2$e per year)**




*Source:* WRI analysis based on IEA (2012), EIA (2012), EPA (2012), Houghton (2008), and OECD (2012).

## Is Carbon Sequestration an Achievable, Large-Scale Option?

For more than a decade, both academic research and demonstration projects devoted to agricultural greenhouse gas mitigation has focused primarily on ways of sequestering carbon in agricultural soils, restoring wetlands, or planting trees on agricultural lands.[325] In its most recent assessment, the Intergovernmental Panel on Climate Change (IPCC) estimated that such forms of sequestration provided 90 percent of the global technical and economic potential for agricultural mitigation.[326] Most of the policy focus has been on paying for these carbon sequestration efforts by selling credits to power plants and other industrial sources of emissions as "offsets," so those sources can reduce their emissions less than otherwise required.[327] Such a strategy, if successful, does not reduce agricultural emissions. It is a technique for offsetting emissions by increasing the sink of carbon, and credits those offsets to industrial emissions, not to agriculture.

There are many reasons to believe that researchers have overemphasized the technical and practical potential to increase carbon sequestration, although selective opportunities for sequestration do exist. Understanding the weaknesses of prior estimates helps to understand the true opportunities.

### Conceptual, Technical and Practical Limitations

Many prior estimates of carbon sequestration potential have in effect double-counted plants, carbon, or land. For example, several of the means of sequestering additional plant carbon in soils or standing vegetation requires diverting that carbon from some other valuable use. Farmers can build soil carbon by mulching trees and shrubs, by adding manure (which has much carbon as well as nitrogen and phosphorus), or by leaving more crop residues in the soil. But tree mulch only shifts carbon from above-ground to below-ground storage. And while a fraction of the manure or residues farmers add to the soil will remain over time, these uses often come at the loss of the valuable uses of manure and residues as animal feed or household energy.[328] Researchers have also pointed to the potential to store more carbon by planting trees on agricultural land, or by restoring wetlands. But these efforts would typically come at the expense of using these lands to produce food—double counting the capacity of land to generate carbon. The double counting implies economic competition as farmers are understandably reluctant to give up animal feed, energy, and land for food production. The issue is also one of basic accounting: if various forms of biomass and land are diverted to carbon storage, the carbon to replace them still has to come from somewhere, potentially sacrificing carbon storage elsewhere. In a particular circumstance, the use of biomass to build carbon, or of land to sequester carbon, may be more advantageous than the alternative, but determining those circumstances requires a nuanced analysis.

In addition to adding more carbon to soils and vegetation, the other means of sequestering carbon involves diminishing its decomposition by microorganisms in the soil. But most means of doing so have turned out to be scientifically doubtful. Much hope has rested on the belief that plowing soils less thoroughly should reduce this decomposition and build soil carbon. "No-till" techniques that drill seeds into the ground without overturning the soil have, in particular, commanded attention. Because the original plowing of grassland or cut-over forests leads to the loss of soil carbon, the plausible theory has been that reducing annual soil turnover should expose less of that soil carbon to decomposition by microbes. Many field studies appeared to support this view. But in 2007 an important paper pointed out that these studies focused only on shallow soil depth, often the top 10 centimeters, and that studies measuring soils to a full meter showed no consistent pattern of change in soil carbon.[329] Subsequent analyses of deeper soil layers have sometimes found small carbon gains, and sometimes no carbon gains at all.[330]

Even if no-till generates small carbon gains in some soils, almost no farmers practice no-till for more than a few years, and occasional plowing would presumably undo most or all benefits. Studies have also found that no-till often increases emissions of nitrous oxide for at least several years, enough to cancel out any gains from soil carbon unless no-till is maintained much longer than is typical.[331] The science of soil carbon sequestration continues to evolve, and no-till and reduced tillage can provide other benefits by improving water retention, reducing soil erosion and limiting the energy required for plowing. But at this time, the combined doubts about carbon sequestration effects, the likely effects of plowing, and increases in nitrous oxide emissions together undermine any judgment that reduced tillage techniques by themselves will reduce greenhouse gas emissions.

Improved rangeland management has also turned out to be scientifically more nuanced than originally estimated. The impact of improved rangeland management practices on soil carbon is highly complex, site-specific, and in some cases hard to predict.[332] In some regions, less intensive grazing leads to more grassland productivity and soil carbon in those lands, and in some cases less. Stranger still, truly poor grazing practices that undermine grassland productivity may actually promote carbon sequestration by favoring tree growth.[333] A recent global modeling study suggests that optimizing grazing everywhere, and planting legumes on a global basis could sequester the equivalent of up to 0.6 gigatons of carbon dioxide per year, around 40 percent of the IPCC's estimate in 2007 of the carbon sequestration potential on grazing land, and roughly 20 percent of agriculture's production emissions. However, the modeling of these carbon sequestration opportunities is still rough and uncertain, and even if the estimate is accurate, truly achieving such gains would require changes to billions of hectares of land.

Financing carbon sequestration efforts through offsets also faces a number of daunting challenges. One is the inability to guarantee that the carbon sequestration will be permanent, which has limited Europe's willingness to approve carbon sequestration projects for offset payments.[334] A second challenge is that small farmers also tend to lack the resources to bear the upfront costs of implementing practices to sequester carbon, and most projects are unwilling to pay for sequestered carbon before it is generated.[335] Projects therefore in practice will often require an intermediary to front the money and assume the risk that the full carbon sequestration will not occur, which limits the growth potential of this market. Small farmers are also poorly positioned to make long-term commitments to a single management practice because their economic vulnerability generates a large need to adapt to changing circumstances.[336]

Overall, research estimating soil carbon sequestration potential has emphasized the simple fact that many of the world's agricultural soils can technically store more carbon than they do today, and that practices exist to enhance that carbon. But that analysis is too simple. The world's banks have plenty of extra room to hold more money, and people have many ways of earning it, but those facts do not reveal much about the realistic potential of the world to become richer. Just as the key limiting factor to growing wealth is not space in the banks, the key limiting factor to increased soil carbon is not the capacity of the soil. Analyses of the realistic capacity to sequester carbon must fully take into account the costs in time, labor, and the valuable use of land or plant carbon for other purposes. The realistic potential to sequester carbon rests in those opportunities in which these costs are low—opportunities which we explore below.

## Promising Opportunities

The most promising technical opportunities to sequester carbon will most often involve efforts that increase the growth of vegetation and therefore that absorb more carbon from the atmosphere rather than efforts that compete for the uses of plant material and its carbon for other uses. The techniques that farmers are most likely to adopt will be those that increase agricultural productivity and revenue.

Our section on improved soil and water management describes the success and promise of agroforestry and related practices in the Sahel region that build carbon by increasing plant growth. Rather than diverting carbon from another source, agroforestry in the tropics adds to carbon uptake by growing year-round and tapping into resources of light and water that annual crops often cannot. In tropical systems, shade from trees is typically not a problem because light is less limiting or not at all, while trees can increase humidity or add nutrients.

Because trees store carbon above ground, their contributions are larger, more certain and more verifiable. However, it is agroforestry's potential to improve agricultural productivity and provide wood and tree products—leading to increases in production and revenue in the short term—that have led farmers to embrace it. The modest boosts in carbon will help the farm and the environment over the medium and long term, but are not the reason farmers implement the practices. The lesson here is to find practices that increase carbon sequestration that make sense to farmers for other reasons.

In broader contexts, efforts that increase cropland and pasture productivity have the potential to help build soil carbon by contributing more roots and residues. Some studies have found carbon gains from the additions of compost even to highly managed annual grasslands in the United States or the United Kingdom, and gains may in some contexts greatly exceed the carbon added directly by the compost because of the improvements in grassland productivity.[337]

The relationship between carbon and productivity goes to the heart of African agricultural challenges. African crop soils are unproductive in part because they have lost carbon, but they also have lost so much carbon in part because crops are so unproductive. On those African soils with highly depleted carbon, the response of crops to fertilizer may even become so low that fertilizer use becomes unprofitable.[338] Yet adding carbon may not generate returns for many years and may still only be profitable if it can be combined with additional fertilizer. For example, one Kenyan study found that many farmers would achieve net economic gains by leaving 50 percent to 75 percent of their residues on soils to boost yields, even if that required them to buy napier grass to replace their crop residue as feed for their cows.[339] But those gains occurred only as part of a broader change in agricultural practices that included substantial application of fertilizer (40 kg/hectare). Options that quickly provide economic returns and build carbon are needed, and that is precisely why some forms of agroforestry appear to have potential.

Other opportunities exist where the carbon sequestration opportunities coincide with public needs. For example, overgrazing and inappropriate cropping have led to large-scale soil erosion in parts of western China that result in annual, large, and unhealthy dust storms, which spread to Beijing. In large part to address these concerns, the World Bank helped to fund a massive tree planting and vegetation restoration program on the Loess

Plateau, and China is moving ahead with a variety of projects to reduce grazing pressure and restore healthier grasses and trees in large regions.[340] Scientific reviews support the conclusion that these efforts are simultaneously sequestering carbon.[341]

Other opportunities may exist for tree planting in areas that now generate little food. In the IPCC's 2007 assessment of mitigation potential, large reforestation potential was estimated in the forestry section. But the study did not analyze reforestation potential in the context of a global land budget and therefore did not address the implications for food production of reforesting large chunks of agricultural land. Some projects have tried to avoid this problem by planting trees in hedgerows and around the periphery of farming areas.[342] Other projects have focused on reforesting marginal farming areas alongside efforts to intensify production on the more productive lands.[343] Marginal areas often include cropland or pasture land that is steeply sloped. Efforts to reforest marginal farming areas will reduce global agricultural land area and thus require yet greater productivity gains on remaining lands, but doing so may also allow the redirection of limited agricultural labor and investment into potentially more productive areas—possibly resulting in overall gains for food production.

The restoration of peatlands that have already been abandoned by agriculture provides a special opportunity. As long as the drainage systems remain in place, abandoned peatlands continue to degrade, sometimes catch fire, and emit large volumes of carbon dioxide even though they do not contribute to food production. Abandoned peatlands cover extensive areas in Russia and parts of Southeast Asia. Wetlands International has estimated that while 4.7 Mha of peatlands in Indonesia are in agricultural use today, another 4.7 Mha are abandoned but remain drained.[344] Restoration efforts are in their infancy, but in general, rewetting wetlands should eliminate or at least greatly reduce emissions.

In summary, carbon sequestration gains on agricultural land will most likely result from efforts to boost productivity of crops and grasses—providing ancillary carbon sequestration benefits to the primary goal of increasing food production on existing agricultural land. Agroforestry is one such strategy that has particular potential in Africa. Opportunities also exist where carbon sequestration gains are ancillary to other important public purposes, such as the restoration of grasslands in western China to reduce dust storms and associated health impacts. Some marginal agricultural lands are so unproductive that restoring forests fits well as part of a broader intensification strategy. And in the case of abandoned peatlands, restoration provides a major opportunity because of the vast quantities of carbon they emit.

## The Gains From Improved Efficiency

The single most important greenhouse gas mitigation option that the 2007 IPCC report insufficiently emphasized was in some sense the most obvious: produce agricultural products more efficiently. Studies have increasingly demonstrated the potential reductions in emissions per ton of food by increasing the efficiency of raising livestock, fertilizing crops, and using water and energy. The farms with the greatest opportunity for efficiency gains measured in this way are those in developing countries, often managed by small farmers. The same measures will often boost production and generally improve economic performance.[345]

In many situations, the same activities that reduce emissions per ton of food will also increase total emissions on that particular farm. Such efforts therefore do not fit well with conventional carbon offset programs. But in a world that needs to both combat climate change and produce more food, such gains in efficiency lower emissions overall.

### MENU ITEM | Improve the efficiency of ruminant livestock

Cows, sheep, and goats are able to break down fibrous feeds, but that process leads to high quantities of methane and waste and does not provide enough nutrition for animals to produce milk and meat at high levels. More digestible and higher protein feeds improve the output of ruminants and reduce the methane and nitrous oxide ruminants generate for each ton of feed. This combination results in more meat or milk per ton of greenhouse gas emissions. Improving pasture management in ways discussed previously will reduce not only land use demands, but also methane and nitrous oxide emissions. Improved mixed livestock/cropping systems for cattle hold out even greater potential to hold down emissions and simultaneously to reduce poverty. This high potential is due to the fact that small, mixed farms comprise the vast bulk of the roughly 900 million livestock keepers in sub-Saharan Africa and South Asia,[346] and women farmers play a particularly prominent role.[347]

One FAO study highlights the potential to improve the efficiency of ruminants. It found that dairy production in the United States generated one-fifth of the greenhouse gases per liter of milk as that in Africa.[348] It also showed that dairy and meat production in the developing world does not need to become industrial to become more efficient. Even today, compared to African dairy cows, Indian dairy production emits only half as much greenhouse gases per liter of milk, according to the same FAO study. Other studies likewise have calculated that reasonable improvements in the dominant mixed livestock feeding systems in Africa could reduce methane emissions per liter of milk by two-thirds.[349]

One opportunity for improving the efficiency of such systems is to produce and use higher quality forages. In East Africa, many small farmers have made large gains by adopting napier grass, a highly nutritious and productive grass that grows in a wide range of tropical and subtropical locations.[350] Despite common use, large potential exists to expand and improve napier production through more precise matching of grass varieties to environments, improved fertilization, and closer integration into cropping systems.[351] Experiments in Kenya, Tanzania, and Uganda have shown that intercropping a leguminous forage with maize and planting napier grass in border areas can boost yields both by improving soil productivity and by attracting stem borers, a problematic pest, away from the maize. At harvest, the maize stalk, napier grass, and legumes provide quality fodder for livestock.[352] But at present, various diseases threaten napier production and require urgent attention.

In the tropics, many forages have naturally high levels of tannins—and related polyphenols—that reduce methane production and help animals to retain more of the nitrogen they consume. The better integration of such forages into mixed livestock systems therefore has the potential for additional greenhouse gas emissions reductions. The use of nitrogen-fixing shrubs is spreading rapidly in East Africa and could spread even further, offering additional potential.[353] Adding legumes to dedicated forage areas also has high potential to increase feed quality and reduce methane emissions, while helping to fix nitrogen to improve cropping.

In mixed, small-scale systems, crop residues are the most important source of cattle feed, and adoption of grain varieties with more digestible stalks and stovers (cobs) is another way to improve feed quality. The International Livestock Research Institute has developed several varieties of cereals with more

digestible residues,[354] and sweet potatoes bred for high quality fodders also hold promise. Importantly, breeding for stover quality need not come at the expense of crop yields.[355]

Many farmers in India have adopted varieties with more digestible stovers. In contrast, few African farmers have adopted these varieties, although doing so should be able to greatly improve both milk output and greenhouse gas emissions performance.[356] For African farmers to fully exploit grain varieties with more digestible resides, those varieties will need to be adopted into local African breeding programs. Other technical opportunities have long existed to improve stover digestibility by treatment with urea. Aid programs have initiated many pilot efforts, but cumbersome labor requirements have hindered adoption.[357] If simple forms of mechanization could reduce these labor requirements, the potential would be promising.

Improved breeding of cattle provides another opportunity to improve ruminant livestock efficiency. Within cattle populations, some animals are more efficient at converting feed to milk or meat than others, and these traits are moderately inheritable. In developed countries, studies have predicted that selection for these traits consistently over 25 years would reduce cumulative methane emissions substantially, while increasing output.[358] There is no reason to believe the same benefits would not occur in developing countries. Improved breeding need not imply replacing longstanding African cattle species with European imports, which may sacrifice greater protection against disease and heat. Instead, long-established local breeds could be improved through selective breeding.[359]

FAO recently estimated that greenhouse gas emissions from livestock would decline by a third if producers could match the practices of the 10 percent of best producers that employ the same basic livestock production system in the same region and climate.[360]

## MENU ITEM | Make fertilization more efficient

The world has high potential for more efficient use of fertilizer. Some regions use far too much fertilizer, such as parts of China and India. Some regions could improve fertilizer use efficiency through better technology, such as the United States and Europe. And other regions need better fertilization, particularly Africa.[361] Studies have found that reducing fertilizer use in China without altering yields would reduce total Chinese greenhouse gas emissions by 2 percent.[362] In some cases, reducing fertilizer use might mean just applying less fertilizer. In others, careful timing and synchronization of fertilizer with crop varieties would result in far greater crop uptake, higher yields, and less fertilizer surplus with the same amount of fertilizer.[363]

In Africa, more nutrients are removed from the soil each year than are added, and extraordinarily

low fertilizer application rates impede crop production.[364] The key challenge in Africa is how to improve fertilization. In addition to greater use of inorganic fertilizer, some studies suggest high potential for increased bean production in Africa, which could fix nitrogen and improve yields of cereal crops as well. This approach will require overcoming pest limitations and lack of phosphate.[365] And one of the reasons agroforestry holds promise in Africa and other regions lies in the benefits of nitrogen-fixing shrubs and trees.

Although efficiency gains alone can go a long way, they are probably not adequate by themselves to reduce emissions as much as would be desirable. Adequately reducing emissions will probably require some major improvements in technology that change the forms of applied fertilizer.

Nitrogen fertilizer is mostly applied in a chemical form that directly neither runs off the field nor turns into nitrous oxide, a global warming gas. But microorganisms turn that nitrogen into forms that do, particularly ammonia, which escapes through the air, and nitrate, which escapes by leaching. The formation of that nitrate, and its further breakdown into nitrogen gas by other organisms, creates nitrous oxide. But chemical compounds—so-called "nitrification inhibitors"—exist that impede or otherwise slow the transformation of nitrogen in fertilizer into nitrate. Other compounds exist that release nitrogen more slowly and therefore closer to when crops need it, reducing the time available for nitrogen to escape or be turned into nitrous oxide. Studies have found substantial reductions in nitrous oxide from all these compounds in general, although the results vary greatly from field to field.[366]

These technologies have been around in some form for decades. Unfortunately, they are only modestly used. For the most part, farmers only use these compounds if they wish to apply fertilizer well in advance of the time plants will need the nitrogen but fear the fertilizer will escape in the meantime, or if farmers have soil types that experience large nitrogen losses. Their goal is to maintain crop yields using normal fertilizer application under abnormal conditions. As a result, there is little data exploring whether farmers under normal conditions could use these compounds, apply less fertilizer, and save enough money to cover the costs of the inhibitors.

In addition, only a few compounds have been identified and are manufactured by a small number of companies. Because of the limited market to justify private research, and little or no public research money, the technological potential has been underexplored. In general, nitrification inhibitors and other means of shifting the form of fertilizer applied have high potential to provide cost-effective emissions mitigation, although an integrated research, implementation, and refinement program will be necessary to make that occur.

### MENU ITEM | Manage rice paddies to reduce emissions

For rice, the most commonly accepted greenhouse gas emissions mitigation strategies involve drawing down water levels during the mid-season, or even better, alternatively flooding and drying the rice paddy. This kind of water management also seems capable of boosting yields on many farms compared to continuous flooding, and alternative wetting and drying greatly reduces irrigation demand. Furthermore, incorporating rice straw into the farm paddy increases greenhouse gas emissions, thus removing the rice straw reduces emissions.[367] Together, and separately, these practices can dramatically reduce greenhouse gas emissions from rice production.

In China, where water management infrastructure is good, farmers generally draw down water levels during the growing season. This practice lowers emissions compared to permanent flooding, but research indicates that farmers could reduce emissions even more by using multiple drawdowns of water. Yet drawing down water levels requires a number of technical capacities, including the capacity to drain off rainwater, which is impossible in many rice producing areas during the wetter seasons. It also requires the ability to rewet the rice paddy after a period of drawdown, which requires a reliable and controllable source of irrigation water. That capacity will depend on irrigation systems, and for much of the world's rice fields, such capacity does not exist. Spreading these practices in some locations should be technically quite feasible, particularly areas that irrigate through pumping systems. Other regions would require improvements to water management systems, which should also boost yields, but may be expensive or impractical in some locations.

Scientists have also identified a variety of promising, less-established methods to reduce emissions from rice paddies. They include potassium inputs in some fields, a variety of unusual crop rotations, water-saving rice varieties, use of fertilizer in the form of golf-ball-sized granules, and draining fields outside of the rice production season.[368] In some of the smaller rice fields in mountainous regions of China, farmers spread a plastic film over their fields to retain soil moisture without flooding the fields, a practice that also reduces methane emissions and that reduces greenhouse emissions substantially overall when combined with a nitrification inhibitor.[369]

In general, although scientists have identified these mixes of measures, most of the analysis is broad rather than detailed. Remarkably little work has been done on the technical feasibility of implementing most of these greenhouse gas emission mitigation options in different farming systems, the obstacles to introducing them, and ways of overcoming those obstacles. Such feasibility studies are an obvious next step. Yet even without much further analysis, the principle of increased efficiency in the use of inputs can help guide mitigation efforts.

Chapter 6

# FISH

Fish are an important source of animal protein for billions of people. However, the supply of fish caught in the wild–particularly from the oceans–has already receded from its peak, and future supply is under threat. As the wild fish harvest has stagnated, aquaculture has grown to meet the world's growing demand for fish. In this chapter we explore trends in fisheries and aquaculture and prospects for further increasing the productivity of aquaculture.

Fish, including finfish, crustaceans, and mollusks, contributed 16 percent of global animal-based protein for human consumption in 2009, and are the primary source of animal protein for nearly 1.3 billion people.[370] Fish also contain important micronutrients—such as vitamin A, iron, and zinc—and omega-3 fatty acids that are essential for maternal health and early childhood development, but that are often deficient in developing country diets.[371] People consumed 128 Mt of both wild-caught and farmed fish in 2010, an all-time high, and demand is projected to grow over the coming decades.[372]

However, the supply of fish caught in the wild—particularly from the oceans—has already receded from its peak, and future supply is under threat. The wild fish catch from marine and inland water bodies grew steadily from 19 Mt in 1950 to a peak of 95 Mt in the mid-1990s, but has since declined modestly to roughly 90 Mt by 2010.[373] During this time, the percentage of overfished stocks has continued to rise—indicating that the current level of fishing effort[374] is unsustainable, and suggesting that marine catches will probably decline in coming decades absent a reduction in fishing effort. In 2009, 30 percent of marine fish stocks were overexploited, another 57 percent were fully exploited, and only 13 percent were exploited at less than their full potential.[375] Fisheries exploitation is greatest in the tropics—particularly in Southeast Asia—while stocks appear to be on the rebound along the coasts of a few developed countries such as Australia, Norway, New Zealand, and the United States.[376] Globally, overfishing is estimated to result in at least $50 billion per year in economic losses.[377]

## MENU ITEM | Reduce and then Stabilize Wild Fish Catch

The first step toward a sustainable fish supply is to reduce the wild fish catch in the short term to allow depleted stocks to recover. The World Bank, FAO, and UNEP suggest that world fishing effort needs to decline by up to 50 percent of today's levels to allow fisheries to rebuild.[378] Rebuilding generally requires some form of fish catch limitations, habitat protection, limitation of by-catch, and closure of fish breeding areas.[379] The result would be catches that are stable over the long term—possibly even as high as today's catches in a best-case scenario.[380]

Widespread adoption of these solutions is difficult as they result in declines in economic activity in the short term and create longer term winners and losers—and potential losers often wield enough power to thwart reform and restoration efforts.[381] In many developing countries, fishing is often a livelihood of last resort in coastal communities; restrictions can lead to severe hardship and governments are reluctant to impose them. Illegal, unregulated, and unreported fishing is also a widespread problem, particularly in countries with weak governance, and probably represents an additional catch of between 11 Mt and 26 Mt that goes unmanaged.[382] Despite these challenges, continued business as usual will probably result in a long-term decline in fish catch.

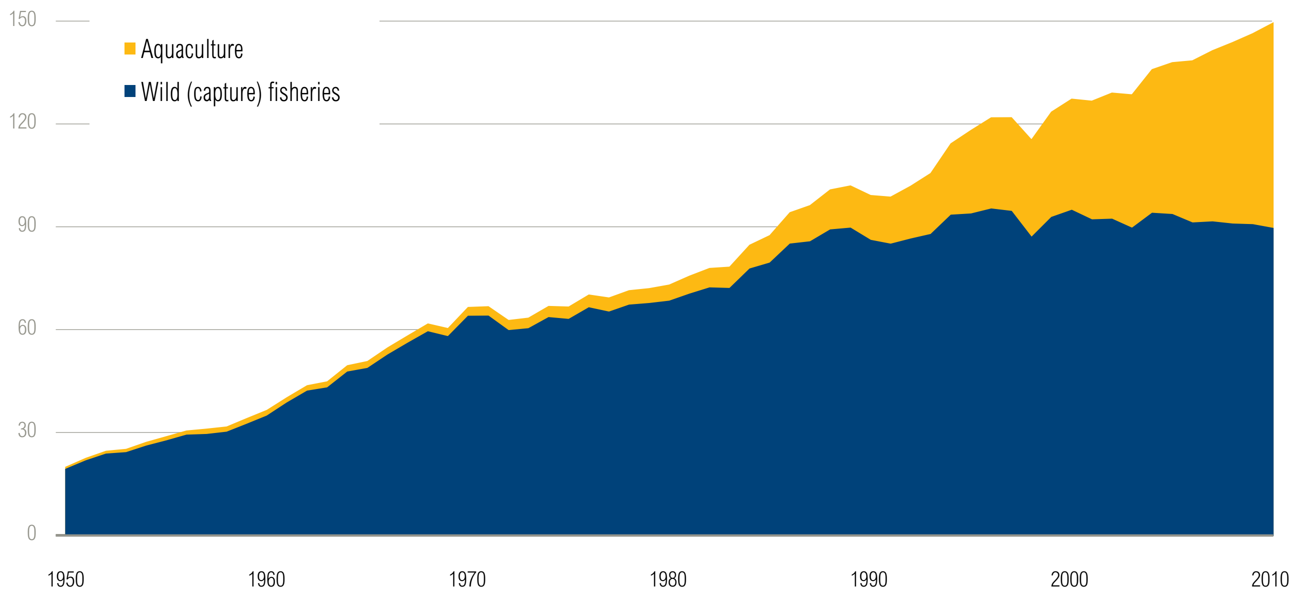
## MENU ITEM | Increase Productivity of Aquaculture

As the wild fish harvest has stagnated since the 1990s, aquaculture—the farming of aquatic animals and plants[383]—has grown to meet the world's growing demand for fish (Figure 34). At an average annual growth rate of 6.2 percent per year between 2005 and 2010, aquaculture is the world's fastest-growing animal food producing sector.[384] In 2010, aquaculture produced nearly 60 Mt of fish—nearly half of all fish consumed globally by people in that year.[385] Because of the limitations on wild catch, aquaculture production will supply all of the increase in fish consumption in the future, rising to 100 Mt by 2030,[386] and to 140 Mt by 2050 if growth continues at the same rate. Growth in aquaculture production to 140 Mt by 2050 would boost fish protein supply to 20.2 Mt, or 8.7 Mt above 2006 levels.[387] This increase would meet 17 percent of the increase in global animal protein consumption estimated by FAO for 2050.[388]

Asia accounts for nearly 90 percent of global aquaculture production, and China alone for 61 percent. Sub-Saharan Africa has the fastest growing industry by rate of growth, but still contributes less than 1 percent of global production.[389]

Aquaculture is diverse, producing more than 300 fish species through a wide variety of production systems in 2010. But just six species groups—carps, mollusks, shrimps, tilapias, catfish, and salmonids—account for 87 percent of production.[390] Sixty-two percent of all aquaculture production takes place

Figure 34 | **Since the 1990s, growth of aquaculture has provided nearly all increases in world fish production (million tons)**




*Note:* "Aquaculture" includes the culture of all aquatic animals (finfish, mollusks, and crustaceans). Excludes aquatic plants.
*Source:* FAO (2012b).

in freshwater, 30 percent in marine water and 8 percent in brackish water, including coastal ponds.[391] Globally, aquaculture employed almost 17 million fish farmers in 2010. When accounting for secondary sectors such as fish processing and marketing, the number of people reliant on aquaculture for a living rises to 100 million.[392]

In a resource-constrained world, aquaculture could be an attractive option for expanding animal protein supply. Because finfish are cold-blooded, excrete waste nitrogen directly as ammonia, and are supported by water, they devote less energy to metabolism and bone structure than terrestrial animals. Most farmed species therefore convert feed into edible meat quite efficiently—similar to the efficiency of poultry (see Figure 12).[393]

Another group of common aquaculture stock, filter feeders, can be even more efficient. Filter-feeding carp species, clams, mussels, and oysters obtain all their food from plankton and dead and decaying organic matter suspended in the surrounding water. Thus, there is no "food-out/terrestrial feed-in" ratio. Furthermore, clams, oysters, and mussels provide the added benefit of removing excess algae and nutrient pollution from coastal waters.[394]

However, aquaculture growth poses a number of important environmental and social issues, including water pollution and competition for water with other human needs. Other issues include chemical and energy use, the potential spread of diseases or genetic contamination to wild fish, and social conflicts over resource use.[395] We focus here only on two core constraints to future aquaculture expansion: (1) the demand for land, and (2) the demand for wild fish for feed. Aquaculture has already made impressive efficiency gains in both areas, but challenges remain.

## Demand for land

Aquaculture uses land directly for fish ponds and indirectly for feed, in particular oilseeds, pulses, and cereal grains. Aquaculture's indirect land use efficiency—which is linked to its feed efficiency—is quite high, comparable to that of poultry. However, aquaculture differs from poultry in that direct land use needs for fish ponds can be substantial.[396]

As with other forms of food production, land conversion for aquaculture can lead to ecosystem degradation. Since the 1990s, nongovernmental organizations and policymakers have focused on curbing the expansion of extensive, low-yield shrimp farms into mangrove forests in Asia and Latin America.[397] As a result, mangrove clearance for shrimp farms has greatly decreased, thanks to mangrove protection policies in affected countries and the siting of new, more high-yield shrimp farms away from mangrove areas.[398]

Still, current aquaculture production occupies a significant quantity of land, both in inland and coastal areas. We estimate that inland aquaculture ponds occupied between 12.7 Mha and 14.0 Mha of land in 2010, and that brackish water or coastal ponds occupied approximately 4.4 Mha—for a combined area of roughly 18 Mha, overwhelmingly in Asia.[399] Many of these ponds were converted from rice paddies and other existing cropland rather than newly converted natural lands—but even so, aquaculture adds to world land use demands when it displaces crops. In 2008, global land use efficiencies of inland and brackish water ponds averaged 2.3 tons of fish per hectare per year (t/ha/yr).[400] Expanding aquaculture to 140 Mt by 2050 without increases in that average efficiency would imply an additional area of roughly 24 Mha directly for ponds—about the size of the United Kingdom.[401]

The area under aquaculture ponds is small compared to total cropland, but this level of expansion would be significant environmentally in absolute terms. As the indirect land demands for feed are comparable between aquaculture and poultry, such increases in direct land use would also make aquaculture in ponds less efficient as a source of animal calories and protein than poultry.[402] At least as importantly, little new land is available for aquaculture or any agricultural expansion in Asia, where most aquaculture exists.[403] A key challenge, therefore, will be for aquaculture to more than double production by 2050 with no or minimal land expansion—and preferably to limit any needed expansion to economically and environmentally low-value areas.[404]

## Demand for wild fish for feed

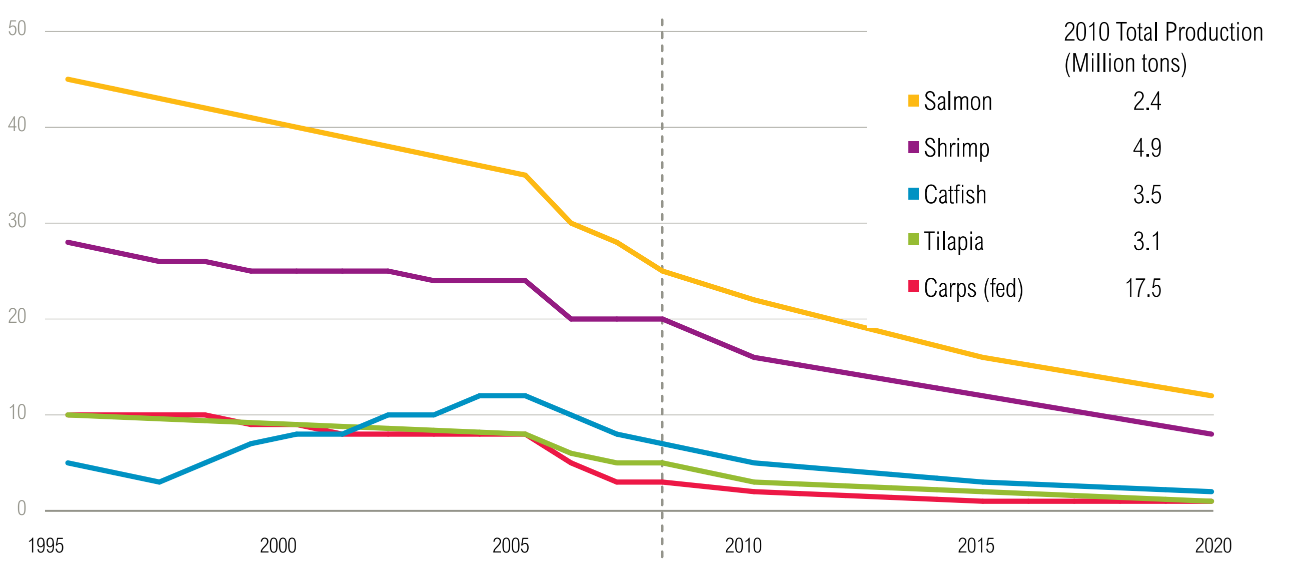
Much of the early environmental debate about aquaculture focused on whether it truly served as a net source of fish because carnivorous[405] species such as salmon, shrimp, and many other marine fish consume more wild-caught fish in the form of fishmeal and fish oil than they produce as food. This concern may have been overstated, as most aquaculture production consists of omnivores, herbivores, and filter feeders that consume little to no fish-based ingredients.[406] In addition, the fishmeal fed to carnivorous fish resulted primarily from diversions of fishmeal otherwise destined for livestock.[407] Aquaculture has also made great progress in reducing its reliance on fishmeal, enough to reduce its overall consumption of fishmeal modestly since 2005, even while continuing to produce more fish.[408]

Yet an issue still remains: Can aquaculture more than double production by 2050 without exceeding the global limits of fishmeal and fish oil supply? The catch of small fish from "industrial" fisheries[409] used for fishmeal is on the decline, dropping by half from 30 Mt in 1994 to 15 Mt in 2010.[410] Aquaculture has still grown, in part by diverting more and more of the fishmeal and oil from livestock feeds. But aquaculture now consumes 63 percent of global fishmeal and 81 percent of fish oil and therefore there is little left to divert from other uses.[411] Adding to the challenge, aquaculture must increasingly compete with the growing market for fish oil as a dietary supplement for people.[412]

As Figure 35 shows, aquaculture has greatly reduced the levels of fishmeal and fish oil in farmed fish diets since 1995, mainly by replacing these fish-based ingredients with plant-based proteins and oils.[413] Experts predict that the shares of both fishmeal and fish oil in aquaculture diets will continue to decrease at least through 2020.[414] Even if this progress is achieved, we calculate that aquaculture's total use of wild fish will slightly increase from 16.3 Mt in 2010 to 18.2 Mt in 2020, due to continued high growth in overall aquaculture production (Figure 36). As long as the global amount of wild fish converted to fishmeal and fish oil remains steady between 15 Mt and 20 Mt, by 2020 aquaculture's demand would roughly equal the total feed supply from industrial fisheries.

In order for aquaculture then to continue to grow to meet projected 2050 production levels, it will need to continue to improve feeds and feeding practices to further reduce its reliance on fish-based ingredi-

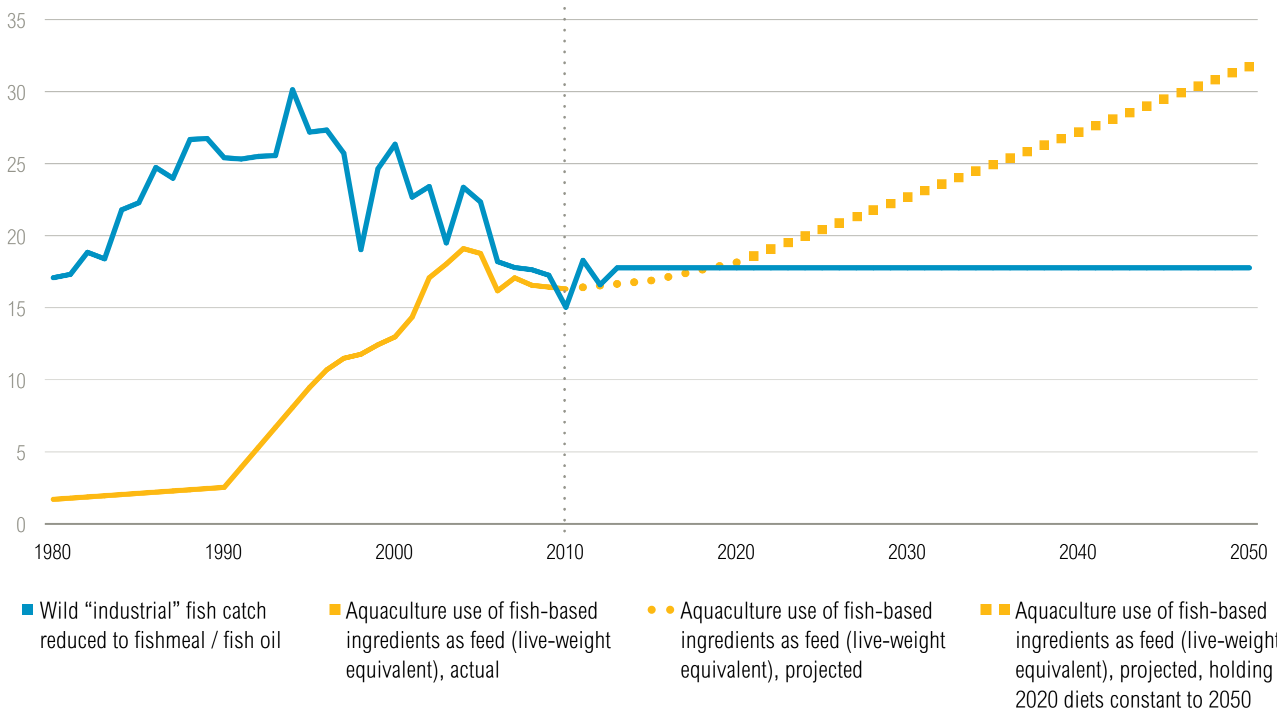
Figure 35 | **The aquaculture industry has reduced the share of fishmeal in farmed fish diets (percent)**




*Note:* Fishmeal use varies within and between countries; the figures presented are global means. Data represent observations between 1995-2008, and projections for 2009-2020.

*Source:* Tacon and Metian (2008), Tacon et al. (2011).

Figure 36 | **The aquaculture industry will need to further reduce the share of fishmeal and fish oil in farmed fish diets in order to prevent hitting limits in global supply of these ingredients (million tons)**




*Note:* Assumes the following to 2050: a linear growth in aquaculture production to 140 Mt, the same species mix as projected in 2020, and the same shares of fishmeal and fish oil in farmed fish diets as projected in 2020.

*Source:* FAO (2012f), FAO (2012g), OECD and FAO (2012), Seafish (2011), Tacon et al. (2011), Tacon and Metian (2008), WRI analysis.

ents. The shares of fishmeal and fish oil predicted for 2020 diets are already quite low, but more reductions will be necessary. Assuming the 2020 mix of farmed fish species and their diets remains constant to 2050, which implies that production remains overwhelmingly in carp and other herbivorous and omnivorous species, aquaculture's demand for wild fish as feed would still rise to 31.7 Mt. That level of demand would outstrip the industrial fisheries supply. If fish production shifted toward more carnivorous species, the problem would become larger.

## Some potential technical strategies

Despite its productivity gains over the past couple of decades, aquaculture must continue to evolve in at least two principal ways to realize its potential to contribute to a sustainable food future:

- **Use more intensive and efficient methods to produce more fish per hectare.** If aquaculture is to more than double production while slowing or halting its expansion onto new lands, it will need to greatly increase the amount of fish it produces per hectare. Intensification of fish production already occurs in many areas. While the average fish pond on a global basis produces between 2–3 t/ha/yr, intensive carp ponds in China produce 15 t/ha/yr, and intensive catfish ponds in Vietnam produce more than 100 t/ha/yr.[415] Expanding cage and pen aquaculture, either in inland or marine water bodies, could also produce more fish without requiring new land and freshwater.[416] Integrating aquaculture with other agricultural land uses—for example, the integrated rice-fish production system that currently occupies 1.5 Mha in China—can likewise make better use of scarce land and water resources.[417] Finally, although use of recirculating aquaculture systems has been limited so far, these systems achieve much higher efficiencies in the use of land and water and produce very little waste.[418]

- **Meet aquaculture's demand for fish oil and fishmeal without further wild fish catch.** Beyond continued reductions in the share of fish-based ingredients in aquaculture diets past 2020, increasing the use of fish processing wastes as feed ingredients could provide an effective short-term measure for meeting the demands of aquaculture. Already today, an estimated 6 Mt of fish waste is converted to fishmeal and fish oil, and various experts assume this figure will rise enough to meet the 2020 demand.[419] Conversion of by-catch now thrown away at sea into fishmeal and fish oil could further increase the supply of these ingredients without additional catch. The discards ban recently adopted by the European Union has the potential to facilitate such an increase.[420] Into the future, shifting the species mix produced by aquaculture away from carnivores and toward herbivores and filter feeders may become important. The alternative would be to develop plant-based substitutes for fish oil and meal. One involves the use of algae, some of which have a better nutritional profile for farmed fish than do other plant-based ingredients. The other involves the engineering of oilseed plants or yeast to produce feed ingredients high in omega-3 fatty acids, which are suitable replacements for fish oil.[421]

These strategies present many challenges. Intensification generally requires a range of investments—including more expensive feeds, deeper ponds, and electrified pumps to oxygenate and recirculate water—that will be beyond the reach of some farmers. Intensification will generally lead to higher energy use and, if not done carefully, may lead to more water pollution.[422] At this time, intensive systems are also more expensive and may produce fish that are too expensive for poor consumers. A subsequent installment will examine the practical challenges and opportunities.

Aquaculture production will need to grow dramatically to meet the world's demand for fish in 2050. But to do so sustainably, aquaculture will need to produce more fish per unit of land and water, and reduce its reliance on wild-caught fish for feed.

Chapter 7

# BIOENERGY

This report's analysis of future crop needs has followed the FAO lead and assumed that biofuels in 2050 will provide no more than roughly the same 2.5 percent of global transportation fuels that they provide today. However, existing goals for larger quantities of biofuels and other forms of bioenergy have even larger implications for food production and land use and threaten to widen the calorie gap.

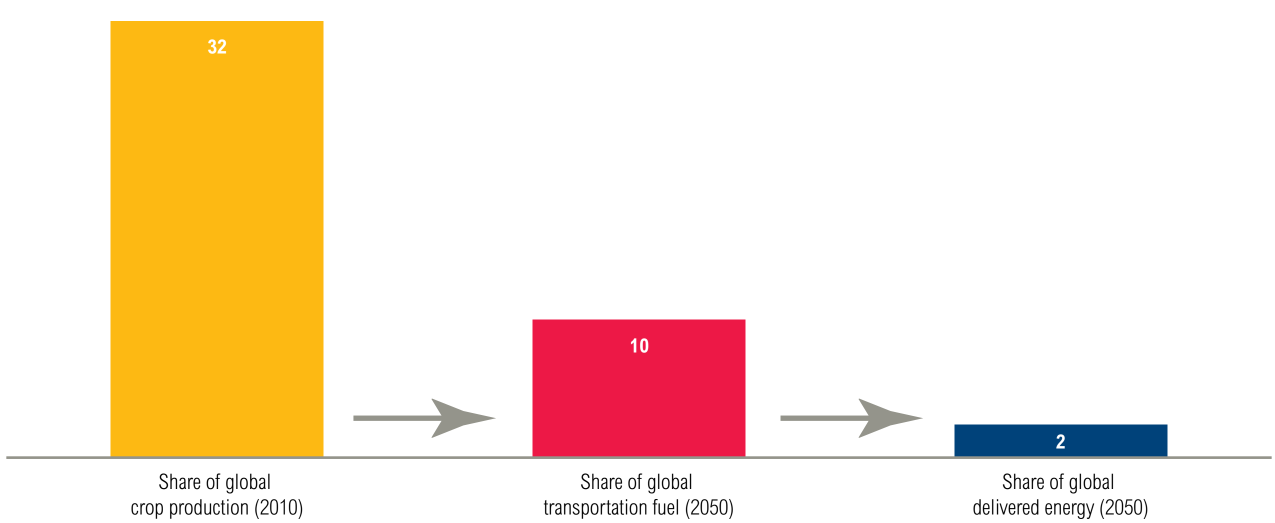
Several governments—including the United States and Europe—have adopted requirements to produce at least 10 percent of transportation fuels from biofuels by 2020.[423] Additional goals are also in place for broader forms of bioenergy. For example, the European Union has adopted a requirement that its members generate 20 percent of their energy for all uses from renewable sources, and national action plans indicate that, on average, countries intend bioenergy to meet 60 percent of that target, or 12 percent of energy overall.[424] Much of that bioenergy will derive from the harvest of wood for electricity and power. Likewise, the International Energy Agency (IEA) has announced roadmaps for the future with the goal of generating 20 percent of the world's energy from bioenergy in 2050.[425] What is the potential impact of these targets on a sustainable food future?

## Crops to biofuels

One way to answer this question is to determine the total percentage of the world's crops necessary to meet these different bioenergy goals. Producing 10 percent of the world's liquid transportation fuel by 2020 would require 22 percent of the energy in all of the world's crops harvested in 2010. Providing that same level in 2050 would require 32 percent of today's crop energy.[426] This large share of crop-based energy would generate just 2.4 percent of the world's delivered energy by 2050 on a gross basis. After accounting for the additional energy needed to generate biofuels compared to gasoline and diesel, the net energy gain would be less than 2 percent (Figure 37).[427]

These calculations indicate that a much larger increase in today's total production of crops would be necessary to meet not only growing food demands but also the 10 percent transportation fuel target from biofuels. The needed increase in crop production to close the calorie gap discussed in chapter 2 assumed that bioenergy production in 2050 would hold steady at today's level of 2.5 percent of global transportation fuel. However, the higher biofuels target of 10 percent would increase the calorie gap between 2006 and 2050 from 69 percent to roughly 100 percent.[428]

Figure 37 | **32 percent of global crop energy in 2010 would be needed to produce 10 percent of transportation fuel and 2 percent of global energy demand in 2050 with present biofuel mix (percent)**




*Source:* Heimlich and Searchinger (forthcoming).

These figures reflect the significant limits on how much energy food crops can even theoretically provide. All of the gross energy contained in 100 percent of the world's crops in 2010 equaled just 14 percent of the world's primary energy consumption in 2010.[429] In other words, 14 percent is the maximum share of the world's total energy needs that crops could fill if the world stopped eating and were able to use those crops just as efficiently as the world uses fossil fuels. But because conversion of biomass into energy is never as efficient as fossil fuels,[430] the real share would probably be less than 10 percent.

The inability of crops to make a large dent in global energy demands becomes even more apparent looking out to 2050. Primary energy consumption will rise by almost two-thirds between 2010 and 2050, according to OECD projections.[431] Devoting all of today's crop production to bioenergy would provide only about 8.5 percent of primary energy in 2050 on a gross basis and probably only about 6 percent on a delivered or net basis.

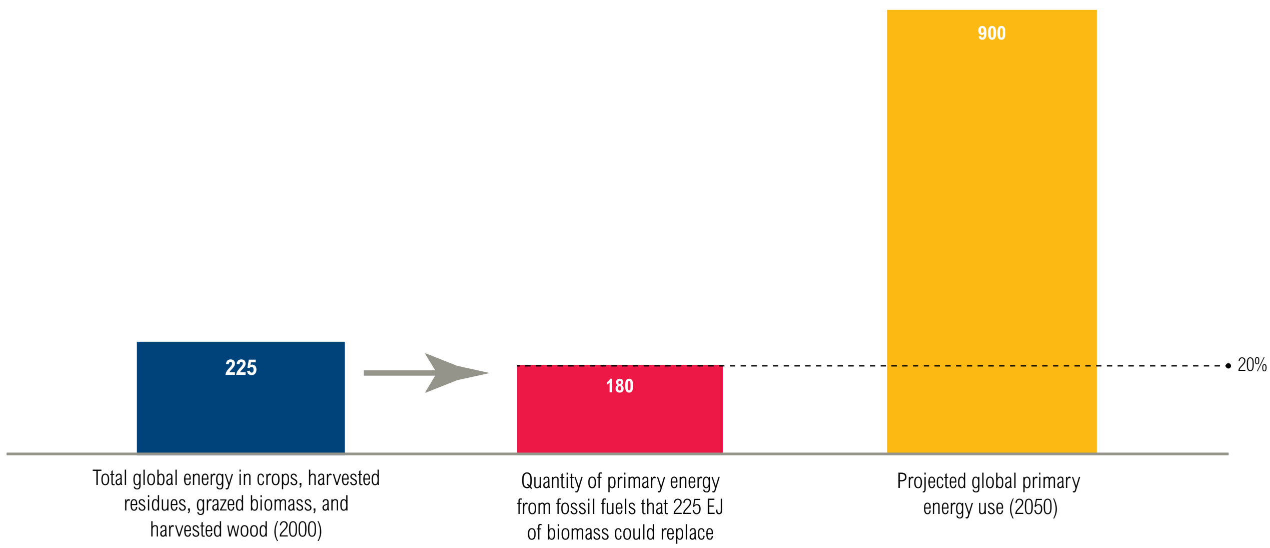
These calculations are based on the energy in all crops (including fruits and beans). If crops were used to make biofuels, of course, they would not rely on all crops but rather on those crops with the largest energy content, such as maize and sugarcane. As of 2010, biofuels used 3 percent of the world's cropland measured by the global average yield.[432] If biofuel production in 2020 relied on the same mix of crops as today, it would use around 15 percent of the world's present harvested area to meet 10 percent of transportation fuel. That land use figure appears more moderate than the 22 percent of actual energy in crops, but it also understates the challenge because high energy crops require wetter and better cropland overall than less productive crops. Using up 15 percent of the world's better lands for high energy crops would displace far more than 15 percent of the productive capacity of the world's cropland. Even so, 15 percent is a large amount of cropland to provide less than 2 percent of the world's delivered energy in 2020, and the figure would grow far more to provide that level of energy by 2050.

Producing 10 percent of the world's transportation fuel from crops in 2050 would increase the food gap from 69 percent to 100 percent. On the other hand, eliminating the use of crop-based biofuels for transportation would reduce the gap to 55 percent.

### Biomass to energy

Governments have offered incentives to switch biofuel feedstocks away from edible crops to grasses, trees, and other "cellulosic" or "second generation" sources of biomass, and to many commentators, switching to cellulosic feedstocks appears to avoid competition with food. But doing so is unlikely to alter the implications for food production if producers use agricultural land to produce these energy crops. Cellulosic ethanol does not necessarily generate any more ethanol per hectare once ethanol yields from crops are adjusted to reflect their feed byproducts. For example, a hectare of U.S. maize can now produce roughly 1,600 gallons of ethanol after adjusting for byproducts (roughly 6,000 liters).[433] For that same hectare to produce the same quantity of ethanol from fast-growing grasses, those grasses must achieve

Figure 38 | **Using all of the world's harvested biomass for energy would provide just 20 percent of the world's energy needs in 2050 (exajoules per year)**




*Source:* Heimlich and Searchinger (forthcoming).

very high yields of 16 t/ha/year of dry matter, and very high conversion efficiencies of 100 gallons (376 liters) per ton. Such biomass yields are in the range of those optimistically predicted by some renewable energy researchers in the highest producing locations in the United States,[434] but roughly double those estimated by the U.S. Environmental Protection Agency in a major recent rulemaking.[435]

Crop residues may provide alternative potential for biofuels without increasing pressure on food supplies and land, but their potential is highly limited. After accounting for residues that are already harvested for animal feed, bedding, or other purposes, the best estimate is that the remainder could generate perhaps roughly 14 percent of present world transportation fuel, or almost 3 percent of today's delivered energy.[436] But that "technical potential" assumes unrealistically that biofuel producers would harvest half of the crop residues from every crop and every field in the world. The economics of harvesting and hauling such a bulky, low energy source of biomass would probably restrict the harvest to limited areas of highly concentrated, highly productive crops with large quantities of residues. Even more importantly, this estimate also mostly ignores the critical role residues play in maintaining soil carbon and crop productivity, reducing erosion, and enriching soil microbial activity. Only in a few highly productive farming systems is there the potential for residue use beyond the needs of soil replenishment.[437] Even in as productive an agricultural system as the U.S. maize belt, the potential for residue removal to negatively affect yields appears substantial.[438]

The global goal of 20 percent of world energy from bioenergy by 2050 put forth by IEA's roadmap assumes the use of biomass from existing forests and many other sources beyond crops. The land use implications of such a target are vast. Producing that much bioenergy would require not merely 100 percent of all crops, but also 100 percent of all the world's harvested trees, grasses consumed by livestock, and crop residues in 2000.[439] Put another way, diverting all the world's recent annual harvest of biomass toward energy use would generate only around 20 percent of world energy in 2050 (Figure 38).

What explains these disproportionate numbers is the limited efficiency of photosynthesis. Even the most productive plants in the best growing areas are unlikely to convert more than 0.5 percent of solar energy into the energy contained in biomass, and typically much less.[440] By the time that biomass is turned into a useable form of energy such as electricity, the ratio will generally be one-quarter to one-third of that,[441] which ultimately yields efficiencies in the most optimistic cases of 0.2 percent and more realistically around 0.1 percent for most crops. By contrast, solar photovoltaic cells on the market today generally produce electricity with a solar conversion efficiency of 10 percent, and using solar cells to provide the power for electric vehicles would consume less land and generate much lower greenhouse gas emissions than using biomass.[442]

The inherent inefficiency of plant production means an enormous quantity of biomass procures a relatively small amount of energy for human use. The energy used by humans today is derived overwhelmingly from coal, oil, and natural gas, which were derived from plant growth long ago. But that accumulation of plant growth took place over millions of years and has become compacted into energy-dense fossil fuels.

Of course, bioenergy is already used intensely in many countries in the form of wood and charcoal, which is generally highly inefficient.[443] Some of these countries also use little energy overall, and may have few alternatives to bioenergy, particularly in rural regions. The efficient use of bioenergy to replace inefficient bioenergy consumption may provide an opportunity to enhance energy resources and reduce environmental impacts in these areas, and is worth pursuing.

## MENU ITEM | Reduce biofuel demand for food crops and agricultural land

Any effort to generate a meaningful percentage of human energy from biomass would either reduce food production, lead to large-scale land use change, or produce some combination of both.[444] To achieve a sustainable food future, the world should instead move in the opposite direction and give up the use of crop-based biofuels for transportation. Giving up the use of crop-based biofuels for transportation—a strategy more in line with a sustainable food future—would close the crop calorie gap in 2050 (Figure 5) by roughly 14 percent, or about 885 trillion kcal per year in 2050.[445]

Chapter 8

# SOME KEY TAKEAWAYS

Because this report is far from the first to address the food-development-environment nexus, in this chapter we highlight the conclusions that we believe are new, that diverge from common notions, and that have not received as much emphasis as they should.

## The challenge of closing the food gap by 2050 without land use change is more substantial than several other analyses suggest

Agriculture-related greenhouse gas emissions could easily reach more than 15 Gt of $CO_2e$ per year by 2050. Those emissions would constitute 70 percent of the maximum allowable emissions in 2050 from all human activities if the world is to meet the commonly shared goal of limiting warming to just 2° C. As a practical matter, 15 Gt of agriculture-related emissions would make it impossible to meet that climate goal.

Although many standard estimates project that today's 5.5 Gt of $CO_2e$ emissions from land-use change will rapidly decline over coming decades, we consider an estimate of stable emissions from land use change to be more likely under true "business as usual" for several reasons:

First, to eliminate land-use emissions under our adjusted FAO baseline through crop yield increases alone, crop yields would have to grow 32 percent more than they grew between 1962 and 2006. Yet 1962–2006 included the green revolution, when irrigated area doubled, water use for agriculture grew five-fold, and much of the world adopted synthetic fertilizer and scientifically bred seeds. Looking forward, climate change now appears likely to harm yields significantly and more than previously projected.

Second, demands for pasture will probably grow to meet projected growth in demand for beef and dairy of 80–90 percent by 2050. Projected annual demand growth for ruminant calories from 2006 to 2050 is 40 percent higher than during the period of 1962 to 2006, a period that witnessed a 270 Mha increase in grazing land.

Third, even if the world could eliminate net agricultural expansion, cropland is likely to continue to shift and therefore expand into forests, savannas, and wetlands even as cropping is abandoned elsewhere. This underappreciated shifting of land uses will continue to damage ecosystems and the services they provide, particularly carbon storage.

Finally, under business as usual, emissions from drained peatlands are likely to grow substantially.

## Bioenergy at any meaningful level would cause large-scale competition between energy demand, food production, and natural ecosystems

Meeting a modest 10 percent biofuel goal for world transportation fuel by 2050 would provide a net contribution of less than 2 percent of world delivered energy, yet would require 32 percent of current world crop production. That modest level of biofuel production would expand the calorie gap between now and 2050 from roughly 70 percent to roughly 100 percent, meaning the world would need to double the amount of crop calories produced per year by 2050.

The International Energy Agency and others have called for much broader bioenergy goals, such as producing 20 percent of world energy in 2050 via biomass of all sorts. Meeting such a goal, however, would require an additional harvest of biomass for bioenergy roughly equal to 100 percent of all the plants people presently harvest on the planet, including not only crops but also timber, crop residues, and grasses consumed by livestock.

On the other hand, if the world were to abandon the use of crop-based biofuels for transportation—a strategy more in line with a sustainable food future—the calorie gap between 2006 and 2050 would close by 14 percent.

## Some solutions have been incorrect or overemphasized

**USE OF ABANDONED CROPLAND AND WET SAVANNAS |** Several papers have identified abandoned cropland and Africa's savannas that are wet enough for cropping to be part of an environmentally low-cost "land reserve" suitable for sustainable agricultural expansion. But the regeneration of trees and grasses on abandoned agricultural land plays a large role in mitigating climate change, restoring ecosystems, and securing freshwater resources even as agriculture shifts and clears new land elsewhere. The wet savannas in Africa are also used by local communities and have high levels of carbon and biodiversity.

**AGRICULTURAL CARBON SEQUESTRATION STRATEGIES |** Most of the thinking about agricultural greenhouse gas mitigation has focused on soil carbon sequestration. Although some feasible opportunities do exist, the main strategies of focus are technically and practically more difficult and more scientifically uncertain than previously appreciated. Soil carbon sequestration is more likely to occur as an ancillary benefit of measures that boost food production and increase carbon uptake by plants, such as agroforestry.

## Some solutions may be somewhat harder than previous analyses have suggested but are strongly worth pursuing

**REDUCE FOOD LOSS AND WASTE |** Global food loss and waste currently amounts to 24 percent of world food production by calories, 32 percent by weight. If the rate of food loss and waste could be cut in half, the result could close the calorie gap between 2006 and 2050 by 20 percent. In developing countries, the largest opportunities lie with improving storage and harvesting technologies, while in developed countries the largest opportunities lie in changing consumer behavior.

**ACHIEVE HEALTHIER DIETS BY REDUCING EXCESSIVE MEAT CONSUMPTION |** If wealthier countries reduced their meat consumption meaningfully, they could not only improve human health but also greatly reduce the challenge of producing more food with less land conversion, less water consumption, and fewer greenhouse gas emissions. Such efforts have great potential, but they may not close the food gap because they may be necessary just to provide room for some of the world's poorest people to consume more animal products while holding the growth in meat consumption to the levels estimated by the FAO.

**INCREASE PRODUCTIVITY OF AQUACULTURE |** Aquaculture—apart from filter-feeding species—does not convert feed into food with efficiencies close to one to one, as some analyses have claimed. Yet overall, farmed finfish share with chicken the highest conversion efficiencies of all commonly consumed animal products, and there is room for further improvement in aquaculture's conversion efficiency. Because wild fish catches have stagnated and are not expected to rise, aquaculture production will need to grow dramatically to meet the world's demand for fish. But to do so sustainably, aquaculture will need to produce more fish per unit of land and water, reduce its reliance on wild-caught fish for feed, and mitigate environmental and social impacts associated with intensification.

> The technical potential to create a sustainable food future is real. Some solutions have been incorrect or overemphasized, others will be difficult but are strongly worth pursuing, and several opportunities deserve dramatically more emphasis.

## Several opportunities deserve dramatically more emphasis

**SHIFT TO A MORE EFFICIENT MIX OF ANIMAL PRODUCTS, AND RAISE CATTLE MORE EFFICIENTLY |** The majority of agriculture's existing global land use, recent land expansion, and greenhouse gas emissions all result from the production of beef and dairy products. Beef is by far the most inefficient animal product in converting feed into calories and protein—approximately one-fourteenth as efficient as chicken for calories[446]—and its production generates several times the emissions per calorie or gram of protein. Much of the world eats more beef than is healthy, and our adjustments to FAO's projection show an increase in beef consumption of 92 percent by 2050 because even more people will do so. Three strategies could address these challenges:

- **Shift to a more efficient mix of animal products.** Shifting even 20 percent of projected future beef consumption to virtually any other animal product, let alone a vegetarian alternative, could reduce land use demand by hundreds of millions of hectares because other animals convert feeds to calories and protein more efficiently. Although beef cattle use much rangeland and consume various waste products that would otherwise go unused, future growth in beef consumption over coming decades will lead to further conversion of forests and wet savannas into pasture. Holding down growth in beef consumption would prevent this conversion.

- **Increase productivity of pasture and grazing lands.** Improving grazing efficiency by intensifying the use of the world's wetter pasturelands is a necessity for holding down land use demands. Demonstrated techniques exist, provide economic gains, and are widely practiced, although the precise mix of desirable measures across the landscape remains to be fully explored.

- **Improve livestock feeding overall.** Feeding improvements and improved health care for livestock, even using techniques available to small-scale farmers in Africa and Asia, could double or triple the production of beef and milk per cow and reduce greenhouse gas emissions per liter of milk or kilogram of beef by two-thirds or more.

**HELP COUNTRIES' EFFORTS TO ACHIEVE REDUCTIONS IN FERTILITY RATES, PARTICULARLY IN SUB-SAHARAN AFRICA |** Half the world's additional population between 2012 and 2050 will be born in sub-Saharan Africa—and virtually all additional population growth will occur in the region thereafter. Sub-Saharan Africa also is the region with the highest levels of hunger, the lowest crop yields, and the only region with a total fertility rate still far above the replacement level. Reducing child mortality, enabling girls to remain in school longer, and improving access to family planning and reproductive health services have led to dramatically lower fertility rates around the world, and are also working in parts of sub-Saharan Africa. These approaches would not only hold down food demands but also make valuable contributions to a wide range of social and economic goals, including the empowerment of girls and women.

**IMPROVE CROP YIELDS IN SUB-SAHARAN AFRICA |** Improving yields in sub-Saharan Africa is a key to reducing world hunger, protecting ecosystems, and limiting greenhouse gas emissions from land use change. In the Sahel and other comparable climates, low-cost practices such as agroforestry, water harvesting, and fertilizer microdosing provide demonstrated opportunities for immediate improvements.

**ENSURE THAT ANY AGRICULTURAL EXPANSION IS ON LOW-CARBON DEGRADED LANDS |** Properly defined, low-carbon degraded lands provide opportunities for raising crops and livestock in a manner that has economic benefits and minimal environmental impacts. The *Imperata* grasslands of Indonesia and Malaysia provide the world's best example of low-carbon degraded land that is suitable for increased production of the world's most popular oil crop—palm oil—and are a viable alternative to converting peatlands and forests. The restoration of an estimated 5 Mha of abandoned and drained peatlands in the region could also reduce ongoing emissions at a level highly disproportionate to their area.

**ADDRESS BOTH GROSS OVERUSE AND UNDERUSE OF FERTILIZER |** Parts of China, India, and the United States extensively overuse fertilizer, while parts of Africa underutilize it. Reducing overuse in the former would reduce costs, greenhouse gas emissions, and water pollution, while increasing fertilizer use in the latter would help spare ecosystems and carbon by avoiding the need for cropland expansion. Improvements in the use of techniques to stabilize nitrogen in fertilizer hold promise and should be a focus for efforts going forward.

**INTEGRATE AGRICULTURAL IMPROVEMENTS WITH PROTECTION OF NATURAL ECOSYSTEMS |** Because agricultural land is likely to shift at the expense of carbon and natural ecosystems, boosting yields enough to hold net agricultural land use constant is necessary but not sufficient to meet sustainability goals. To protect natural lands, countries must enforce policies that link agricultural yield improvements with conservation of natural resources. Success also implies maintaining a focus on boosting the yields of those who already farm on existing farmland, which will often be smaller farmers, and should yield multiple economic and community benefits.

Chapter 9

# THE POTENTIAL SYNERGIES FROM CLIMATE-SMART AGRICULTURAL POLICY

A common ingredient in our *Creating a Sustainable Food Future* menu is a push for increased efficiency in the use of natural resources for food production—including in the uses of land, water, fertilizer, feed for livestock, and even fish oil. Despite the challenges this report has recognized, this linkage highlights a reason for hope: through these efficiency gains, there are genuine win-win solutions that boost food production, protect ecosystems, hold down climate change, and can increase economic opportunities for the poor.

Achieving efficiency gains sufficient for sustainability will require changes in public policy. Fortunately, because using natural resources often has at least some financial cost, the agricultural sector should have—and has exhibited—a general self-interest in improving these efficiencies over time. Our baselines assume many improvements without any assistance from public policy. Unfortunately, these improvements are not enough to avoid growth in the use of these natural resources to a degree that will still have unacceptable consequences for climate change, water, and ecosystems. There also is no market guarantee that production will provide enough and appropriate food for the world's poor at a price they can afford, nor a guarantee that the methods by which production increases will help those poor who farm. The principal challenge for policymakers, private companies, and civic organizations is how to accelerate these gains in natural resource efficiency so that they account for as much of the increase in production as possible at an affordable price and in a manner that also provides economic opportunities for hundreds of millions of rural poor.

Market forces will be critical to boosting food production in response to growing demand, but those forces are unlikely to achieve our sustainability criteria by themselves. Markets work through price signals, but price changes alone will have both positive and negative effects. Rising food prices can encourage improvements in efficiency of the uses of land and water, but those same higher prices can also send signals to farmers to expand agricultural production on new land—or to use more water or chemicals—where they can. Although some small farmers will use the opportunity to improve their production, the same high prices will lead other large farmers to accumulate more land, and in some cases, to use their political influence to obtain large quantities of land from the government. Higher prices will increase the welfare of those small farmers with surpluses to sell, but they will also cause consumers to cut back on food consumption, and those who cut back the most will generally be those who need food the most.[447] In sheer numbers, the hungry and poor who are net buyers of food exceed those who are net producers.[448] Prices, of course, increase when there are food shortages, so avoiding food shortages is important to avoid negative impacts on both the poor and the environment.

One appropriate policy response to the resource efficiency challenge will probably involve restrictions on the use of land and other natural resources to push production to expand on existing agricultural land. But such initiatives alone do not meet the needs of the poor or spur food production in areas where it is today growing too slowly, such as sub-Saharan Africa. And if food production does not grow rapidly enough and at a low enough cost, political support for natural resource protection will probably decline.

These considerations recognize roles for public policy in protecting natural resources, in spurring increased production in ways that sustain those resources, and in helping poor farmers with the least opportunity to improve their incomes through non-farming means. As we have shown in this report, the technical potential to create a sustainable food future is real. Reducing food losses and waste saves emissions, land, energy and, in most cases, money. Improved breeding can make possible higher yields with fewer inputs and greater stability for all classes of farmers. Helping small farmers to feed cows more efficiently improves their income, and reduces emissions and land use demands. There are some genuine trade-offs, but many win-win solutions exist. The policies to realize those solutions are the subject of future installments of the 2013–14 World Resources Report.

# ENDNOTES

1. UNDESA (2013). 9.6 billion people in 2050 reflects the medium-growth scenario.
2. "Middle class" is defined by OECD as having per capita income of $3,650 to $36,500 per year or $10 to $100 per day in purchasing power parity terms. "Middle class" data from Kharas (2010).
3. Foresight (2011a).
4. FAO, WFP and IFAD (2013).
5. FAO, WFP and IFAD (2012).
6. Between 2006–2050, worldwide available food calories would need to increase by 65 percent. See Box 3 for a discussion of the two approaches to measuring the 2050 food gap. The UN Food and Agriculture Organization (FAO) measures food in terms of "food availability." Food availability reflects edible food intended and available for human consumption. In general, it is the amount of food produced. See Box 4 for a discussion of food availability and the other pillars of food security.
7. This figure is based on WRI adjustments to FAO projections. The next section articulates the FAO projections and WRI adjustments.
8. Ravallion et al. (2007).
9. World Bank (2012c).
10. World Bank (2008).
11. FAO (2007); World Bank, FAO and IFAD (2009).
12. FAO (2011a).
13. Millennium Ecosystem Assessment (2005).
14. Figures exclude Antarctica. FAO (2011b).
15. Kissinger et al. (2012).
16. Millennium Ecosystem Assessment (2005). In this paper, we treat the negative impacts on ecosystems to imply a negative impact on biodiversity, as well.
17. WRI analysis based on UNEP (2012), FAO (2012e), EIA (2012), IEA (2012), and Houghton (2008) with adjustments. This figure excludes downstream emissions from the entire food system in processing, retailing and cooking, which are overwhelmingly from energy use, and which must be addressed primarily by the broader transformation of the energy sector.
18. Foley et al. (2005).
19. Selman and Greenhalgh (2009).
20. Bai et al. (2008). This paper defined land degradation as areas with declining annual plant production, which was estimated by 23 years of data from remote sensing, with efforts to control for other alterations, such as rainfall pattern changes. Various other methods, all with major limitations, have also been used to assess land degradation. See Gibbs (2009).
21. Paeth et al. (2009).
22. IPCC (2007).
23. IPCC (2007).
24. Based on the FAO Food Balance Sheets, daily calorie availability from both plant- and animal-based foods in 2009 was 2,831 kcal/person. Multiplying this figure by the 2009 global population of 6,834,722,000 yields a total daily global calorie availability of 19,349,097,982,000 kcal. Spreading this amount of calories evenly among the projected 2050 global population of 9,550,945,000 people results in a daily calorie availability of 2,026 kcal/person. FAO's suggested average daily energy requirement (ADER)–the recommended amount of caloric consumption for a healthy person–for the world in 2010–12 was 2,248 kcal/person/day. For developed countries, the ADER was 2,510 kcal/person/day. We assume that in 2050 the global ADER will not increase to current developed country levels but will slightly increase to 2,300 kcal/person/day as people currently undernourished become taller as their diets improve. To determine how much food needs to be available in order for people to consume 2,300 kcal per day, we factored in the current global average rate of food loss and waste of 24 percent, thereby arriving at approximately 3,000 kcal/person/day. This figure assumes that no person is over-consuming calories.
25. Alexandratos and Bruinsma (2012).
26. This adjustment does not reduce calorie consumption in any region. In sub-Saharan Africa and India, where FAO projects calorie availability less than 3,000 calories per person, we assume increased consumption equal to the availability of 3,000 calories per person, including food lost and wasted.
27. To be precise, biofuels contributed 2.5 percent of world transportation energy in 2010 (authors' calculations presented in Heimlich and Searchinger (forthcoming)). For this comparison with FAO projections, we use data provided by FAO for the crops used for biofuels in 2050 and back-calculated the quantity of ethanol and diesel.
28. More precisely, the FAO projection for increases in total crops implies a 68.8 percent increase in crop calories from 9,491 trillion kcal per year in 2006 to 16,022 trillion kcal per year in 2050. Without any growth in biofuel production, the increase in crop production would be 57.3 percent. There is no one perfect measure of the production increase challenge. This figure does include the rise in crops fed to livestock measured in calories, rather than the calories in the livestock products themselves. Doing so recognizes that animal products only return a small percentage of the calories in crops fed to them. However, this calculation does not reflect the additional calories from grasses that livestock also consume to provide people with milk and meat. The number reported in the text has the advantage of fully estimating the total increase in crop production, including that for feed and biofuels. But it leaves out the increase in pasture and other feeds that must be generated to produce the additional animal products.
29. Alexandratos and Bruinsma (2012), Table 4.8. FAO data estimate an increase in arable land in use of 220 million hectares from 1962 to 2006. According to FAOSTAT, pasture area has increased by 270 million hectares since 1962.
30. In this publication, "food loss and waste" includes food that was intended for humans but ends up getting fed to animals. It does not include food intentionally grown for animal feed or the food people consume beyond recommended caloric needs.
31. FAO (2011d).
32. FAO (2011d).
33. The FAO estimate is the best currently available, although experts note that these figures are rough and should not be considered precise.
34. The FAO Food Balance Sheets convert metric tons into calories per type of food.
35. Unless otherwise noted, figures and data in the rest of this section come from WRI analysis based on FAO (2011d).
36. Rejinders and Soret (2003).
37. Personal communication with Jess Lowenberg-DeBoer, Associate Dean and Director of International Programs In

Agriculture and Professor of Agricultural Economics, Purdue College of Agriculture.

38. Developed by WRI and the World Business Council for Sustainable Development, the Greenhouse Gas Protocol is the globally accepted standard for companies and other entities to measure their greenhouse gas emissions. It defines what emissions are to be measured and how to do it. For more information, visit <www.ghgprotocol.org>.
39. European Parliament (2012).
40. In our business-as-usual scenario, global daily kcal availability of food for direct human consumption in 2050 is 31.8 trillion kcal. The rate of global food loss and waste in 2009 was 24 percent. Cutting this in half is 12 percent. The 12 percentage points of avoided food loss and waste translate into 3.818 trillion kcal (0.12 x 31.8 trillion kcal) per day or 1,394 trillion kcal per year.
41. Emissions beyond the farm-gate level that are the focus of our analysis mostly involve energy used in everything from food processing to grocery stores and even home cooking. Some studies estimating these emissions are summarized in Garnett (2011).
42. WHO (2012), Campbell et al. (2006).
43. WHO (2012).
44. FAO, WFP and IFAD (2013).
45. OECD (2010a).
46. Gortmaker et al. (2011).
47. Cecchini et al. (2010).
48. FAO, WFP and IFAD (2012), Figure 16.
49. Gortmaker et al. (2011).
50. OECD (2010b).
51. Gortmaker et al. (2011).
52. Elinder (2005).
53. Andreyeva et al. (2010).
54. In the United States, the price of all farm products contributes only 17 percent to the total amount of money spent on food. These are the authors' calculations of total retail food expenditures compared to farm gate commodity revenue after deducting costs of feed to avoid double counting. Data from U.S. Department of Agriculture available at: <http://www.ers.usda.gov/data-products/price-spreads-from-farm-to-consumer.aspx#25676> (last accessed December 8, 2012). An increase in the price of maize by 50 percent translates into less than a 1 percent increase in retail food prices. Data from USDA/ERS (n.d.). In turn, people spend only around 10 percent of their incomes on food, and the result is that a rise in crop prices results in substantial declines in both the quantity and consumption of food for the food-insecure, but has little to no effect on the world's wealthy (HLPE 2011, p. 23).
55. This estimate 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. As Hall et al. (2011a) explain, the 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 mid-point of 2,850 kcal, and assuming that an acceptable diet would consist of 2,350 kcal per person, this estimate also implies that the elimination of obesity would reduce consumption by 500 kcal per person per day.
56. The table below shows how we derive the figure of 261 trillion kcal per day. This figure represents the reduced calories consumed, including meat and milk, not merely crop calories. As such, the percentage needs to be calculated by the calorie consumption gap, not the total crop production gap, which includes feed grains and non-food uses of crops. The total food consumption gap is 4,331.5 trillion kcal (rather than the 6,500 trillion kilocalorie total crop gap).

| | OVER-WEIGHT | OBESE | TOTAL |
|---|---|---|---|
| Population 2008 (millions) | 900 | 500 | 1,400 |
| Population in 2050 BAU (assuming 50% increase) (millions) | 1,350 | 750 | 2,100 |
| Excess calorie consumption (kcal/person/day) | 250 | 500 | n/a |
| Associated food loss and waste (assuming 24% rate of loss and waste, i.e. the line above / 0.76) | 78.9 | 157.9 | n/a |
| Total excess consumption in 2050 (million kcal/day) | 444,015 | 493,425 | 937,440 |
| Total excess consumption in 2050 (trillion kcal/year) | 162.1 | 180.1 | 342.2 |
| Savings assuming elimination of obesity and 50% cut in number of merely overweight (trillion kcal/year) | 81.05 | 180.1 | 261.15 |

57. Godfray et al. (2010).
58. Neumann et al. (2010a).
59. Pica-Ciamarra et al. (2011).
60. WHO, FAO and UN (2007).
61. FAO (2011c).
62. WHO (2012), Campbell et al. (2006).
63. FAO (2011c).
64. Steinfeld et al. (2006).
65. Numbers cited in Brown (2009), a critic of meat efficiencies, are based only on human edible feeds, while 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.
66. Wirsenius et al. (2010).
67. FAO (2011c).
68. Conversion to pasture directly releases less carbon because carbon content of soils will typically remain high and may even decrease, unlike conversion to cropland. However, the output of livestock products will probably be lower, so the carbon loss per unit of meat or milk will probably be larger.
69. Brown (2009).
70. "Edible output" refers to the calorie and protein content of bone-free carcass. Sources for terrestrial animal products (ad-

justed from carcass weight values to bone-free carcass weight values through personal communication with S. Wirsenius): Wirsenius et al. 2010 (extra unpublished tables), Wirsenius (2000). Sources for finfish and shrimp: Authors' calculations based on USDA (2013), NRC (2011), Tacon and Metian (2008), Wirsenius (2000), and FAO (1989).

71. The authors of a recent global FAO livestock analysis, Gerber et al. (2013), provided background information on protein efficiencies for poultry of 19 percent and pig meat of 12 percent. They are lower than the global estimates of protein efficiencies by Wirsenius (when bones are counted as in other analyses) of 26 percent for poultry and 18 percent 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 percent. CAST's estimates of protein efficiency were similar where comparable. For example, CAST estimated identical protein efficiencies for poultry in the U.S. of 31 percent and Wirsenius estimated 31 percent for poultry efficiencies in North America and Oceania. Using the same regional comparisons, CAST estimated protein efficiency for pork meat at 19 percent versus 23 percent for Wirsenius, and identical beef protein conversion efficiencies in these regions of 8 percent. The biggest difference in comparable areas was the energy efficiency of beef, at 7 percent for CAST versus 2.5 percent for Wirsenius. We are skeptical of this particular CAST estimate. The differences between energy and protein efficiencies are almost always large for all livestock in all regions, and CAST's estimated energy and protein efficiencies for U.S. beef are close.
72. Stehfest et al. (2009).
73. Foley et al. (2011) calculates that one-third of all crops are used for animal feed while data used for Alexandratos (2012) suggest that figure is 25 percent calculated on a caloric basis.
74. FAO (2011b) and FAOSTAT.
75. Foley et al. (2011).
76. Stehfest et al. (2009); Eshel et al. (2009).
77. For example, average yields from 2000–07 were 4.8 tons/ha/year for maize compared to 0.8 tons/ha/year for pulses according to data from FAOSTAT.
78. Stehfest et al. (2009) report that livestock products are substituted entirely by increased consumption of pulses (beans of various kinds), 60 percent of which are soybeans. The healthy diet also includes a consumption of fish per day slightly greater than the total of ruminant meat and pork. This fish production is assumed to avoid land use, but for reasons we show in the discussion on aquaculture, such a level of additional production would not be feasible.
79. Eshel et al. (2009).
80. Foresight (2011b).
81. Data from U.S. Economic Research Service downloaded October 20, 2013. Total consumption of red meat and poultry declined from 221.7 lbs./person in 2007 to 202.2 lbs./person in 2012. This figure counts "total disappearances," which include wastes.
82. Foresight (2011b).
83. Tilman et al. (2011).
84. These figures are just modestly higher using metabolizable (instead of gross) energy and offering credits for co-products. There are many ways of measuring the energy value of feed and of meat. Gross energy (GE) represents the maximum energy released by perfect combustion (ignoring the water content). Metabolizable energy (ME) calculates the net energy absorbed by the organism. Because ME is different for each animal, as well as each feed, Wirsenius et al. (2010) compares animals using gross energy. However, using ME somewhat improves the efficiency for beef as the ME of beef is roughly 85 percent of GE, while the ME of all feeds is roughly 50 percent of GE. According to that paper's calculation, accounting for all of the energy consumed by the whole herd relative to beef output globally, the ratio of GE in to GE out is 0.75 percent, while the ratio for ME in to ME out would be roughly 1.25 percent. There is also some case for allocating some of the feed used to raise cows to cow byproducts, such as tallow and hides. (A counterargument would be that we could replace those products without using land.) Allocating feed inputs based on economic value to byproducts, which U.S. studies have estimated at 16 percent (Environmental Working Group 2011), and using metabolizable energy, would raise the ultimate efficiency of beef to 1.5 percent.
85. Authors' calculations from Wirsenius et al. (2010) (extra unpublished tables), refers to the energy and protein content of bone-free carcass.
86. Based on data sources available, this fish calculation is for digestible energy in versus digestible energy out, which will result in a slightly better ratio than GE in and out, and therefore is not perfectly comparable to beef, chicken and pork.
87. The precise mix depends on the type of grassland reduced. Wirsenius et al. (2010, Table 7) estimated a decline of 500 million hectares, or roughly 16 percent of global grazing area. The authors did not separately analyze ruminant meat substitution compared to the business-as-usual "reference scenario," but only compared it to a scenario of somewhat intensified meat production. The ruminant meat substitution caused the 15 percent drop in feed demand. The proportionate drop should be the same for the reference scenario. We applied the same percentage and also assumed the present consumption is halfway between 1994/95 consumption analyzed by the authors and the 2030 reference scenario.
88. Authors' analysis based on UNEP (2012), FAO (2012e), EIA (2012), IEA (2012), and Houghton (2008) with adjustments.
89. de Vries and de Boer (2009).
90. Gerber et al. (2013)
91. FAO (2011c).
92. According to FAOSTAT, peak North American consumption of 169 kcal/capita/day and 160 g/capita/year in 1976 declined to 108 kcal/capita/day and 107 g/capita/year in 2009. European consumption of 129 kcal/capita/day and 69 g/capita/year in 1990 declined to 68 kcal/capita/day and 44 g/capita/year in 2009.
93. Wirsenius et al. (2010).
94. Statistics New Zealand (2013). 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.
95. UNDESA (2013). 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."

96. Many of these studies, going back decades, are summarized in Shapiro and Gebreselassie (2008).
97. UNDESA (2013).Total population by major area, region, and country (medium fertility scenario).
98. UNDESA (2013).Total population by major area, region, and country (medium fertility scenario).
99. FAO, WFP and IFAD (2013), USDA (2012).
100. The precise figures, measured by weight, were 24.5 percent of cereals, 65.7 percent of vegetable oils and 13.7 percent of animal products. Authors' calculations based on FAO food balance sheets.
101. Authors' calculations from FAOSTAT.
102. Swift and Shepherd (2007).
103. According to FAO figures and projections in Alexandratos and Bruinsma (2012), the region imported 17.5 percent of crop calories in 2006 and will import 12.4 percent of crop calories in 2050.
104. Authors' calculations based on Alexandratos and Bruinsma (2012) and UNDESA (2013).
105. This figure is based on analysis for this paper by Sarah Harper and George Leeson of the Oxford Institute of Population Ageing at the University of Oxford. The estimation for an assumed closed population is based on a simple approximate mathematical relationship at the population level between the total fertility rate (TFR), total population size, and the number of births in the population on the one hand (No. of births = TFR x total population/α), and between the TFR, the total population size, and the number of deaths in the population on the other hand (No. of deaths = TFR x total population/β). The coefficients α and β are estimated from the respective series of data from the UN. The replacement level fertility scenario of this estimation to 2050 assumes the TFR declines uniformly from its 2010 level to around 2.1 by 2050. Population births and deaths are then estimated in line with the above and the population size estimated simply as follows: Estimated total population(T) = Total population(T-1) + Births(T-1,T) – Deaths(T-1,T).
106. Based on modeling analysis of the Oxford Institute of Population Ageing.
107. Authors' calculations. The reduction in population of 390 million people in 2050 (relative to the UNDESA projection), each of whom would consume an average of 3,000 kcal per day, results in a total reduction in food consumption of 427 trillion kcal per year—an amount equivalent to 10 percent of the gap in food consumption between 2006 and 2050. (Note that this calculation uses the gap in food consumption rather than the gap in food production; see Box 3 for further discussion.) Similarly, the precise reduction in sub-Saharan Africa's food gap would be 26 percent.
108. Coale (1973).
109. World Bank (2012a).
110. World Bank (2012b).
111. For studies showing strong statistical correlations between declines in fertility and increases in girls' education, declines in infant mortality and increased access to family planning, see Shapiro and Gebreselassie (2008), Leeson and Harper (2012), Upadhyay and Karasek (2010).
112. Shapiro and Gebreselassie (2008); Bbaale and Mpuga (2011) shows that education is correlated with declining family size and increased use of condoms in Uganda and cites many studies from other countries; Bloom and Canning (2004).
113. Foresight (2011a).
114. Schmidt et al. (2012).
115. Chaaban and Cunningham (2011).
116. WHO (2013b).
117. World Bank (2012e).
118. Shapiro and Gebreselassie (2008); Bongaarts (2005); Bbaale and Guloba (2011); Bbaale and Mpuga (2011).
119. Shapiro and Gebreselassie (2008) found that among twenty-four 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 backsliding, that fertility rates tended to stall instead of drop further. Hossain et al. (2005) found that reduced mortality rates correlated with reduced fertility in Bangladesh.
120. WHO (2013a), WHO (2013b), CIA (2012).
121. World Bank (2010b).
122. World Bank (2012f).
123. UNICEF (2008).
124. World Bank (2012a).
125. World Bank, FAO, and IFAD (2009).
126. Pool (2007).
127. 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, South Korea, Singapore, Taiwan, and Thailand.
128. Sippel et al. (2011).
129. Foley et al. (2011).
130. Houghton (2008); Malhi et al. (2002).
131. For a summary of the uncertainties and methods, see Searchinger (2011).
132. UNEP (2012). That represents 3.95 gigatons of CO2 equivalent emissions from forest loss and another 1.25 gigatons from the decay of drained peatlands.
133. For example, another recent paper put the mid-level estimate for 2011 at 3.3 gigatons of CO2 equivalent from land use change, but did not include drained peatland (Le Quere et al. 2012). By combining estimates from various satellite based studies and peat drainage, Searchinger (2012) also suggested using 5 gigatons per year.
134. Burney et al. (2009); Foresight (2011a).
135. The GLOBIOM results deliberately include no growth of biofuels. The FAO predictions include an increase in crop calories for biofuels from 2006 equal to 14 percent of the estimated crop gains by FAO, but these land projections are for a level of crop growth for food and feed that is roughly 9 percent lower than our adjusted projection. It therefore can be viewed as roughly equivalent to a projection of land use needs just to provide the food increases we incorporate in our baseline. The OECD/IMAGE model we present did include large growth of biofuels, but we removed the growth in biofuels from the estimated growth in land use that we present.
136. The study actually estimates some increase in cropland, but that is entirely due to expansion of biofuels.

137. For example, Alston et al. (2010) includes a chart showing large declines in annual crop yield growth rates from the period 1961–90 versus 1990–2007. See also Foresight (2011a).
138. Authors' calculations from FAOSTAT. This comparison is between the average yield from 1961–63 and the average yield from 2005–07.
139. To calculate the "historical" rate of yield growth, we calculate the change in kilograms per hectare per year for each crop between an average yield over the years 1961–63 (the 1962 yield) and yields in 2006 estimated by FAO. We then calculate the growth rate for that crop necessary to produce all the crop production estimated by FAO for 2050 for that crop on the same harvested area. The FAO yield, area, and production for 2006 and 2050 are based on spreadsheets provided by FAO. With our adjustments to the growth in food demand for the higher population projection, future growth rates would have to be even larger. Yet we here present the comparison using FAO's own demand projections because we do not want to exclude the possibility that FAO would change its own projections in light of the higher population projections.
140. Any effort to express the need for yield growth in a single number is problematic because different crops have very different yields, nutritional benefits and other uses. Using one figure, such as calories per hectare, to express all crops would overvalue high caloric crops and undervalue crops that produce more protein, vegetable oil, or vitamins (such as fruits and vegetables). Although we express the general food goal in calories, we are careful to express land use needs based on the actual types of crops FAO projects will produce those calories, so our projections involve a mix of crops that also generate proteins, vitamins, and the other valued products. We derive our 32 percent estimate the following way. First, we calculated that if each crop categories' yields were frozen, it would require 790 million hectares of additional land to meet crop needs in 2050. We calculated that if yields grew at their historical rates for each crop, there would be a need for 192 million more hectares of harvested land each year. In effect, that means that in such a scenario area expansion would provide 24 percent of the projected needs (192 Mha/790 Mha), and yield gains would provide 76 percent. By this rationale, yield gains would have to grow 32 percent more (24.4/75.6) to meet all the food needs themselves.
141. To make this comparison, we calculated the growth in harvested area in 2050 for all crops assuming yields grew at global average historical rates and generated the production projected by FAO for 2050. That figure of 125 Mha compares to the FAO projection of 127 million hectares for the individual crop categories evaluated by FAO. FAO's total harvested area expansion of 131 Mha includes a 4 million hectare growth rate for other, unspecified crops, which we assume would be roughly the same at historical rates. (The increase in harvested area exceeds the growth in cropland area estimated by FAO shown in Table 3 because of an increase in double-cropping and other forms of cropping intensity discussed below. Harvested area counts each hectare planted and harvested twice in a year as two hectares.)
142. Mueller et al. (2012).
143. Alexandratos and Bruinsma (2012).
144. Shiklomanov (2000).
145. Alexandratos and Bruinsma (2012).
146. Siebert and Doll (2010b).
147. Alexandratos and Bruinsma (2012).
148. Gleick et al. (2009); Zongxue (2010).
149. Authors' calculations from FAOSTAT.
150. Evenson and Gollin (2008).
151. As of 2010, biofuel production, which barely existed in 2000, required the equivalent of 38 million hectares of cropland after accounting for byproducts by our estimate. The precise hectares devoted to biofuels are unknown because farmers produce crops for total demand, and some of these crops end up as biofuels (and byproducts). Our calculation accounts for the land area needed to produce the crops for biofuels at world average yields.
152. Foley et al. (2011).
153. Mathematically connecting emissions from land use change to the area of net expansion of harvested area, and from that to the rate of yield growth, is not simple. To start, even if yields grow in the next 44 years the same as the previous 44 years, harvested area will not grow by the same amount because the yield gains are growing on a larger cropland area due to the expansion of cropland since 1962. Over time, due to this math, the net expansion declines even to provide the same amount of additional food and with the same level of yield growth. Our figure that 80 percent of yield growth levels would result in roughly 200 Mha of expansion of harvested area is calculated by assuming that each individual crop category analyzed by FAO expands at 80 percent of the rate between 1962 and 2006. Expansion of harvested area, however, does not translate directly into the area of land clearing for many reasons: the potential for double-cropping area could reduce actual area of cropland expansion. On the other hand, the shifting of agricultural land discussed below also causes emissions even if net land use change remains the same. In addition, emissions from drained peatland are expanding dramatically, and drained peatlands continue to emit carbon for decades therefore. Pasture expansion is another major form of agricultural expansion. Overall, in light of the uncertainties, we consider a reasonable BAU projection to be that emissions from land use change will continue at present rates.
154. Relative to 1980–99 levels. IPCC (2007).
155. For the most recent IPCC assessment of climate change impacts on climate, see WGII 5.4, SPM. For recent assessments suggesting the more likely adverse consequences of climate change in colder regions, see Semenov et al. (2012). For increasing scientific evidence of the role of direct heat stress on crops, see Asseng et al. (2011), Lobell et al. (2012), and Shah et al. (2011). For evidence of adverse impacts of climate change on crops and the disruptive consequences of more likely extreme events, see Battisti and Naylor (2009), Lobell and Field (2007), Schlenker and Roberts (2009). For increased evidence of likely adverse effects in Africa, see Schlenker and Lobell (2010).
156. World Bank (2012d).
157. World Bank (2012d).
158. World Bank (2012d).
159. World Bank (2012d).
160. The increase in economic output is measured in dollars, but it assumes constant prices for the different outputs. In theory, because the relative prices of different agricultural outputs vary, the specific time used to fix those prices could influence these calculations, but in reality, the growth of economic

output does not vary much by this time-frame.
161. Fuglie and Nin-Pratt (2012).
162. Fuglie and Nin-Pratt (2012).
163. Cassman (1999).
164. Nature (2013).
165. NRC (2004).
166. Snell et al. (2012)
167. Greenpeace International has long been a leading opponent of genetic engineering. A review of its website reveals concerns about the potential consequences of genetic engineering on human health but no claims of actual harm to human health to date from the actual engineered crop. More information accessible at: <http://www.greenpeace.org/international/en/campaigns/agriculture/problem/genetic-engineering/failings-of-ge/>.
168. Séralini et al. (2011).
169. NRC (2004).
170. Ronald (2011) gives an example.
171. NRC (2004).
172. NRC (2004), NRC (2010), EU Joint Research Centre (2008), AMA (2012), AAAS (2012).
173. NRC (2010).
174. NRC (2010).
175. Benbrook (2012).
176. Gasnier et al (2009).
177. Benbrook (2012).
178. Krishna and Qaim (2012).
179. Wang et al. (2009) found large reductions in the use of pesticides in China despite occasional problems with increased growth of secondary insects. A later article also found reductions, but smaller (Zhao et al. 2011). Other evidence found an increase in beneficial predators in fields that use Bt cotton (Lu et al. 2012).
180. Benbrook (2012).
181. NRC (2010).
182. International Survey of Herbicide Resistant Weeds. Accessible at: <http://www.weedscience.org/summary/MOA.aspx?MOAID=12> (accessed April 20, 2013).
183. For example, the weed palmer amaranth, which can grow 3 inches a day and can release 1 million seeds from a single plant, has begun to overrun cotton fields in south Georgia and, once established, is almost impossible to eradicate (Charles 2012).
184. Benbrook (2012).
185. NRC (2010).
186. NRC (2010).
187. Stone (2012) provides a summary of the wide volume of literature on the yield effects of Bt cotton in India, and Smale et al. (2009) provides summaries of the literature on the broader economics, including yield, of Bt crops in many developing countries.
188. Sexton and Zilberman (2011) provide an example of the challenge. They found enormous yield gains through GM crops by regressing the yield growth in countries that have broadly adopted GM crops against that in countries that have not. Yet countries that have adopted these crops, such as Brazil, Argentina, China and the United States, have also made other large investments in agriculture, and it is difficult to segregate the consequences just of GM crops.
189. NRC (2010).
190. Fernandez-Cornejo and Wechsler (2012).
191. Stone (2012).
192. Gruere and Sun (2012).
193. Supporting this judgment is the fact that studies that have tried to control for selection bias or use methods that should not reflect selection bias still find significant yield gains (Crost et al. (2007); Kathage and Quaim (2012); Gruere and Sun (2012), and the fact that the overwhelming majority of peer-reviewed studies, biased or not, do find yield gains.
194. Gonsalves et al. (2007).
195. Davidson (2007).
196. Kathage and Quaim (2012); Smale et al. (2009).
197. Wiggins (2009) provides a good summary of the debate about the productivity and advantages and disadvantages of small versus larger farms in developing countries.
198. Witty et al. (2013).
199. Gurian-Sherman (2012).
200. Lusser et al. (2012).
201. Schroeder et al. (2013).
202. Foresight (2011a).
203. Von Caemmerer et al. (2012).
204. Hall and Richards (2012).
205. Hall and Richards (2012).
206. Economist (2010).
207. Hall and Richards (2012); Jannink and Lorenz (2010); Nakaya and Isobe (2012).
208. Varshney et al. (2012).
209. Nelson et al. (2004).
210. Nelson et al. (2004).
211. Nelson et al. (2004).
212. See: http://www.cgiar.org/our-research/cgiar-research-programs/cgiar-research-program-on-grain-legumes/
213. Alston et al. (2000).
214. Alston et al. (2000).
215. Foresight (2011b).
216. Foresight (2011b).
217. Fuglie (2012). This analysis identifies source of growth in total factor productivity, which is the ratio of economic output to inputs, not total output and not yield alone, which is the ratio of output (typically measured in crops) to land area.
218. Lobell et al. (2009).
219. Neumann et al. (2010b).
220. Lobell et al. (2009); Neumann et al. (2010b).
221. See http://www.yieldgap.org/web/guest/home.
222. FAO (2012a).
223. This figure is revised downward from 93 million hectares in the 2009 publication due primarily to a change in the estimate of cropland in 2005–07. That was in turn adjusted due to differing views of cropping intensity and some changes in estimates of China cropland data. Bruinsma (2009) and Alexandratos and Bruinsma (2012).
224. Alexandratos and Bruinsma (2012), Table 4.9.
225. Modeling using the GAEZ model accessible at: <http://webarchive.iiasa.ac.at/Research/LUC/GAEZ/results/5_7.htm>.
226. The 150 million hectare double-cropping derives from spatial analysis of cropping intensity in Siebert et al. (2010). The figure can be derived from Table 1 by calculating the total number of hectares harvested in 2000 (CE-FE) and multiplying that by 13 percent to reflect the judgment that this cropland has a harvest intensity of 1.13. Table 4.9 of Alexandratos and

Bruinsma (2012) indicates that at least 70 million hectares of irrigated land must be double-cropped, assuming that all irrigated arable land is harvested every year.

227. FAOSTAT indicates a 251 million hectare difference between total arable land (including land devoted to permanent crops such as trees) and harvested area in 2009. These figures differ somewhat from the 299 million hectares presented in Alexandratos and Bruinsma (2012) which adjusted arable land and harvested land in a couple of ways. However, assuming that roughly 150 million hectares were double-cropped for reasons discussed above, that means 400 million hectares were not harvested at all.
228. Siebert et al. (2010a).
229. For example, FAO reported 163 million hectares of U.S. cropland in 2009 (FAOSTAT). However, in 2007 (the most recent year for which USDA is reporting data), it reported 136 million hectares of U.S. cropland including planted areas that could not be harvested and summer fallow areas. Datasheet, Cropland used for crops, by region and States, United States, 1945–2007, downloaded from http://www.ers.usda.gov/data-products/major-land-uses.aspx#25964 (December 12, 2012). The roughly 70 million hectare difference consists roughly equally of two land categories, idled cropland, which is primarily Conservation Reserve Program lands, and cropland used for pasture.
230. Nefedova (2011); Ioffe (2005); Kuemmerle et al. (2010); Kurganova et al. (2007). FAO data for 2009 categorize 44 percent of arable land in the former Soviet Union as unharvested. The region abandoned croplands in vast numbers after the fall of the Soviet Union, and this figure suggests that it includes some or much of that land. But this land has been reforesting and otherwise sequestering carbon.
231. Mertz et al. (2009).
232. Liniger et al. (2011).
233. Bationo et al. (2006).
234. Bot and Benites (2005); Marenya and Barrett (2009a); Marenya and Barrett (2009b).
235. World Agroforestry Centre (n.d.).
236. Personal comm. Trent Bunderson, Executive Director, Total Land Care, June 14-15 2012.
237. This information is from work by two researchers from the University of Niamey (Prof. Yamba Boubacar and Mr. Sambo), who undertook a quick study in five villages in the Kantché department (Southern Zinder) to look at re-greening and food security. A blog about this work is accessible at: <http://africa-regreening.blogspot.com/2012_03_01_archive.html>.
238. From the research work of Boubacar and Sambo (2012).
239. Yamba (2006), Larwanou and Adam (2008).
240. Rockström et al. (2003).
241. For instance, studies in Mali on the impact of ridge tillage, a water harvesting technique, found increases in water infiltration by 66 percent, soil moisture content by 17 percent, and fertilizer-use efficiency by 30 percent. McGahuey (2012), based on Doumbia et al. (2009) and Kablan et al. (2008).
242. Stroosnijder and Hoogmoed (1984).
243. Hassane et al. (2000) show that yield improvements from water harvesting can vary from 500 to 1000 kg/ha, depending on other factors such as soil fertility. Sawadogo (2013) found that farms in Burkina Faso using water harvesting techniques increased yields 50–100 percent when compared with adjacent cultivated land not using harvesting techniques. An increasing number of farmers in the Sahel have used water harvesting techniques to reclaim lands that had been out of production for generations. In areas close to Tahoua, Niger, they were able to convert very low potential lands into productive lands (as measured not only by yields but by land prices). Mazvimavi et al. (2008) found that water harvesting, combined with conservation agriculture, increased yields per hectare by 50 percent on average across nine districts in Zimbabwe.
244. Reij, C. Personal communication. Senior Fellow, WRI. July 2012.
245. Mazvimavi et al. (2008). Gross margins were measured in $/hectare and return on labor in $/day. Data comes from nine districts in Zimbabwe, representing high, medium, and low rainfall zones.
246. Hayashi et al. (2008); Tabo et al. (2007); Sanginga and Woomer (2009); ICRISAT (2009).
247. Aune and Bationo (2008); Vanlauwe et al. (2010).
248. Sawadogo (2013).
249. Sanders and Ouendeba (2012).
250. Based on a geographic information system analysis and calculation by the World Resources Institute. Total land area within rainfall range of 400–1000 mm is 762 Mha. When protected areas, wetlands, rocky and nonarable land are excluded, available cropland is about 319 Mha. We assumed average cereal yields (of mainly millet, sorghum, and maize) of 600 kg/ha. Thus, a 50 percent increase equals 900 kg/ha, or an additional 300 kg/ha over 75 Mha (25 percent of 300 Mha), which is 22.5 million tons. We assume 2.9 million kcal/ton of cereal (e.g., maize, sorghum). Thus, 2.9 million kcal/ton X 22 million tons yields 64 trillion kcal of food. A 50 percent increase in production is conservative, when data show increases of 100 to over 200 percent in yields from these practices.
251. Figures include both biomass and necromass (Fairhurst et al. 2010). Land with less than 40 tC/ha could be converted without incurring a "carbon debt" according to the World Agroforestry Center (Dewi et al. 2009.).
252. Karama et al. (1993).
253. Fairhurst and McLaughlin (2009).
254. Soyatech (n.d.).
255. European Union Delegation to Malaysia – Trade and Economic Section. 2012.
256. Corley (2009).
257. The information for this paragraph is taken from Miettinen et al. (2012) and Page et al. (2011).
258. Page et al. (2011).
259. Miettinen et al. (2012) projects that because of accelerating rates of conversion of peatlands for oil palm in Indonesia alone, the present area of industrial peatlands of 3 Mha will grow to 6–9 Mha by 2020. Of that existing area, roughly two-thirds are for oil palm and roughly one-third is for industrial forest plantations.
260. Miettinen et al. (2012).
261. UNEP (2012).
262. Gingold (2010).
263. This figure reflects the area classified as "grassland" by Sarvision's radar-based satellite imagery of Kalimantan in 2010. Unpublished analysis conducted by WRI.
264. Garrity et al. (1997).
265. von Uexküll and Mutert (1994).

266. Gingold et al. (2012). The method for identifying degraded lands potentially suitable for sustainable oil palm applies a suite of objective criteria including land cover type (e.g., grassland), zero peat, no conservation areas, elevation, slope, rainfall, soil type, soil acidity, minimum contiguous hectares, and more. Designed with input from industry, government agencies, non-governmental organizations, and other experts, the method is consistent with international sustainability standards, such as those of the Roundtable on Sustainable Palm Oil, and Indonesian laws and regulations.
267. WRI has created a "Suitability Mapper," which allows users to create and customize maps of degraded lands potentially suitable for sustainable oil palm in Indonesia. To access the system, visit: <http://www.wri.org/applications/maps/suitability-mapper/>.
268. For example, this approach is implicitly taken in discussions of available land by FAO in its major agricultural projections, including Alexandratos and Bruinsma (2012). One World Bank study (Morris and Byerlee 2009) used this line of thinking to call explicitly for the conversion of hundreds of millions of hectares of the wetter savannas and sparse woodlands of Africa to cropping. Business consultants (e.g., Roxburgh et al. 2010) have endorsed such thinking. Biofuel studies engage in the same analysis and end up focusing heavily on these savannas. For discussion of this part of bioenergy potential studies, see Searchinger (2010).
269. The carbon implications of converting these areas are implicitly demonstrated in West et al. (2010). The biodiversity values of wetter savannas can be seen by comparing the areas identified as appropriate for crop conversion in Morris and Byerlee (2009) and the maps presented by Grenyer et al. (2006).
270. The best summary of these maps and other related efforts to identify degraded land is in Gibbs (2009).
271. See discussion of various bioenergy papers using this approach in Searchinger (2011).
272. This study is presented in two related publications: Campbell et al. (2008) and Field et al. (2008). These papers did not identify which portion of these abandoned lands had originally been only grazing land, but communications with the lead author clarified that they were the majority and are discussed in Searchinger (2011). The original study also identified some wetter abandoned lands that it claimed have not shown up on present land use maps as forests. That probably partially represents lands that are in the process of reverting to forests, and other lands that have reverted to grasslands and are still accumulating carbon. Although this study is the best available, it by necessity must include a high level of error. Even among satellite photograph studies, there is a high level of error because the different satellite maps disagree with each other regarding which land areas are forests and which are in some other use. The abandoned land study error rate must be substantially higher still because it attempts to map agricultural land from periods well before satellite photographs, which can only be done roughly. These estimates identified tens of millions of hectares of abandoned cropland that has not yet reverted to forest in some of the wetter countries of Europe, including the United Kingdom, but no study in Europe itself has managed to identify such lands.
273. See Figure 31 and accompanying discussion.
274. Discussed in Koh and Wilcove (2008).
275. For summaries of the relative biodiversity value, see Gibson et al. (2011); Ramage et al. (2013); Koh and Wilcove (2008).
276. Pan et al. (2011).
277. Authors' calculations from FAOSTAT; Steinfeld et al. (2006).
278. FAO data places cropland at 1,530 Mha in 2011, and permanent meadows and pastures at 3,374 Mha in 2011 (Alexandratos and Bruinsma 2012, p. 107). Estimates vary greatly and appear to vary based on the number of livestock that researchers assume must be present before they call an area a pasture. Estimates can be as high as 4.7 billion hectares (Erb et al. 2007).
279. By one estimate, cattle ranching accounts for 75 percent of the 74 Mha of deforestation in the Brazilian Amazon (Barreto and Silva 2010). Aide et al. (2012) shows the pattern continuing across Latin America. See also Murgueitio et al. (2011).
280. Wirsenius et al. (2010).
281. The rise in oilcakes is 70 percent and the rise in cereals is 48 percent. Presented as a figure in Alexandratos and Bruinsma (2012), p. 84, Figure 3.8. Because the study predicts a larger rise in pork and poultry, which rely much more heavily on feeds, the implicit rise in the use of feeds for ruminants is even less able to keep up with forages.
282. Using even FAO's relatively low estimate of world pasture land of roughly 3.2 billion hectares, and assuming pasture yields of meat and milk do not increase, an increase in production of 70 percent would require an additional 2.2 billion hectares if it occurred on a cross-section of lands that average the same productivity of all world pasturelands today. In reality, based on recent experience, expansion would occur primarily in wetter, more productive lands, generally through the conversion of tropical forests and wetter savannas. That expansion would reduce the total quantity of land conversion needed but would still leave a requirement, at a minimum, for hundreds of millions of hectares.
283. FAO (2012a).
284. According to FAOSTAT data, permanent pasture area actually declined on a net basis by 69,000 hectares from 2000–09. We caution again about the use of FAOSTAT pasture data because of definitional issues, but to the extent valid, those declines resulted overwhelmingly from a decline in pasture area in Australia, as drought caused Australians to recategorize much of its drier grazing land, and to a lesser extent from reforestation programs in China and other parts of Southeast Asia. Pasture clearing continued in Latin America and Africa. (Worksheet: Changes in FAOSTAT Permanent Pasture 1961–2009).

**Changes in production of various animal products and changes in feed quantities by type and overall feeding efficiency in IMAGE model results for OECD (%) (source and data provided by PBL)**

| | DAIRY CATTLE | NON-DAIRY CATTLE | PIGS | POULTRY | SHEEP AND GOATS | TOTAL |
|---|---|---|---|---|---|---|
| Animal products (used as feed) | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Food crops | 21.3 | 41.4 | 24.1 | 48.8 | 73.3 | 35.0 |
| Grass and fodder | 38.4 | 51.0 | 0.0 | 0.0 | 47.4 | 48.6 |
| Residues | 50.9 | 61.8 | 30.0 | 50.9 | 75.0 | 48.1 |
| Scaveng-ing | 120.2 | 27.4 | 0.0 | 0.0 | 51.5 | 56.0 |
| Total | 52.2 | 49.1 | 27.2 | 49.7 | 49.5 | 46.9 |
| Production | 36.8 | 70.4 | 33.4 | 58.1 | 109.8 | 43.0 |
| Feed efficiency | -10.2 | 14.3 | 4.8 | 5.6 | 40.3 | -2.6 |

285. Our analysis of data kindly provided by the IMAGE team is as follows:
286. Government of Brazil (2008). Analysis presented in Cohn et al. (2011) shows that ranching-related improvements are responsible for roughly 75 percent of the mitigation set forth in Brazil's nationally appropriate mitigation activities. Brazil developed a low-carbon agriculture plan described in Strassburg (2012).
287. Wirsenius (2010).
288. d'Alexis et al. (2012); d'Alexis et al (2013a); d'Alexis et al. (2013b).
289. McGhee (undated).
290. For example, a study of grazing intensities in the western Sahel on drier, low-carbon lands found no response in carbon content to grazing intensity (Badini et al. 2007). For good reviews, see Lipper et al. (2011), McCarthy et al. (2011), and Derner and Schuman (2007).
291. Strassburg (2012) and Goldemberg and Guardabassi (2009) describes increases in pasture output in São Paulo State.
292. Presentation of Strassburg at Pasture Intensification Workshop, Paris, November 2012, convened by WRI, INRA, and CIRAD. See also Strassburg (2012).
293. Murgueitio et al. (2011); Presentation of J. Chara, CIPAV, at Pasture Intensification Workshop, Paris, November 2012, convened by WRI, INRA, and CIRAD.
294. Brazil produces 15-20 percent of the world's beef, so doubling would produce 15-20 percent more beef, a small amount relative to the 90 percent gap. Data are from FAOSTAT.
295. Kling and Machado (2005). Carbon losses from conversion to crops are estimated in the supplemental information in Fargione et al. (2008), and are a large fraction of the carbon losses due to agricultural expansion in recent decades estimated in Searchinger et al. (2008).
296. Barona et al. (2010).
297. According to FAO data in FAOSTAT based on reporting from Brazil, from 2005 to 2010, Brazil reported no increase in either cropland or pasture, but it reported a 6.6 Mha decline in forest land. For 2000 to 2005, Brazil reported a decrease of 206,000 hectares in pasture land, only a 3 Mha increase in cropland, and a 15.4 Mha decrease in forest land. A decline in forest land does not occur merely because trees are cut. Instead, there has to be a change in use. These figures are therefore inconsistent. One possibility is that some land considered low forest was also included as pasture because it was occasionally grazed, so the subsequent true conversion of that forest does not show up as an increase in grazing land.
298. Bowman et al. (2012).
299. Barreto and Silva (2010).
300. Barreto and Silva (2010); Macedo et al. (2012).
301. Dixon and Coates (2009); Decruyenaere et al. (2009); Swain et al. (2011).
302. Boval and Dixon (2012); Boval et al. (2007); and Fanchone et al. (2012).
303. See the discussion of economic findings by Embrapa studies in Searchinger and Amaral (2009).
304. Rueda et al. (2003).
305. Strassburg (2012).
306. For papers about Brazil and pasture intensification, see Cohn et al. (2011) and Walker et al. (2009).
307. Angelsen and Kaimowitz (2001); Ewer et al. (2009); Rudel (2009).
308. Gallett (2009).
309. Alexandratos and Bruinsma (2012), Table 4.8.
310. Alexandratos and Bruinsma (2012), Table 4.8.
311. Reprinted from Figure 11 of FAO (2012e).
312. Aide et al. (2012).
313. West et al. (2010).
314. Grenyer et al. (2006).
315. Our emissions primarily rely on the estimates of agricultural emissions of methane and nitrous oxide by the U.S. Environmental Protection Agency (2012). We adjust these figures first by adopting the most recently recommended 100-year "global warming potentials" to convert methane and nitrous oxide into carbon dioxide equivalents. The EPA report uses old "global warming potential" figures of 21 for methane and 310 for nitrous oxide, and we use the new figures of 25 and 298. Because the EPA study focuses only on nitrous oxide and methane, we add in 0.11 Gt of emissions of carbon dioxide due to the carbon component of several fertilizers as estimated by the International Fertilizer Association. EPA also incorporates emissions from ruminant wastes on pastures into its total for emissions from agricultural soils. To provide a more accurate view of total ruminant emissions, we add the FAO estimate of emissions from ruminant wastes on pasture to the ruminant category and deduct that level of emissions from the EPA's estimate of emissions on agricultural soils. We use the Sims (2011) estimate for energy emissions in agricultural production, which do not include emissions from any form of crop or food processing, transport, or retail. In general, these estimates are close to those of others including UNEP (2012)

and Del Grosso et al. (2009).
316. Smith et al. (2007). Other studies since that date–such as Popp et al. (2010)–come to the same conclusion.
317. Sims (2011).
318. Popp et al. (2010), Figure 9, estimates agricultural emissions at more than 7 Gt of $CO_2e$ by 2010 without including either energy emissions or biomass burning.
319. Examples include EPA (2012) and IPCC (2007).
320. Although a later installment will provide more precise estimates based on different scenarios, the many scientific uncertainties regarding emissions, combined with the many alternative paths of technological development, imply that only a broad estimate is appropriate. Our projection implies a 46 percent increase in agricultural production emissions from 2010 to 2050. That compares to our estimate of roughly a 70 percent increase in crop production and roughly an 80 percent increase in livestock production, which are based on a 2006 base. Emissions growth to 146 percent of present levels for a crop production level of 170 percent of present levels implies an emissions intensity improvement of 14 percent, while for livestock an increase in emissions of 146 percent for a 180 percent increase in production implies a reduction in emissions intensity of 19 percent.
321. Cassman et al. (2002).
322. van Groenigen et al. (2012).
323. OECD (2011).
324. UNEP (2013) puts that figure for stabilization at 22 gigatons. The 2° Celsius scenario roughly corresponds with the scenario RCP 2.6, which is the lowest climate change scenario analyzed by global modeling teams for the new assessment by the Intergovernmental Panel on Climate Change. That ambitious assessment, which actually relies on negative carbon emissions in the later part of the century, also assumes that emissions of carbon dioxide, nitrous oxide, and methane fall to roughly 21 gigatons of $CO_2$ equivalent by 2050, which includes reductions of methane by roughly 50 percent. (Authors calculations from data presented in Van Vuuren (2011), Figure 6.
325. Seeberg-Elverfeldt and Tapio-Biström (2010); Smith et al. (2007).
326. Smith et al. (2007).
327. Lipper (2011); DePinto et al. (2011).
328. Powlson et al. (2011); McCarthy et al. (2011).
329. Baker et al. (2007) ; Powlson et al. (2011).
330. Powlson et al. (2012); Luo et al. (2010); Blanco-Canqui and Lal (2008)
331. Six et al. (2004).
332. McCarthy et al. (2011), Derner and Schuman (2007). For example, a study of grazing intensities in the western Sahel on drier, low-carbon lands found no response in carbon content to grazing intensity (Badini et al. 2007).
333. Asner and Archer (2010), Giller et al. (2009).
334. De Pinto et al. (2010), Haya (2009).
335. McCarthy et al. (2011), Lipper (2011).
336. Cacho (2009).
337. Ryals and Silver (2013); Powlson et al. (2012).
338. Marenya and Barrett (2009b).
339. Bryan et al. (2011).
340. Kemp and Michalk (2011).
341. Wang et al. (2011).
342. Henry et al. (2009).
343. Seeberg-Elverfeldt and Tapio-Biström (2010);
344. Wetlands International (2011), Table 1.
345. Branca et al. (2011).
346. McDermott et al. (2011), Tables 2 and 3; Pica-Ciamarra et al. (2011).
347. FAO (n.d.)
348. Gerber et al. (2010).
349. Thornton and Herrero (2010).
350. Bryan et al. (2011).
351. Orodho (2006).
352. Hassanali et al. (2008).
353. Place et al. (2009).
354. Blummel et al. (2009).
355. Blummel et al. (2008)
356. Thornton and Herrero (2010).
357. Walli (2011).
358. Alford et al. (2006).
359. Ejlertsen et al. (2012), Marshall et al. (2013).
360. Gerber et al. (2013)
361. Mueller et al. (2012), Liu (2010).
362. SAIN (2010).
363. Zhang et al. (2011)
364. Mueller et al. (2012).
365. Unpublished crop modeling using the DSAT model by Phil Thornton of CCAFS estimates that sub-Saharan Africa could support bean yields above the world average even without added nitrogen fertilizer, assuming that pest and phosphate problems are solved.
366. Akiyama et al. (2010).
367. Yan et al. (2005), Yan et al. (2009).
368. Presentations of Tapan Adhya, and Chris van Kessel at workshop on rice and nutrient management convened by WRI, INRA, and CIRAD, Paris, October 2012.
369. Presentation of Xiaoyuan Yan at workshop on rice and nutrient management convened by WRI, INRA, and CIRAD, Paris, October 2012.
370. Authors' calculations from FAO (2012a). Figures include both wild-caught and farmed fish. Nearly 1.3 billion people live in countries where the level of animal protein consumption coming from fish exceeds 25 percent.
371. WorldFish Center (2011).
372. FAO (2012d).
373. FAO (2012b). However, the overall global stability in marine fish catches over the past 20–30 years masks important trends by region and fish species. For instance, developed country landings are decreasing, while landings in developing countries are on the rise (FAO 2012d).
374. As defined by the World Bank and FAO (2009), fishing effort is "a composite indicator of fishing activity. It includes the number, type, and power of fishing vessels and the type and amount of fishing gear. It captures the contribution of navigation and fish-finding equipment, as well as the skill of the skipper and fishing crew."
375. FAO (2012d).
376. Examples summarized in CEA (2012).
377. World Bank and FAO (2009).
378. World Bank and FAO (2009), UNEP (2011), Costello et al. (2012).
379. CEA (2012).
380. See, for instance, World Bank and FAO (2009), UNEP (2011),

Costello et al. (2012), Srinivathan et al. (2010), and NEAA (2010). Climate change adds a new dimension of uncertainty in forecasting future marine catches, but models estimate that low latitude and tropical regions are likely to suffer decreases in marine fish catch potential due to climate change, while potential catch levels in high latitude countries are predicted to benefit from a warmer climate (Merino et al. 2012, Cheung et al. 2010).

381. The following observations are based upon and more thoroughly examined in CEA (2012).
382. Agnew et al. (2009).
383. The focus of this section is on aquaculture's potential to contribute to animal protein supplies, and thus all data on aquaculture production in this section omit production of aquatic plants (seaweeds).
384. FAO (2012a), FAO (2012b).
385. FAO (2012d). In 2010, 20 million tons of wild fish catch went to "non-food" uses, the majority of which was for aquaculture feeds.
386. Hall et al. (2011b).
387. Authors' calculations based on a growth in aquaculture production to 140 million tons, the same ratio of fish protein weight to total fish weight as in 2009 (which implies the same mix of fish species), assuming that all aquaculture production will feed humans, and assuming a 10 percent decrease in wild fish capture for food.
388. Authors' calculations. As an upper-bound estimate, building off of FAO projections (Alexandratos and Bruinsma 2012), we predicted an increase of 46.9 million tons in consumption of animal protein between 2006 (63.9 million tons) and 2050 (110.8 million tons). This would imply that an increase in animal protein provided by aquaculture of 8.7 million tons over that period would be equal to 18.6 percent of the total increase in animal protein consumption over that period. For *Creating a Sustainable Food Future*, we adjusted total 2050 calorie consumption upward from the FAO estimates to assure production of sufficient calories for all 9.6 billion people. If we assume a 3 percent increase in animal protein consumption relative to the FAO scenario, corresponding to our ~3 percent upward adjustment of FAO calorie consumption projections, total animal protein consumed in 2050 would rise to 114.1 million tons, the increase between 2006 and 2050 would be 50.3 million tons and the contribution of aquaculture growth (8.7 million tons) to that increase would be 17.3 percent.
389. Authors' calculations (based on WRR regions) from data in FAO (2012b). Sub-Saharan Africa saw an average compounded annual growth rate in aquaculture production of 29 percent between 2005 and 2010, by far the highest growth rate of any region. Still, the growth in absolute production in sub-Saharan Africa during this time period was only 259,000 tons (from 101,000 tons in 2005 to 360,000 tons in 2010), which is far behind the absolute growth in many other regions that started from a much higher 2005 production baseline.
390. FAO (2012b).
391. FAO (2012d), p. 34.
392. FAO (2012d), p. 18.
393. Costa-Pierce et al. (2012).
394. Hall et al. (2011b).
395. From Tacon et al. (2010) and Kura et al. (2004). Examples of other issues are as follows. Ecosystem degradation: Clearing of mangroves, seagrass beds, and wetlands for aquaculture facilities can lead to loss of habitat and ecosystem services. Water consumption: Losses can occur from seepage and evaporation of ponds and from the frequent water exchanges needed to aerate and filter more intensive pond operations. Water pollution and chemical use: Discharges can contain excess nutrients from fish feed and waste, antibiotic drugs, other chemicals (e.g., pesticides, hormones) and inorganic fertilizers, which in turn can cause degradation of aquatic habitats. Energy use: Pumps to oxygenate and filter water consume energy. Interactions with wild fish populations: Farmed fish can interact with wild fish and spread fish disease (e.g., parasite and disease transfer to wild fish populations) and contribute to genetic contamination (use of non-native species and/or genetically modified organisms that can escape and interact with wild fish populations). Food safety concerns: Excessive antibiotic use can spread antibiotic resistance in human pathogens (e.g., Salmonella). Conflicts over resource use: Fish ponds can conflict with and/or displace coastal fishing and farming communities, reduce access to community resources, and/or conflict with the tourism industry.
396. Aquaculture land use efficiency, however, differs widely by production system. While fish ponds use relatively high amounts of land (Costa-Pierce et al. 2012), flow-through systems (raceways) use less land, while cages and pens suspended in water bodies use very little (if any) land.
397. FAO, Network of Aquaculture Centres in Asia-Pacific (NACA), UNEP, World Bank and WWF (2006).
398. Lewis et al. (2002).
399. Authors' calculations, calculated two ways: 1) applying global-level inland and brackish land use efficiencies from Hall et al. (2011b) (raw unpublished data) to 2010 production data from FAO (2012b); 2) calculating country-level data on aquaculture land use and land use efficiencies as reported in FAO (2012c) (for periods between 2000–08), and applying these efficiencies to 2010 production data from FAO (2012b) for countries that accounted for 93–95 percent of all aquaculture production in 2010. The inland figure also is similar to the estimate of 13 Mha in Beveridge and Brummett (2013).
400. Authors' calculations from Hall et al. (2011b) (unpublished raw data).
401. Authors' calculations, CIA (2012).
402. Efficiency rates of producing animal-based foods (an indicator of indirect land use efficiency) are summarized in Figure 12.
403. FAO (2006b).
404. Croplands that have become too saline for rice cultivation are an example of such lands with low economic and environmental value.
405. Although the terms "carnivore," "omnivore," and "herbivore" are commonly used when describing the feeding habits of a fish species, it is more scientifically and etymologically correct to use the trophic level, which is an indication of how high a species sits in the aquatic food chain. For example, the "carnivorous" Atlantic salmon has a trophic level of 4.43, while the "herbivorous" common carp has a trophic level of 2.96 (Tacon et al. 2010). Farmed fish species have varying digestive and metabolic capacities to deal with different feed resources; for example, a high-trophic level "carnivore" requires a relatively high level of protein in its feed (Tacon et al. 2010). However, distinctions between "carnivores" and other groups

can be misleading in aquaculture, because fish diets can be altered. For example, although the average salmon diet in 2008 contained 25 percent fishmeal and 14 percent fish oil (Tacon et al. 2011), it is technically possible to feed an Atlantic salmon using no fish-based ingredients at all. Still, in this section, we follow common usage to use the term "carnivores" to refer to salmon and shrimp and "omnivores / herbivores" to refer to other fed-fish species.

406. Authors' calculations from FAO (2012b). In 2010, roughly 19 percent of aquaculture production was of predominantly carnivorous species (shrimps and prawns, salmonids, eels, and other marine fish), 43 percent was of fed herbivorous and omnivorous species (fed carps, tilapia, catfish, milkfish and other aquatic animals), and 37 percent was of unfed species (bivalve mollusks, filter-feeding carps, and other unfed freshwater fish).
407. Olsen and Hasan (2012). As aquaculture's demand for fish-based ingredients has grown, the livestock sector has been forced to use plant-based protein and lipid substitutes such as soy (Gerber et al. 2007).
408. Tacon and Metian (2008). The industry has reduced reliance on fish-based ingredients by reducing the inclusion level of fishmeal and fish oil in farmed fish diets, as well as by improving feed conversion ratios.
409. "Industrial" fisheries include small, oily species such as anchovy and sardine.
410. FAO (2012d), p. 14.
411. Tacon and Metian (2008); Seafish (2011). Although aquaculture's consumption of fishmeal and fish oil has approached the global supply of these ingredients from wild-caught whole fish in the past decade, advances in processing fish wastes into meal and oil have kept the total global supply of these ingredients above the total demand from aquaculture.
412. Newton and Little (2013).
413. Olsen and Hasan (2012).
414. Tacon and Metian (2008), Tacon et al. (2011).
415. Hall et al. (2011) (unpublished raw data).
416. However, cage and pen aquaculture can also cause water pollution and other local environmental impacts. The Norwegian salmon industry, which has reduced pollution through zoning and ecosystem-based management and has lowered the amount of fish-based ingredients in salmon feeds, offers an example of the type of progress needed (Asche 2008).
417. Weimin (2010).
418. Hall et al. (2011b). Barriers to wider-scale adoption of recirculating aquaculture systems include high capital and operational costs, high energy demands, and technical complexity.
419. OECD-FAO (2012). In addition to wild fish, byproducts from farmed fish are increasingly being converted into fishmeal and fish oil. However, market prices will determine whether fish byproducts are simply converted to fishmeal and fish oil for aquaculture, or put to higher-value use (e.g., direct human consumption) (Newton and Little 2013).
420. Naylor et al. (2009), SeafoodSource (2013). However, use of by-catch for feeds is seen by some as controversial because of its possible perverse effects on wild fisheries if by-catch regulations are relaxed.
421. Olsen (2011), Hemaiswarya et al. (2011), Verlasso (2013).
422. Hall et al. (2011b), p. 49.
423. Searchinger (2012b), Searchinger (2009).
424. Atanasiu (2010), Bauen (2009).
425. IEA (2008).
426. This calculation is presented in a support paper for this report (Heimlich and Searchinger (forthcoming)). It relies on energy projections from the U.S. Energy Information Agency, FAO data for crop production as of 2011, and energy and water contents from Wirsenius (2000). It calculates the energy in crops measured by their higher heating value as a percentage of that total world energy. That energy use assumes perfect combustion. The energy released by burning biofuels is a percentage of that maximum combustible energy in the crops used to make the biofuels.
427. The net energy gain represents the quantity of fossil fuels saved by replacing gasoline and diesel, taking into account the fossil energy used to produce both conventional gasoline and diesel and ethanol and biodiesel. We used the analysis of these fossil energy savings from the GREET model.
428. This paper has expressed the needed increase in agricultural production in a variety of ways, sometimes focusing on calories for people, which include livestock, and sometimes focusing only on the increase in crops. Our calculation of the increase in crops needed as predicted by FAO and adjusted by us for population is 69 percent. This estimate includes FAO's estimate of a level of crops used for biofuels that is equivalent to roughly 10 percent of world crop production in 2010. The full 10 percent transportation target would therefore require roughly an additional 27 percent of 2010 crops, representing the difference between the 32.2 percent of crop energy needed for biofuels in 2050 versus the 5.6 percent in 2010. However, this paper mainly focuses on the increase from the 2006 base year, when biofuels were less, so the increase in crops would be roughly 30 percent of 2006 crops. (Because we calculated the bioenergy increase in gross energy terms rather than caloric estimates of FAO, this analysis assumes that the increase in crop production in gross energy terms is proportional to the increase in crop production using FAO's calorie estimates of crops.)
429. Calculations by authors using crop data from FAOSTAT, energy and water contents of crops from Wirsenius (2010), and comparing to global energy consumption estimates by the U.S. Energy Information Agency. Primary energy consumption is the energy contained in the fuels used for energy purposes.
430. Note that biomass conversion to energy efficiencies vary with the type of use. Our analysis assumes at least a 25 percent drop in efficiency of converting energy in biomass to useable energy compared to the efficiency of converting fossil fuels to useable fuels and is based on various possible bioenergy uses set forth in Edwards et al. (2011).
431. OECD (2011).
432. Figures between 1 and 2 percent are commonly suggested. These figures use the "local yields" of crops, such as the high yield of maize in the United States, to calculate the area needed to generate a certain quantity of crops for biofuels. They then compare these very high local yields to the total quantity of cropland. These comparisons understate the commitment of land for two reasons. First, they compare the use of the world's best cropland to the total quantity of farmland. If global cropland areas are used in the denominator, then global yields should be used in the numerator to calculate the quantity of cropland devoted to biofuels. Second, using total cropland

overstates the denominator for the reasons discussed in the section on the difference between harvested area and total cropland, "Planting existing cropland more frequently."

433. This calculation assumes 395 bushels of maize per hectare (160 bushels of maize per acre) and 2.8 gallons per bushel, or 1,106 gallons per hectare. It also assumes that 30 percent of the maize reenters the feed supply as an ethanol byproduct, which implies that 0.7 hectares produce that 1,106 gallons, and therefore a full hectare produces 1,580 gallons.
434. Geyer et al. (2012).
435. The larger yields are presented in Wullschleger et al. (2010). The smaller yields used by EPA are described in Plevin (2010).
436. Haberl et al. (2011). This paper also describes estimates of residue potential that can be as much as twice as large, but these other analyses make no effort to distinguish the portion of residues that are already harvested. The Haberl et al. (2011) estimate is of 25 EJ of unused residues, which could generate 12.5 EJ of transportation biofuels according to efficiency estimates by the European Commission's Joint Research Centre.
437. Smil (2009) provides a compelling analysis of the uses and needs for crop residues worldwide.
438. 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 implications for yields.
439. The OECD projects 900 exajoules (EJ) of primary energy use in 2050 (OECD 2011). That would require 180 EJ of bioenergy assuming that the primary energy in bioenergy substitutes for fossil fuels on a one-for-one basis. Adjusting conservatively by just 20 percent for the fact that biomass does not generate useable energy for most purposes as efficiently as fossil fuels, a truer need would be 225 EJ of energy in biomass. That amount of EJ is precisely the amount of EJ in biomass of all kinds for all human purposes harvested in 2000 (Haberl et al. 2012).
440. Mackay (2009). Using the highest estimated potential yields for switchgrass of 24–25 tons of dry matter per year in an extremely optimistic yield predictions by a lab of the U.S. Department of Energy, Geyer et al. (2012) calculated that in the optimal location of the U.S. efficiencies would reach 0.7 percent, although efficiencies across the United States even under high yield projections would vary from 0.1 to 0.7 percent.
441. Mackay (2009), Fthenakis and Kim (2009), and Edwards et al. (2011), Table 9.2.
442. Geyer et al. (2012) (Table 1) analyzed the land use efficiency of using solar cells versus various kinds of biomass to fuel vehicles in the United States. Using highly optimistic yield projections in the best possible region for switchgrass of 24 tons of dry matter per hectare and using that switchgrass to make electricity to power an electric car, solar cells would use 1/34th the land, and land use efficiency could run as high as 1/500th compared to switchgrass in some regions used for ethanol. (This analysis ignores indirect land use change.) Greenhouse gas emissions (even ignoring emissions from land use change) would in all contexts be lower for solar cells on a lifecycle basis.
443. Ballis et al. (2005).
444. In Melillo et al. (2009), the authors modeled a scenario that relied on cellulosic biomass to generate a similar goal to 20 percent of world bioenergy by 2100, and it led to the loss of the vast bulk of the world's natural forests.
445. Authors' calculations from data provided by FAO. The growth in biofuels contributes roughly 12 percent of the increase in demand for crop calories estimated by FAO from 2006 to 2050 and when combined with the crops used for biofuels already in 2006 amounts to 14 percent.
446. As presented in figure 12, the ratio appears to be one-eleventh, but the efficiencies in figure 12 are rounded and the unrounded figures are 0.75 percent (beef) to 10.9 percent for chicken.
447. HLPE (2011).
448. Filipski and Covarrubia (2010).

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