## COURSE 2

# Increase Food Production without Expanding Agricultural Land

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

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CHAPTER 10

# ASSESSING THE CHALLENGE OF LIMITING AGRICULTURAL LAND EXPANSION

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

## The Challenge

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

- **Fertilizers.** Farmers worldwide used very little synthetic fertilizer in 1960. Today, most of the world heavily exploits synthetic fertilizers, and some countries apply far more than needed. Only sub-Saharan Africa as a region uses little fertilizer, and it could make large gains by applying more.[1]

- **Irrigation.** From 1962 to 2006, irrigation area roughly doubled.[2] However, because few additional areas remain that can plausibly be irrigated with available water, FAO projects that irrigated land will expand by only an additional 7 percent between 2006 and 2050.[3]

- **Seeds.** In 1962, most of the world used seeds improved only by farmers. But in the subsequent five decades, much of the world adopted scientifically bred seeds, although use of improved seeds remains low in Africa.[4]

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

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

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

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

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

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

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

## Understanding Other Estimates of Agricultural Land Expansion

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

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

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

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

## Estimates of Yield Growth May Be Overly Optimistic

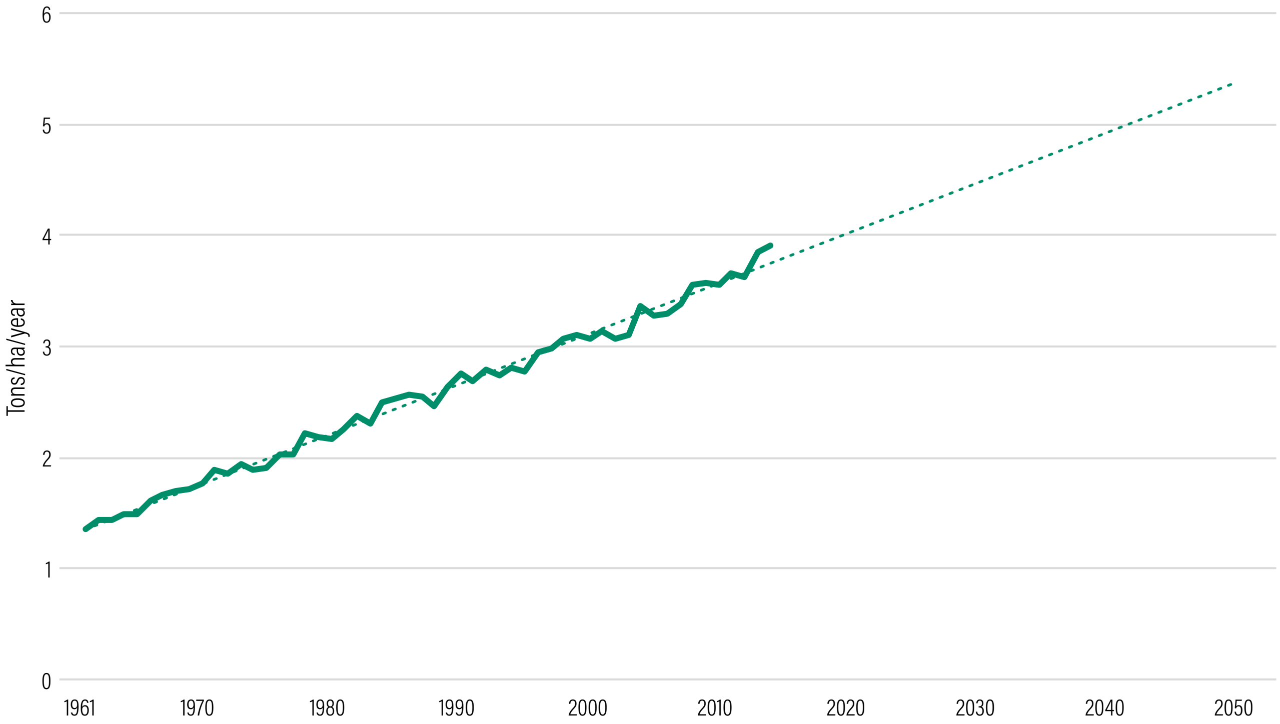
**Population estimates.** Some of the more optimistic projections are now out of date because population projections have been revised upward since the original analysis was completed. For example, the 2012 FAO projection used UN population projections of 9.1 billion for 2050, while the most recent midlevel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

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

### Use of compound (instead of linear) crop growth rates

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

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




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

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

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

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

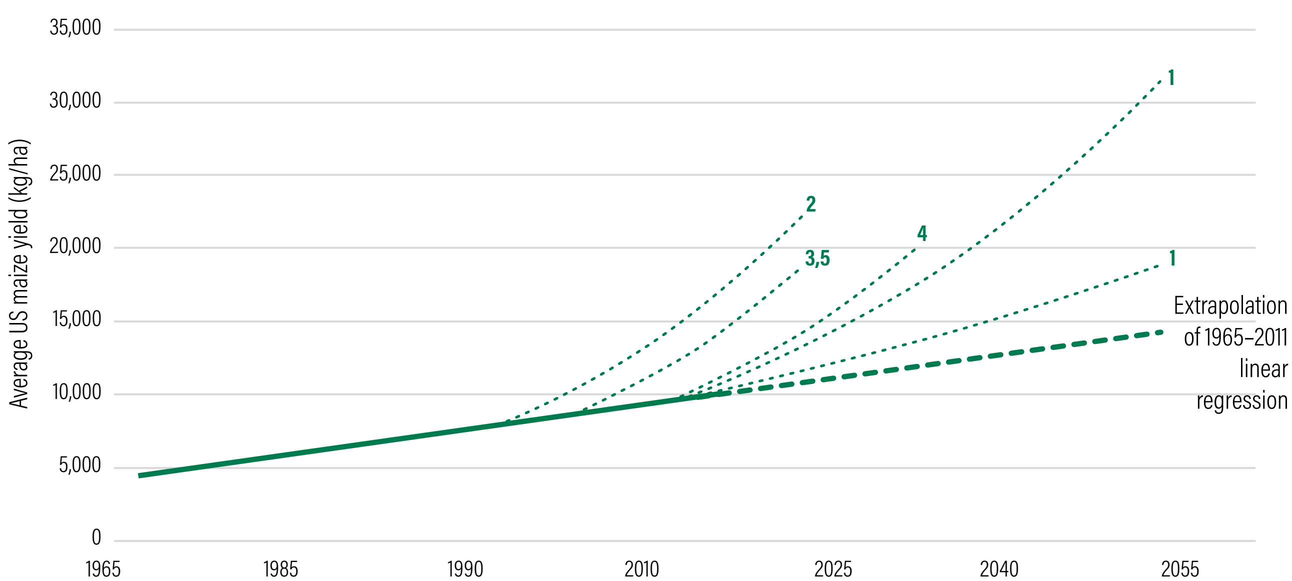
By contrast, other papers improperly project an alarming future by pointing out that percentage growth rates for cereals have been declining: they were 3 percent per year in the 1960s and are now around "only" 1 percent. From this decline, the studies infer a decline in technical improvements and grave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

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

*Notes and sources:*

a. Ausubel et al. (2012). In this paper, the compound growth rate is complicated by the fact that the authors analyzed different contributions to yield growth, but the overall effect was to use a compound rate.
b. For example, Alston et al. (2010) include a chart showing large declines in annual crop yield growth rates from the period 1961–90 versus 1990–2007. See also Foresight (2011a).
c. Authors' calculations from FAO (2019a). This comparison is between the average yield from 1961–63 and the average yield from 2012–14.
d. Alexandratos and Bruinsma (2012).

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




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

### Inconsistency with trend lines

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

### Overly optimistic estimates of economic responses to demand

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

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

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

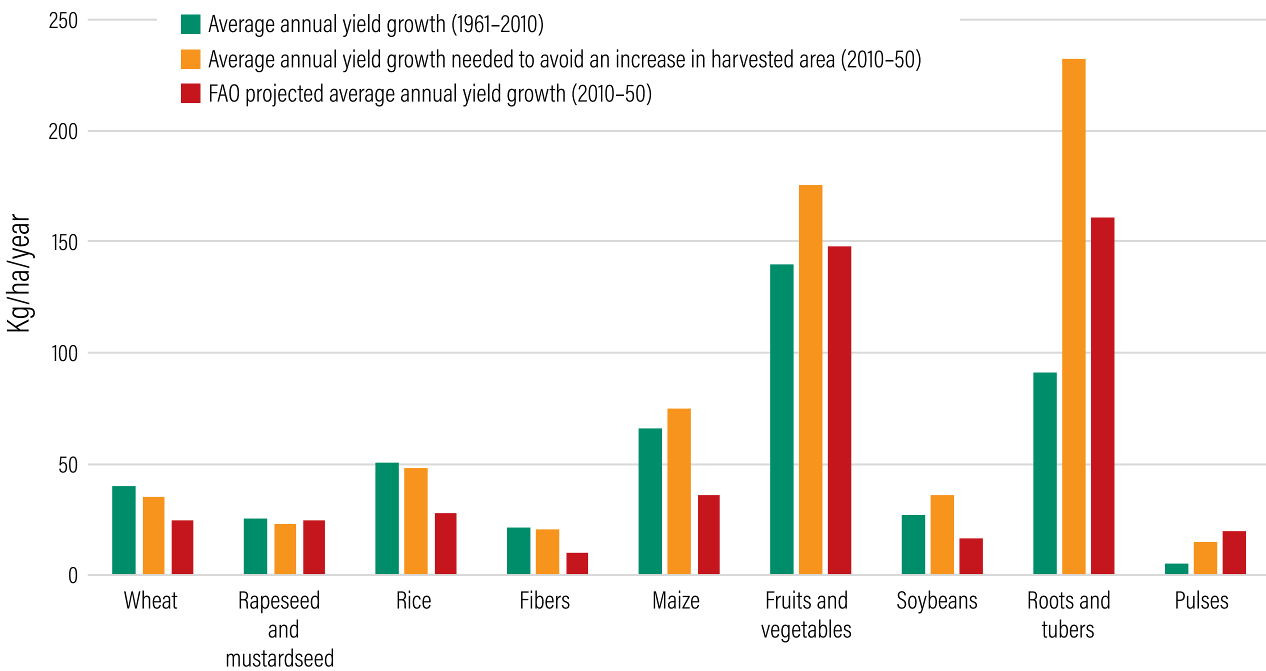
In areas where land is limited, farmers may boost yields because increasing production by means of nonland inputs is, on average, cheaper than accessing new land. This scenario would seem more likely to occur in relatively land-constrained areas, such as Asia and North America. But in other regions where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

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

### Overly narrow focus on grains

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

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




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

## Overly optimistic estimates of government and private action

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

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

### Overly optimistic estimates of pasture efficiency gains

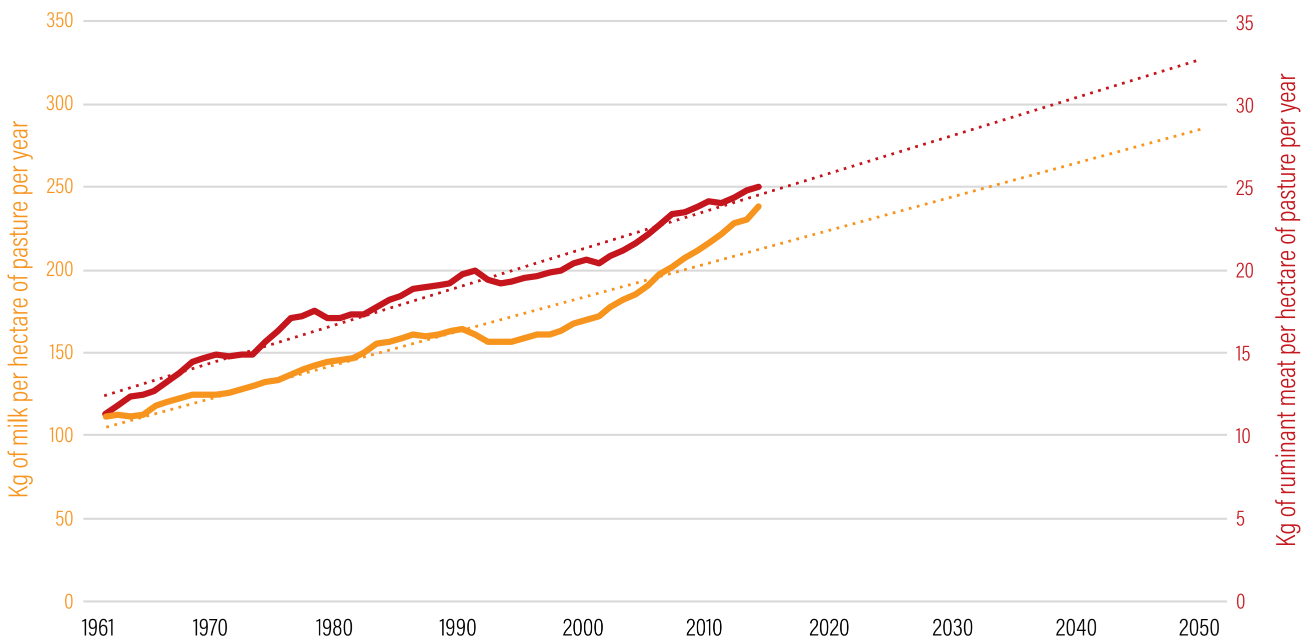
Projecting the future need for pastureland is inherently challenging. Too few solid data exist on which to make projections of increasing yields of ruminant meat and milk per hectare of grazing land. This "pasture yield" depends on the growth in the share of ruminant feed that is derived from crops and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

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

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

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

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




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

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

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

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

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

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

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

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

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

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

Nevertheless, a wide variety of studies, using a wide variety of methods, find substantial yield gaps. Fischer et al. (2014) used this range of evidence, and good scientific judgment, to estimate yield gaps crop by crop and region by region. The study amounts to a case for both optimism and caution when summed to global averages. Among the major crops, the review found that the largest potential for closing yield gaps exists for maize, with a global weighted yield gap of roughly 100 percent (i.e., a potential for doubling), with generally much larger gaps in developing countries. The rice yield gap was similarly found to be large, at roughly 70 percent. The review also found high yield gaps of 100 percent or more in the developing world for other important food crops, including sorghum, millet, and cassava. By contrast, global estimated yield gaps were only roughly 50 percent for wheat, and 30 percent for soybeans. In the case of soybeans, the lower yield gap is explained mainly by the fact that all three countries that dominate global soybean production—the United States, Brazil, and Argentina—have high yields already.

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

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

## Data Limitations Obscure the Extent of Agricultural Land Expansion

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

### Satellite studies of cropland and pasture

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

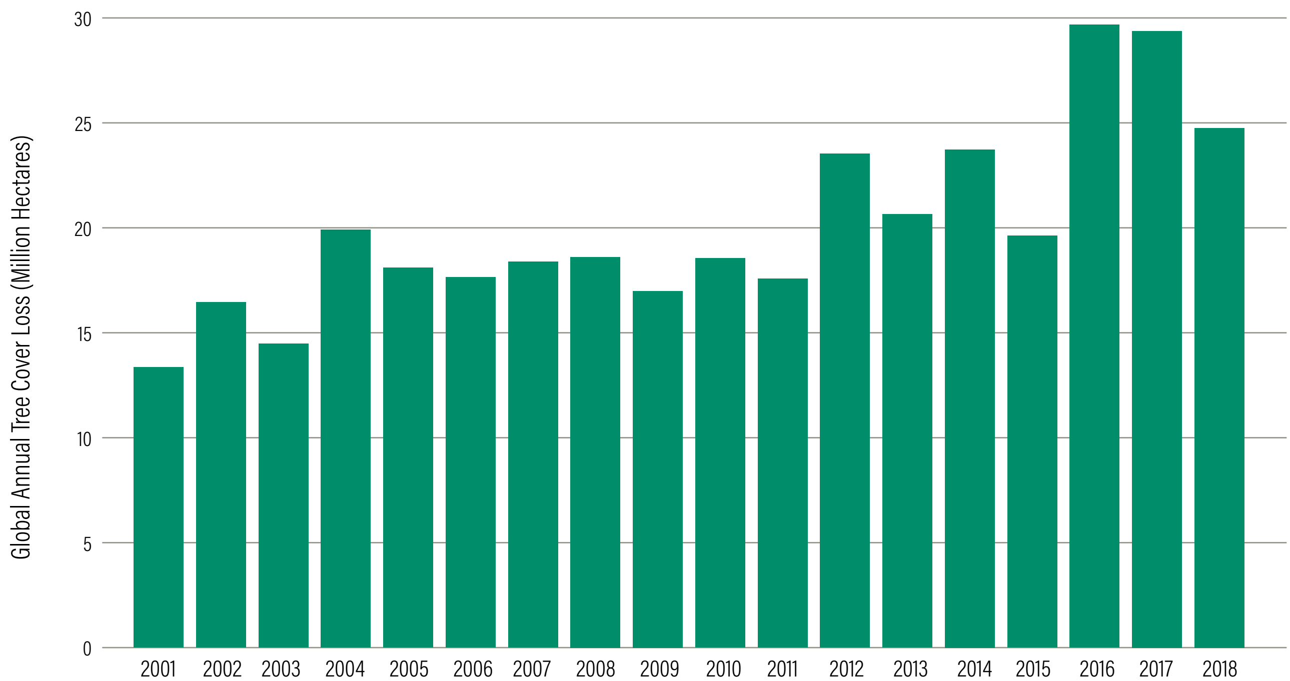
Satellite images cover the whole earth but the images are grainy. Human interpretation of large areas is not practical, although human interpretation is usually more accurate than computer algorithms when analyzing individual satellite images for changes in land use and land cover. As discussed below,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

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

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

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

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




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

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

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

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

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

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

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

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

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

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

### FAO cropland data

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

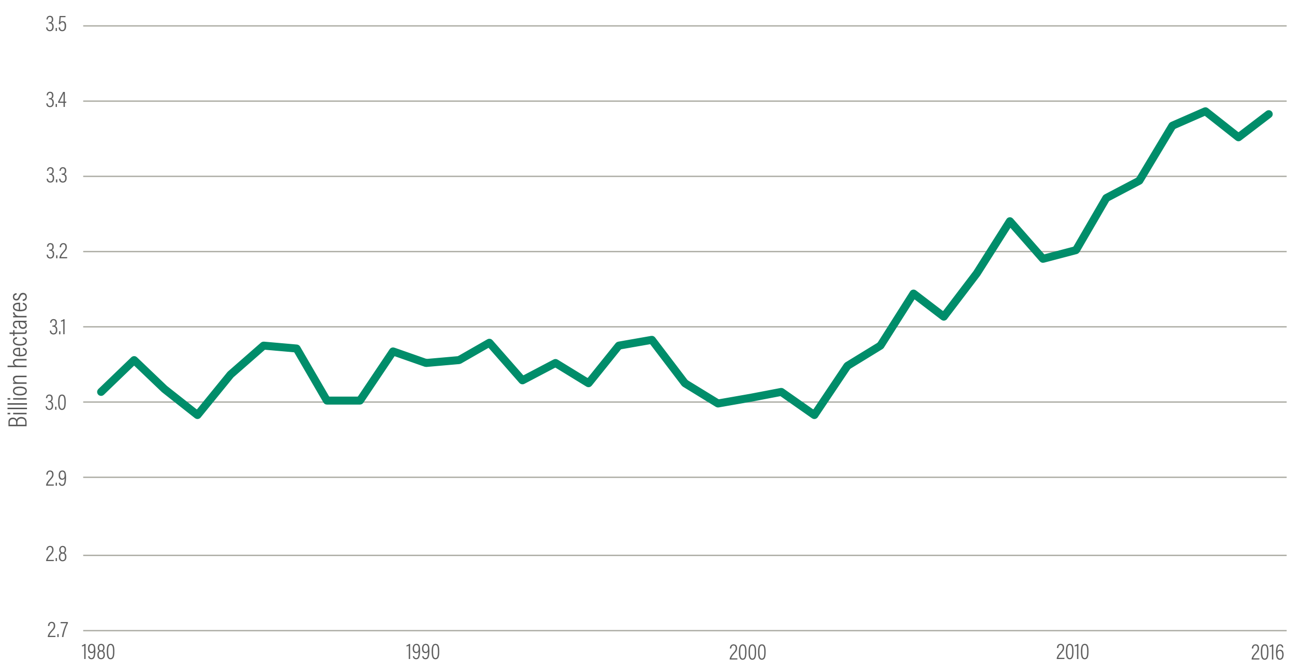
*Harvested area* refers to the number of hectares actually harvested each year, which is different from the area classified as "cropland." If farmers plant and harvest two crops on a hectare in a year, it counts as two harvested hectares, and if they do not plant or harvest crops on a hectare in a year,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

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

In theory, the difference between harvested area and cropland area could reflect a large increase in double-cropping, or a large decrease in the number of hectares left fallow. Both practices increase harvested area without increasing cropland. Some researchers interpret the data in these ways.[53] However, we believe that independent data do not support this explanation, and that the discrepancy probably represents flaws in the data for cropland, or harvested area, or both. For example, the few specific analyses of changes in double-cropping do not support the idea of large increases in the practice. Independent reports suggest that double-cropping in Brazil increased by a total of roughly 6.5 Mha from 2002 to 2014, with nearly all the double-cropping involving maize after soybeans.[54] But elsewhere, the independent data do not show large increases in double-cropping. For example, FAOSTAT data on harvested area versus cropland area would logically imply either an increase in double-cropping or a decline in fallow area of 13 Mha in China from 2000 to 2011.[55] However, a remote-sensing study found a 4 Mha decline in double-cropping and an increase—not a decrease—in fallow lands of 1 Mha during this time period.[56] In the United States, although FAO data might suggest an increase in double-cropping, there was virtually no change in double-cropping from 1991 to 2012, according to U.S. Department of Agriculture (USDA) statistics.[57]

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

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




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

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

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

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

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

### FAO pastureland data

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

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

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

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

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

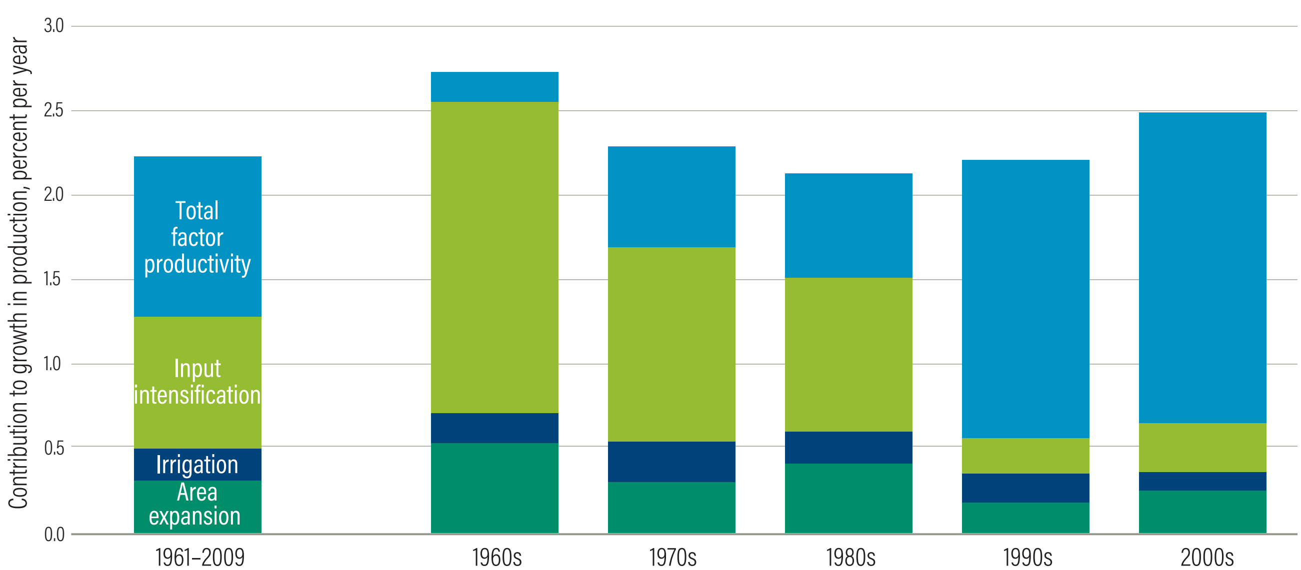
For these reasons, we do not consider FAOSTAT data on pasture reliable and think that net pasture expansion is likely occurring based on the analyses in Latin America. However, on a global and probably also regional basis, there also appears to be a shift from drier, less productive grazing land, such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

## Reasons for Optimism: Smarter Agriculture

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

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

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




*Source:* Fuglie (2012).

CHAPTER 11

# MENU ITEM: INCREASE LIVESTOCK AND PASTURE PRODUCTIVITY

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

## The Challenge

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

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

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

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

### Projected Efficiency Gains

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

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

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

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

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

## The Opportunity

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

### Pork and poultry

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

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

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

### Ruminant meat and dairy

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

- *Production per hectare of land.* Growing improved grasses and shrubs, and fertilizing and grazing them well, will improve both the quantity and quality of forage the land produces and the percentage of the forage ruminants will consume.

- *Production per kilogram of animal feed.* The quality of feed, which is based largely on its digestibility and protein content, determines both how much forage a ruminant will consume and how much growth and milk the ruminant will produce from the forage. Because animals first use food energy to maintain themselves before gaining weight or producing milk, eating feeds with low digestibility provides little additional energy to add weight or produce milk. Once maintenance thresholds are met, improving feed quality results mainly in more growth or milk, which means output grows disproportionately with higher-quality feed.[85]

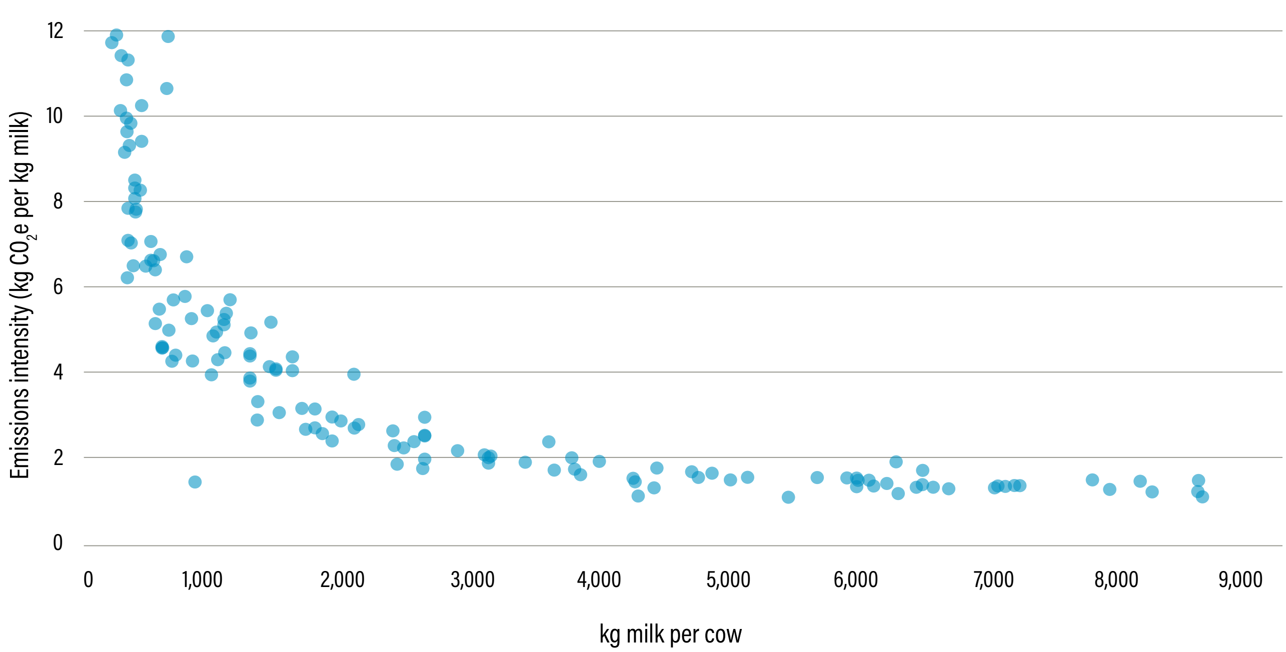
- *Production per animal.* Even when ruminants consume no more energy than they need to maintain themselves, they still produce GHGs. In general, faster-growing or higher-milk-producing animals that receive higher-quality feed direct more of their feed into milk or meat and less into just maintaining themselves. The effect is to reduce the GHG emissions per kilogram of meat or milk produced. Judged on the basis of a whole herd, the gains are even larger. Much of the feed consumed or emissions generated by a herd of cows, sheep, or goats is by mothers engaged in producing their young. And some feed is consumed and some emissions produced by animals that die before being slaughtered or finishing their milk production. As animals increase their reproductive rates and as their mortality declines, they will also increase the amount of meat and milk produced per kilogram of feed or per ton of GHGs. Figure 11-1 illustrates the close relationships between production emissions and output per animal in the case of milk.

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

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

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

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




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

## Technical options

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

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

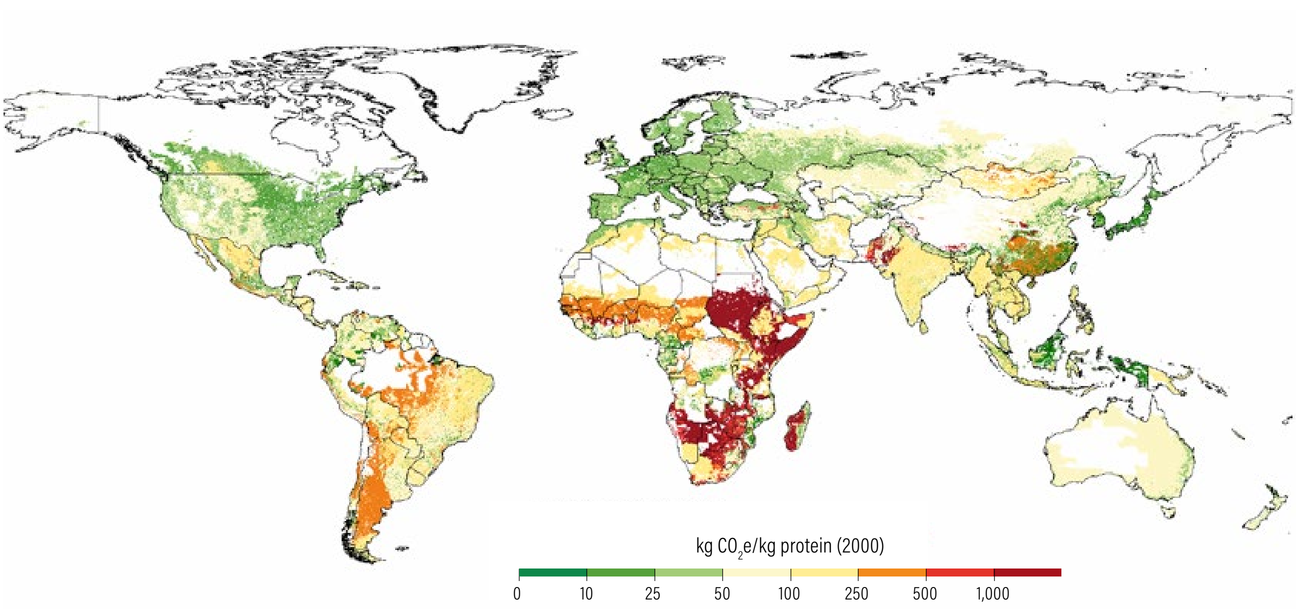
Fortunately, dairy and meat production in the developing world does not need to employ concentrated feedlots to become more efficient. Even today, Indian dairy production emits only half as many GHGs per liter of milk as African dairy production, according to the same 2010 FAO study.[95] The principal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

### Better feeding

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

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

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




*Note:* Maps are for illustrative purposes and do not imply the expression of any opinion on the part of WRI concerning the legal status of any country or territory, or concerning the delimitation of frontiers or boundaries.
*Source:* Herrero et al. (2013).

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

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

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

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

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

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

### Improved health care and overall animal management

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

### Better breeding

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

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

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

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

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

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

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

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

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

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

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

### Overall potential for improvement

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

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

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

| SCENARIO | CHANGE IN AGRICULTURAL AREA, 2010–50 (MHA) | | | ANNUAL GHG EMISSIONS, 2050 ($GT\ CO_2E$) | | | GHG MITIGATION GAP ($GT\ CO_2E$) |
|---|---|---|---|---|---|---|---|
| | Pastureland | Cropland | Total | Agricultural production | Land-use change | Total | |
| No change in livestock efficiencies between 2010 and 2050 | 2,199 (+1,798) | 256 (+64) | 2,455 (+1,861) | 10.6 | 20.6 | 31.2 | 27.2 (+16.1) |
| **2050 BASELINE and Coordinated Effort** (pasture output grows by 53–71%[a] between 2010–50) | **401** | **192** | **593** | **9.0** | **6.0** | **15.1** | **11.1** |
| Less optimistic: 25% slower rate of ruminant feed efficiency gains | 523 (+121) | 203 (+11) | 726 (+132) | 9.2 | 7.1 | 16.3 | 12.3 (+1.3) |
| More optimistic: 25% faster rate of ruminant feed efficiency gains *(Highly Ambitious and Breakthrough Technologies)* | 291 (-110) | 182 (-10) | 473 (-121) | 8.8 | 5.1 | 13.9 | 9.9 (-1.1) |

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

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

What would it take for Latin America to produce these increased volumes of beef and dairy without expanding agricultural land? Of Latin America's roughly 400 Mha of grazing land devoted to beef production (by our calculation), roughly 100 Mha are arid. The arid lands have substantially less potential for intensification without heavy reliance on crop-based feeds. To achieve our estimated 2050 production in Latin America without clearing additional pasture and while intensifying only the 300 Mha of wetter pasture lands, production on those wetter areas would have to more than triple, to around 162 kg/ha. But of these 300 Mha of wetter pasture, some grow native grasses, whose conversion to improved grasses would have adverse consequences for biodiversity—consequences that do not fit our criteria for a sustainable food future.[123] Other hectares are steeply sloped or in remote areas to which supplying inputs is difficult. Assuming intensification occurred on two-thirds of the wetter pastures (200 Mha), production per hectare would have to grow to around 215 kg/ha.[124] According to Cardoso et al. (2016), such increases are possible in the Cerrado, but only under the most efficient present forms of management on some farms. This most efficient management would include fertilizing, plowing, and replanting grasses every five years, and either some substantial reliance on crops for feed in the last 90 days before slaughter or the successful introduction of legumes into pastures (which is usually challenging because animals selectively graze them).

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

## Recommended Strategies

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

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

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

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

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

**Protect natural landscapes.** Even though pasture intensification will be economical in many locations, without efforts to protect natural landscapes, expansion of pasture will still occur wherever it is cheaper than intensification. Analysis by Embrapa, the Brazilian agricultural research agency, has shown that expanding pasture into forest can be cheaper than rehabilitating pasture.[127] One study in the early 2000s showed that a modest form of intensification, fertilizing degraded pasture, was cost-effective in the western Amazon but that a more intensive form, using some supplemental feeds, was not.[128] Another more recent study in the state of Mato Grosso estimated that intensive cattle raising in itself is not profitable unless it is particularly well-managed.[129] A modeling analysis of Brazilian pasture intensification published in 2015 found that intensification was strongly tied to higher land prices and lower transportation costs, themselves related to market centers, and that on average, the intensification options were more expensive than expansion options by $80 per ha.[130] Not surprisingly, Brazil has tended to intensify cattle production in some locations while expanding cattle pastures in others. Between 2000 and 2006, for example, even as cattle density in the Brazilian Amazon greatly increased, the pasture area there still increased by roughly 25 percent.[131]

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

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

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

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

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


CEC XXX- 3
Yuca invitro

CHAPTER 12

# MENU ITEM: IMPROVE CROP BREEDING TO BOOST YIELDS

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

## The Challenge

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

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

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

## The Opportunity

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

### Speeding up "incremental" breeding cycles in developing countries

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

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

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

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

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

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

### The potential of marker-assisted and genomics-assisted breeding

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

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

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

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

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

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

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

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

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

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

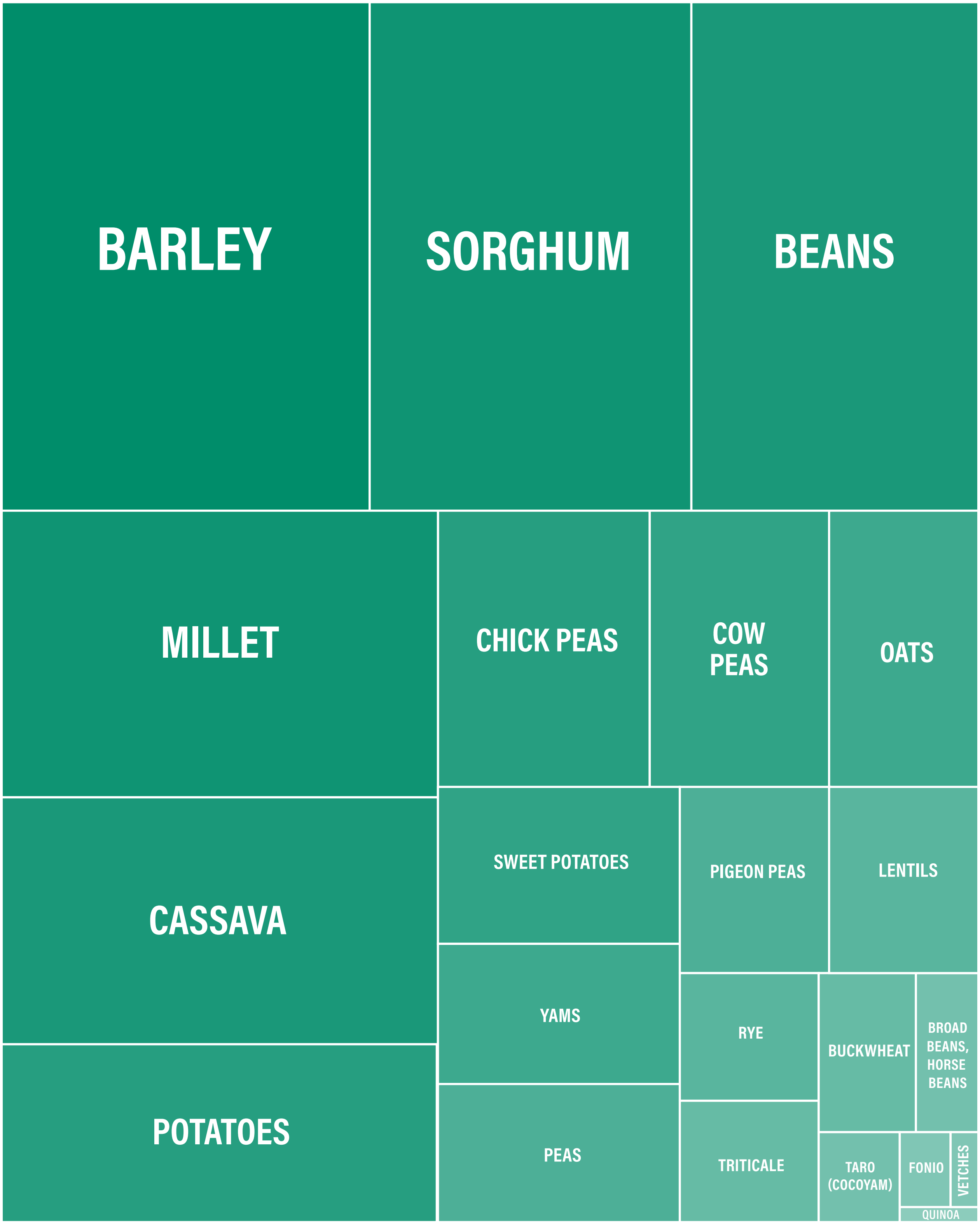
The information gathered will be cumulative. As scientists identify the molecular functions of different strands of DNA and their relationship to traits, they gain increasing ability to predict what combinations of DNA are optimal for specific crop types and environments. In addition, breeding institutions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

### Improvement of orphan crops

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

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

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




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

## Genetic Modification

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

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

### Genetically modified crops: the debate so far

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

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

#### Food safety and human health

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

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

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

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

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

### Environmental toxicity and pest resistance

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

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

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

Growing herbicide resistance is a significant concern for glyphosate-resistant crops. Twenty-four weeds in the United States have become resistant, including several that are major problems, particularly for soybean production.[176] Large seed companies have responded by introducing varieties of soybeans that are also resistant to older herbicides, such as 2,4-Dichlorophenoxyacetic acid (2,4–D) and dicamba. Relative to insecticides, these chemicals (like other herbicides) have lower human toxicity concerns. But these older herbicides pose significant environmental concerns as they are far more toxic to broad-leaved plants and more likely to "drift" on winds from farm fields to adjacent lands and damage nontarget plants.[177]

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

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

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

### Crop yield effects

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

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

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

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

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

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

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

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

### Effects on costs, labor productivity, and equity

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

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

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

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

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

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

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

### Some conclusions regarding the debate over major GM crops

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

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

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

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

### Use of genetic modification to resist diseases

One important reason not to allow the debate over Bt and glyphosate-resistant crops to dictate GM policy is the potential uses of GM technology to breed pest-resistant traits into crops under serious pest attack. In Hawaii, for example, papayas would probably have been wiped out without the benefits of GM technology. Hawaiian papayas faced a virulent virus but were protected by insertion of genes from the virus itself into the papaya, generating a kind of plant immune response.[206] Because of public resistance to GMOs, this variety has not spread much to the developing world.[207] Likewise, current work demonstrates the potential for controlling potato late blight worldwide with GM technology.[208] Transgenic potato varieties under trial in Uganda are unaffected by this pathogen.[209] GM soybeans with resistance to Asian soy rust are under development by a major seed company: this disease causes annual losses of around $2 billion in Brazil, and the chemical sprays used for disease control are losing their efficacy.[210] GM tomatoes have demonstrated resistance to bacterial spot in successive years of field trials in Florida, where the disease has been the number one endemic disease problem affecting tomatoes for over 40 years.[211]

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

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

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

### Emerging new techniques of genetic identification and modification

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

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

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

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

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

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

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

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

## Recommended Strategies

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

### Boost breeding budgets

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

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

## Share genomic advances

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

## Leverage new technologies

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

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

## Increase research on orphan crops

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

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

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

CHAPTER 13

# MENU ITEM: IMPROVE SOIL AND WATER MANAGEMENT

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

## The Challenge

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

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

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

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

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

## The Opportunity

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

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

### Agroforestry

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

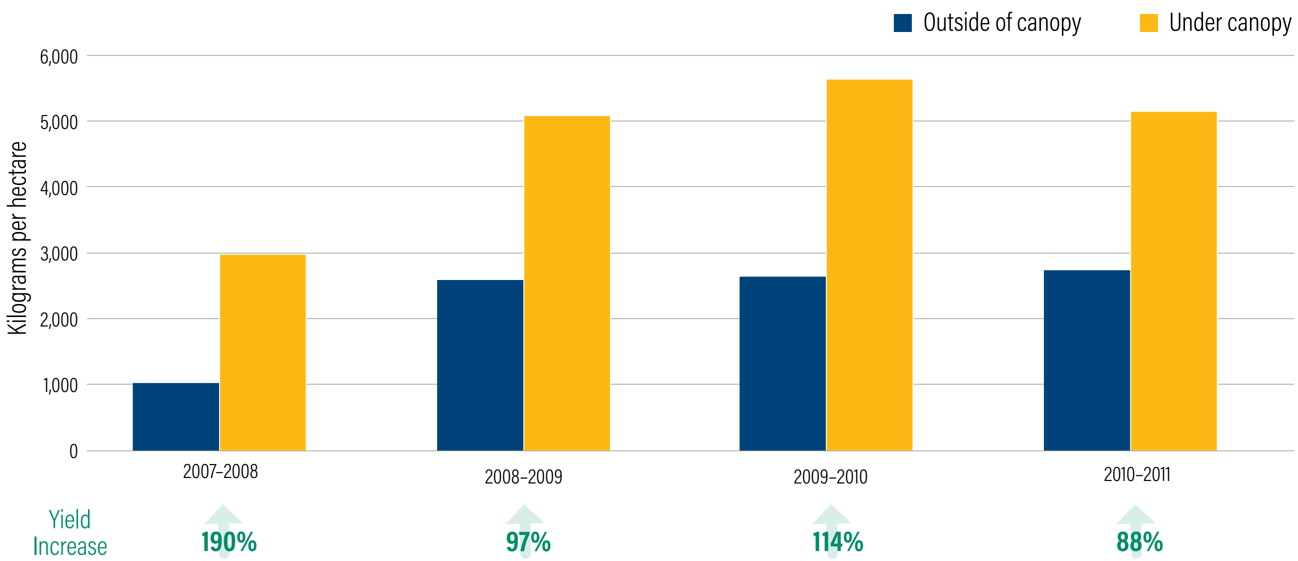
A major success has occurred with the rejuvenation of agroforestry parklands in the Sahel. Since the mid-1980s, farmers have assisted in the regeneration of trees across more than 5 million ha, particularly in Niger but also in Burkina Faso, Mali, Senegal, and Ethiopia.[246]

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

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

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

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




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

## Rainwater Harvesting

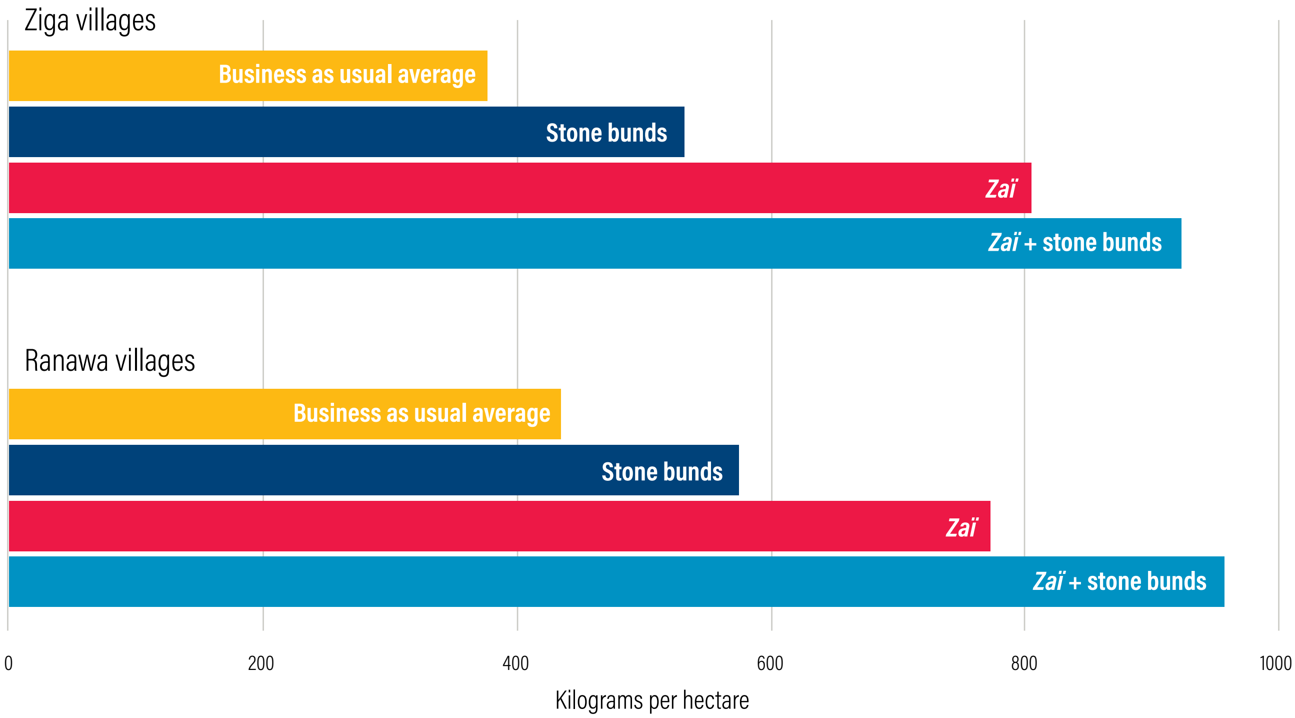
Without attention to soil and water conservation, the loss of rainwater due to runoff from denuded fields can be significant. In Mali, for instance, 70–80 percent of rainwater falling early in the rainy season is lost to runoff, and rainfall runoff takes away about 40 percent of the nutrients applied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

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

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

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

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




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

## Fertilizer Microdosing

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

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

## Conservation Agriculture

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

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

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

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

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

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

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

- **Labor.** Without mechanization and access to herbicides, large reductions in tillage require a great deal more work. Tillage has traditionally been the main way of dealing with weeds, and lack of tillage necessitates either more use of herbicides or laborious hand-weeding. Caring for trees offsite and then mulching them and adding them to soils is also time-consuming. In the absence of mechanization, smallholder farming already requires massive labor efforts, and farmers tend not to have the time or desire to add to these efforts.

- **Caloric needs and agronomic challenges with legumes.** Legumes such as beans provide protein and flavor to diets, but they produce fewer calories than maize, cassava, or yams per ha. Farmers who are already short on calories have less potential to add beans. In much of Africa, beans also face disease problems or various challenges with soil fertility.[273]

- **Competition for residues.** Crop residues are major sources of animal feed, and even farmers who do not have livestock often allow other farmers with livestock to graze their fields.[274]

- **Uncertain yield effects.** At a minimum, uncertain yield effects make investments of both funds and labor risky.

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

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

### New approaches?

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

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

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

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

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

## Recommended Strategies

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

### Strengthen understanding

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

### Increase communication and outreach

Practical methods exist to spread knowledge of conservation management.

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

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

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

## Support institutional and policy reforms

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

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

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

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

## Pursue new models for increasing soil carbon in depleted croplands

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

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

CHAPTER 14

# MENU ITEM: PLANT EXISTING CROPLAND MORE FREQUENTLY

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

## The Challenge

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

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

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

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

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

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

## The Opportunity

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

Recent FAO data appear to suggest a much more rapid increase in cropping intensity than is suggested by its 2050 projection, which we rely on for this report. The data suggest that between 2000 and 2011 alone, increases in cropping intensity provided the equivalent of 101 Mha of cropland farmed each year, and in that way avoided the conversion of 101 Mha of land from forest or other carbon-rich ecosystems.[292] On this basis, some researchers record a rapid escalation in cropping intensity.[293] Unfortunately, for reasons we discuss in Chapter 10 on the land-use challenge, data on cropland extent submitted to FAOSTAT can be highly unreliable, which means the changes in cropping intensity are also unreliable (Chapter 10).

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

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

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

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

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

## Recommended Strategies

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

CHAPTER 15

# ADAPT TO CLIMATE CHANGE

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

## The Challenge

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

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

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


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

## Temperature

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

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

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

## Rainfall

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

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

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

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

## Sea level rise

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

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

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

## The problem of uncertainty

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

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

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

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

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

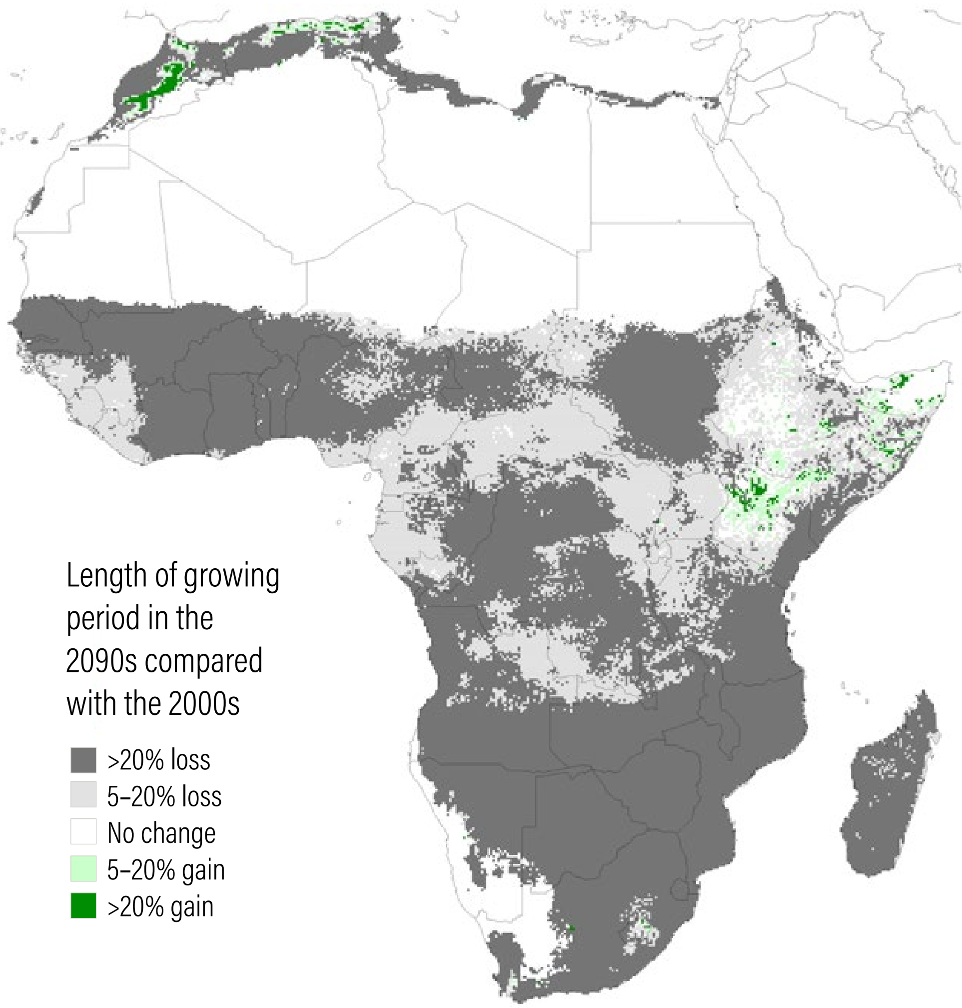
The midrange IPCC projection of yield effects also relies primarily on crop models, whereas analysis using statistical models sometimes projects larger effects. Crop models attempt to simulate dynamic processes of crop growth and their response to variations in soil quality, radiation, rainfall, and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

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

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

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

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




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

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

## The Opportunity

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

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

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

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

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

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

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

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

### Cope with rainfall variability through improved water management

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

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

## BOX 15-1 | Quantitative estimates of adaptation potential

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

## Recommended Strategies

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

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

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

CHAPTER 16

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

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

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

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

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

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

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

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

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

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

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

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

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

# ENDNOTES

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

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

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

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

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

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

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

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

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

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

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

49. Estes et al. (2018).

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

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

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

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

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

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

56. Qiu et al. (2017).

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

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

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

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

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

62. Fetzel et al. (2017).

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

64. Ramankutty et al. (2008).

65. Erb et al. (2007).

66. Stadler et al. (2018).

67. FAO (2019a).

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

69. Graesser et al. (2015).

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

71. Fuglie and Nin-Pratt (2012).

72. Fuglie and Nin-Pratt (2012).

73. FAO (2015b), 30.

74. GlobAgri-WRR model.

75. GlobAgri-WRR model.

76. GlobAgri-WRR model.

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

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

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

80. Lamb et al. (2016).

81. Erb et al. (2009).

82. Shields and Orme-Evans (2015).

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

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

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

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

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

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

89. Punjabi (n.d.).

90. Alexandratos and Bruinsma (2012), 132.

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

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

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

94. Gerber et al. (2010).

95. Gerber et al. (2010).

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

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

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

99. Vellinga and Hoving (2011).

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

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

102. Thornton and Herrero (2010).

103. Walli (2011).

104. Cardoso et al. (2016).

105. Gerber et al. (2013).

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

107. Murgueitio et. al. (2011).

108. Calle et al. (2013).

109. Calle et al. (2013).

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

111. Cardoso et al. (2016).

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

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

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

115. Ooko (2014).

116. Bryan et al. (2011).

117. Orodho (2006).

118. Place et al. (2009).

119. Hassanali et al. (2008).

120. Herrero et al. (2011).

121. Thornton and Herrero (2010).

122. GlobAgri-WRR model.

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

124. Authors' calculations.

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

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

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

128. Rueda et al. (2003).

129. Strassburg (2012).

130. Cohn et al. (2014).

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

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

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

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

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

136. Atlin et al. (2017).

137. Atlin et al. (2017).

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

139. Prigge et al. (2012).

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

141. Hall and Richards (2012).

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

143. Shimelis (2012).

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

145. National Human Genome Research Institute (2015).

146. Chen and Rajewsky (2007).

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

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

149. Varshney et al. (2012).

150. Varshney et al. (2012).

151. Varshney et al. (2012).

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

153. Nelson et al. (2014).

154. CFS (2014).

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

156. NRC (2004).

157. Snell et al. (2012).

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

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

160. Séralini et al. (2011).

161. Séralini et al. (2014).

162. NAS (2016).

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

164. Zhang et al. (2019).

165. de Souza et al. (2017).

166. NRC (2010).

167. Krishna and Qaim (2012).

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

169. NAS (2016).

170. NAS (2016).

171. Porterfield (2017).

172. Visser (2018).

173. Tabashnik and Carrière (2017).

174. NRC (2010).

175. Tabashnik and Carrière (2017).

176. NAS (2016).

177. Schütte et al. (2017).

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

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

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

181. Myers et al. (2016).

182. Hoopman et al. (2018).

183. NRC (2010).

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

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

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

187. NRC (2010); NAS (2016), 127–33.

188. NRC (2010).

189. Fernandez-Cornejo and Wechsler (2012).

190. NAS (2016).

191. NAS (2016), 15.

192. NAS (2016), 111–14.

193. Stone (2012).

194. Gruere and Sun (2012).

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

196. NAS (2016).

197. NAS (2016).

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

199. NAS (2016).

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

201. Tefera et al. (2016).

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

203. NAS (2016).

204. Ronald (2011) gives an example.

205. NRC (2004).

206. Gonsalves et al. (2007).

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

208. McGrath (2014).

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

210. 2blades.org.

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

212. Strange and Scott (2005).

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

214. Jones and Dangl (2006).

215. Jones and Dangl (2006).

216. Jones (2017).

217. NAS (2016).

218. Gepts (2006).

219. Barrangou and Doudna (2016).

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

221. Nelson et al. (2014).

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

223. Beintema et al. (2012).

224. CGIAR (2017).

225. Mukherjee et al. (2018).

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

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

228. See GCP (2014).

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

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

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

232. Place et al. (2013).

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

234. Johnson et al. (2006).

235. Koohafkan and Stewart (2008).

236. Cervigni and Morris (2016).

237. Allison (1973).

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

239. Powlson et al. (2016).

240. Marenya and Barrett (2009a).

241. Rockström et al. (2003).

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

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

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

245. WOCAT (2015).

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

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

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

249. Tropical Forages (2012).

250. Tropical Forages (2012).

251. Yamba and Sambo (2012).

252. Rockström et al. (2003).

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

254. Hassane et al. (2000).

255. Sawadogo (2006).

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

257. Doumbia (2010).

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

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

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

261. Sawadogo (2013).

262. Sanders and Ouendeba (2012).

263. FAO (2012b).

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

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

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

267. Arslan et al. (2013).

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

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

270. Arslan et al. (2015).

271. Giller et al. (2015).

272. Giller et al. (2015).

273. Beebe (n.d.).

274. Duncan et al. (2016).

275. Powlson et al. (2016).

276. Liniger et al. (2011).

277. Mafongoya (2006).

278. Mafongoya (2006).

279. Marenya and Barrett (2009a).

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

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

282. W4RA (2017).

283. Reij and Garrity (2016).

284. Reij and Winterbottom (2015).

285. FAO (2019a).

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

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

288. Kalaiselvi and Sundar (2011).

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

290. Heinimann et al. (2017).

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

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

293. Ray and Foley (2013).

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

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

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

297. Kurganova et al. (2010).

298. Good et al. (2016).

299. Pires et al. (2016).

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

301. Easterling et al. (2007).

302. Porter et al. (2014).

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

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

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

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

307. Zhou et al. (1995).

308. Harrington et al. (2007).

309. Lobell and Field (2007).

310. Jones and Thornton (2013).

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

312. World Bank (2014).

313. Lesk et al. (2016).

314. Dale et al. (2017).

315. World Bank (2014).

316. Porter et al. (2014).

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

318. Leakey et al. (2009).

319. Long et al. (2006).

320. World Bank (2014).

321. Schlenker and Roberts (2009).

322. Liang et al. (2017).

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

324. Lobell et al. (2011).

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

326. IPCC (2014).

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

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

329. Bunn et al. (2015).

330. Jones and Thornton (2015).

331. Porter et al. (2014).

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

333. Nelson et al. (2009).

334. Lloyd et al. (2011).

335. Hewitson and Crane (2006).

336. Vermeulen et al. (2013).

337. Gershunov and Barnett (1998).

338. Estes et al. (2013).

339. Thornton et al. (2011).

340. Sherman et al. (2016).

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

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

343. Xie et al. (2014).

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

345. Watts (2016).

346. Urban et al. (2012).

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

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

349. Dasgupta et al. (2009).

350. Islam et al. (2015).

351. Renaud et al. (2015).

352. Islam et al. (2015).

353. Renaud et al. (2015).

354. Jones and Thornton (2009).

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

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

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

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

## REFERENCES

To find the References list, see page 500, or download here: www.SustainableFoodFuture.org.

## PHOTO CREDITS

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