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Working Paper

Installment 7 of “Creating a Sustainable Food Future”

CROP BREEDING: RENEWING THE GLOBAL COMMITMENT

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SUMMARY

The world needs to close a 69 percent gap between the crops produced in 2006 and the crops the world is on a course to need by 2050. Assuming the present course of diets, population growth, and rates of food loss and waste, crop yields will need to grow one third more in the coming 44 years than they did in the previous 44 years to avoid net expansion of harvested cropland. Achieving this yield growth will be a major challenge. Crop yield growth rates have been high since the 1960s, and farmers in many places are already using more than enough water and fertilizer inputs. At the same time, climate change is adding new stress that could lower yields in many agricultural regions.

Breeding crops to produce more food is a core method of boosting yields. While farmers have been breeding crops since the dawn of agriculture, breeding by scientists became common only during the past century.

Much of the public debate about crop breeding over the past few decades has focused on genetically modified organisms (GMOs). Genetic modification (GM) involves inserting specific genes—often from a different species—into the genomes of a target plant. This approach differs from conventional plant breeding, which involves cross-breeding variants of closely related species through sexual reproduction. Two GM traits have dominated the market to date: resistance to the herbicide glyphosate, and resistance to some pests through the production of a natural insecticide known as “Bt.”

CONTENTS

Suggested Citation: Searchinger, T. et al. 2014. “Crop Breeding: Renewing the Global Commitment.” Working Paper, Installment 7 of *Creating a Sustainable Food Future*. Washington, DC: World Resources Institute. Available online at http://www.worldresourcesreport.org.

The benefits and challenges of genetically modified crops have attracted enormous public attention, primarily around four issues: food safety, toxicity and pest resistance, crop yield effects, and shifts in profits and control to major corporations. Although the merits of existing GM crops can be debated, GM technology may offer other useful potential benefits, particularly traits that help crops resist diseases that cannot be addressed by any other means.

Despite the public attention to GM crops, conventional breeding has been and will probably continue to be the dominant means of increasing crop yields for the foreseeable future. Although some ambitious GM research programs are trying to alter complicated gene combinations, GM technology currently aims at traits controlled by a single gene or a small number of genes. Yet most traits that lead to higher yields result from a large number of genes and their interactions with environmental factors. It is through conventional methods that breeders can affect such a large number of genes.

Recent advances in molecular biology are assisting conventional breeding and have the potential to accelerate yield gains. One advance is marker-assisted breeding, which involves mapping *portions* of plant DNA associated with agronomically useful traits. Mapping makes it possible to screen a large population of seedlings quickly to determine which have the desired gene combinations without having to sow large numbers of seeds or wait for individual plants to grow. This method allows breeders to skip cycles of crossing individuals, thereby realizing yield improvements more quickly. Another advance is genomics-assisted breeding, which applies DNA sequencing and mapping to the *complete* set of DNA within a single cell of a plant. Genomics holds the promise of unveiling the complex combinations of genes that confer desirable crop traits, thereby enabling breeders to screen for plants that have them and saving research time. Both marker assistance and genomics work within conventional breeding programs.

As marker assistance and genomics continue to speed up conventional breeding, agricultural researchers should increase attention to crops that have received relatively little research—“orphan crops.” Orphan crops include sorghum, millet, potatoes, peas, and beans, all of which are important food sources for many people in food-insecure regions. The marginal yield improvement potential of such crops is probably high given the limited research efforts to date. Marker assistance 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, they make it possible for breeders to understand the gene combinations that have already led to yield gains in more intensely studied crops such as maize, rice, and wheat. Breeders can then select for these advantageous gene combinations in the orphan crops to achieve yield gains.

The combination of the great need for crop yield growth over coming decades and the availability of new technologies makes a strong case for improving crop breeding. We offer five recommendations to achieve this improvement:

1. **INCREASE AND STABILIZE CROP BREEDING BUDGETS.** Public funding for agricultural research has grown in recent years, but it is still only $30 billion per year. Increases in private sector research in developed countries help, but marketplace realities limit private sector interest in advancements for many low-profit crops (such as orphan crops) or for noncommercial farming. Realizing the potential of marker-assisted and genomics-assisted conventional breeding, as well as of orphan crops, will require substantially more—and consistent—investment in research and development. We did not uncover a good global analysis of by how much the agricultural R&D should increase, but we recommend an initial goal of increasing funding in low- and medium-income countries from the current 0.5 percent to 1.0 percent of their agricultural production value. This would involve an increase of roughly $15 billion per year. The burden of this growth would have to be shared with high-income countries.
2. **LEVERAGE NEW TECHNOLOGIES.** Although there is room to debate the merits of the dominant GM crops, genetic engineering may play a useful role right now in helping threatened crops resist disease. Even so, conventional breeding will remain more important because it is better able to handle the complex, multigene traits on which yield growth depends. Now that methods to map portions of plant DNA and complete genomes have become fast and relatively cheap, they offer hope for accelerating conventional breeding improvements and should be embraced by researchers, governments, companies, and civil society.
3. **INCREASE RESEARCH ATTENTION TO ORPHAN CROPS.** Researchers at universities, government agriculture ministries, agricultural companies, and independent research institutions should build on recent efforts to

broaden their scope beyond the most intensely researched crops and give attention to increasing the yields of orphan crops. Doing so will require additional, dedicated funding by research institutions and donors.

4. **INCREASE ATTENTION TO ENVIRONMENTALLY ADVANTAGEOUS TRAITS.** Breeders should complement efforts to boost yields with efforts to breed food crops that use nitrogen more efficiently and use less water, and for cover crops that more effectively prevent erosion and sequester carbon. Donors with missions to tackle climate change or improve water security should support research focused on these critical environmental traits.
5. **SHARE GENOMIC ADVANCES.** Universities, government agricultural research centers, and the private sector could accelerate yield enhancements by more aggressively sharing genomic data and new methods with other researchers in the "public commons."

CROP BREEDING ON THE MENU

In the World Resources Report's *Creating a Sustainable Food Future: Interim Findings* (Box 1), we describe how the world food system faces a "great balancing act" to meet three great needs. It needs to close a gap of 69 percent between the crops available in 2006 and those likely to be required in 2050 to adequately feed the planet. It needs agriculture to contribute to economic and social development, particularly because of the large numbers of rural poor who depend on agriculture for their livelihoods. And it needs agriculture to reduce its impacts on climate, water, and ecosystems.

Through *Creating a Sustainable Food Future: Interim Findings* and a series of working papers, we explore a menu of solutions that could combine to meet these three needs. Within the broad category of boosting food production on existing agricultural land, one menu item is to boost yields through "crop breeding," which refers to the art and science of deliberately changing crop traits to generate desired characteristics. Depending on how it is achieved, boosting yields through crop breeding has the potential to satisfy the development and environment criteria described in the *Interim Findings* (Table 1).

This working paper explores the potential for boosting global yields through crop breeding. It begins by summarizing the scale of the yield-growth challenge over the coming four decades and the role of breeding in meeting that challenge. It continues by discussing genetically modified organisms (GMOs), given that disagreement over GMOs has featured prominently in the public debate about pursuing yield improvements through crop breeding. Although evidence suggests GMOs contribute to yield improvements, this working paper finds that the greatest opportunities for boosting crop yields lie with conventional breeding aided by advanced methods such as marker-assisted selection and genomics, as well as with the untapped potential of "orphan crops." The paper concludes by offering five recommendations that could accelerate the world's ability to boost yields through conventional crop breeding.

Box 1 | The World Resources Report: *Creating a Sustainable Food Future*

How can the world adequately feed more than 9 billion people by 2050 in a manner that advances economic development and reduces pressure on the environment?

The world must balance three great needs. First, the world needs to close the gap between the food available today and that needed by 2050. Second, the world needs agriculture to contribute to inclusive economic and social development. Third, the world needs to reduce agriculture's impact on the environment.

The World Resources Report, *Creating a Sustainable Food Future*, proposes a menu of solutions that can achieve the great balancing act. Some menu items address the demand for food, such as reducing food loss and waste and shifting diets. Other menu items address the supply of food, such as boosting yields via improved land and water management, and improving pasture productivity. This working paper focuses on boosting yields through crop breeding.

Since the 1980s, the World Resources Report has provided decisionmakers from government, business, and civil society with analyses and insights on major issues at the nexus of development and the environment. For more information about the World Resources Report and to access previous installments and editions, visit www.worldresourcesreport.org.

THE NEED FOR IMPROVED CROP BREEDING

Attaining global food security will require strong growth in crop yields. Crop-yield growth contributes to food security by boosting productivity and total production to keep food prices low, which is critical as long as hundreds

Table 1 | **How "Boosting Yields through Crop Breeding" Performs Against the Sustainable Food Future Criteria**

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

CRITERIA	DEFINITION	PERFORMANCE	COMMENT
Poverty Alleviation	Reduces poverty and advances rural development, while still being cost effective	●	■ To the degree that improved seed varieties are available and result in yield gains to farmers, crop breeding can increase the net profit to farmers. ■ To the degree that it results in crop varieties that are more resilient to the effects of climate change, crop breeding can enable farmers to adapt to climate change and avoid crop losses.
Gender	Generates benefits for women	●	■ Crop breeding of orphan food crops such as cassava—the production of which is often dominated by women—can help empower women economically.[a]
Eco-systems	Avoids agricultural expansion into remaining natural terrestrial ecosystems and relieves pressure on overstrained fisheries	●	■ To the degree it increases yields per hectare, crop breeding can contribute to preventing further conversion of land into agriculture to meet global food demand.
Climate	Helps reduce greenhouse gas emissions from agriculture to levels consistent with stabilizing the climate	●	■ To the degree it increases yields per hectare and thereby prevents further land conversion into agriculture, crop breeding can help reduce greenhouse gas emissions from agriculture. ■ To the degree it results in crop varieties that reduce the need for fertilizer or use applied fertilizers more efficiently, crop breeding can reduce greenhouse gas emissions from agriculture.
Water	Does not deplete or pollute aquifers or surface waters	●	■ To the degree it results in crop varieties that utilize fertilizers and water more efficiently or consume less water than current varieties, crop breeding can reduce agriculture's contribution to water pollution and pressure on freshwater resources.

Note:
a. CCRP (2013).

of millions of people remain in poverty. One study of the Green Revolution between 1960 and 2000 found that, without improved crop yields, global crop prices would have been one third to two thirds higher, the proportion of malnourished children would have been 6–8 percent higher, and overall calorie intake in the developing world would have been 14 percent lower than it actually was.[1] Looking forward, most economic studies predict rising prices and resulting hunger unless the world increases its rate of crop growth.[2] For example, one study estimated that if the productivity of combined land, chemical, and labor inputs grows 40 percent more than currently projected by 2050, the number of malnourished children will decline by 19 million and food price increases will be far less than projected.[3]

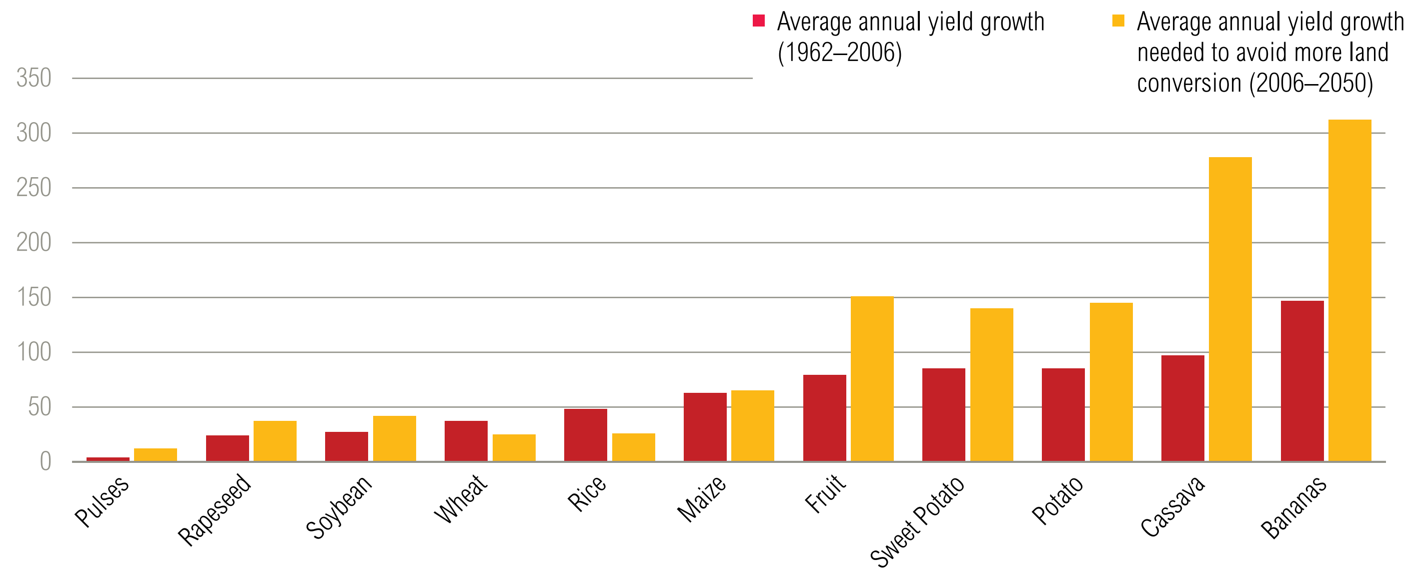
Strong growth in crop yields can also reduce environmental pressures, particularly land conversion. From the early 1960s through the mid-2000s, global agriculture expanded by 500 million hectares, converting an area of forests, savannas, and wetlands equal to about five-eighths of the continental United States.[4] This land conversion greatly harmed ecosystems and the climate.[5] About half of this land was converted to croplands, with the other half to pasture. Without the enormous gains in crop yields during the same period, conversion of natural ecosystems into agricultural land would have been many times higher. Although yield improvements per hectare may trigger some farmers to expand their cropland to increase profits, on a global basis yield improvements nearly always result in less land being farmed because farmers do not need as much land to meet demand.[6]

Demand for strong growth in crop yields will be high in coming decades. In our *Interim Findings*, we explore a menu of solutions that could help close the 69-percent food gap, including shifting to healthier diets, reducing the rate of food loss and waste, reducing biofuel demand for food crops, and reducing long-term population growth by educating girls and lowering childhood mortality. But whether the world can fully realize these demand-side solutions is uncertain. Increased incomes could drive up meat demand even more than our analysis suggests. Overall, our preliminary calculations suggest that, even if demand-side solutions are highly successful, the world will still need to increase food production.[7] And if demand-side solutions are not successful, crop yields (measured in kilograms per hectare) would have to grow one third more per year between 2006 and 2050 than they did from 1962 through 2006 (the period encompassing the Green Revolution) for the world to meet its projected food needs on existing agricultural lands.[8] Average annual yield growth needed for some crops would be even higher (Figure 1).

This growth in crop yields will need to occur in increasingly difficult physical conditions due to a changing climate and increased water scarcity.[9] Climate change is projected to reduce yield growth rates in much of the world, especially in tropical regions.[10] The Intergovernmental Panel on Climate Change (IPCC) reported that climate change might reduce yields per hectare of wheat, rice, and maize by up to 2 percent per decade starting by 2030 compared with projected yields without climate change.[11] The IPCC and others project that many regions will face increased water stress because of rising competition for water resources and altered precipitation patterns linked to climate change.[12] Furthermore, it is unlikely the world will witness the scale of input growth that drove yield gains during the Green Revolution. Except in Africa, fertilizer application is already at or above agronomically or environmentally sustainable levels.[13] And many regions have maximized their use of irrigation.[14]

Strong growth in crop yields, therefore, will have to rely heavily on improved crop breeding (Box 2), along with improved farm management practices.[15] Overall, it is difficult to determine what proportion of yield gains are attributable to improved breeding, versus farm management changes. Many Green Revolution crops produced higher yields only when combined with improved management practices, such as fertilizer application and irrigation. Still, typical estimates claim that breeding alone generated half of all yield gains,[16] highlighting the importance of breeding.[17]

Figure 1 | **Future Yield Growth in Many Crops Will Need to be Higher than in the Past to Meet Projected Food Demand on Existing Agricultural Land (Kilograms per hectare per year)**



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

Box 2 | Multiple ways in which crop breeding improves yields

Crop breeding has formed the basis of agriculture since the beginning of farming 10,000 years ago. Today, scientists breed crops in many ways.[a] Some laboratories breed particular traits into established varieties, and when these changes are significant enough, they announce a new variety. Local breeders often adapt the new varieties to local conditions. These practices are known as "trait" breeding.[b] Much of the gain in yields, however, results from "line breeding," the steady improvement of established varieties by cross-breeding the best-yielding local varieties.

Breeders improve yields partly by increasing the "yield potential" of crops: the maximum yield a crop can achieve under ideal growing conditions. But few farmers obtain these yields in the real world because of a variety of stresses, including pests, drought, and adverse soil conditions. Breeders can improve real yields by breeding crops with reduced susceptibility to these stresses.

Notes:
a. Evenson (2003).
b. Gates Foundation (2013).

GENETICALLY MODIFIED CROPS

The most contentious public policy debate surrounding plant breeding involves genetically modified organisms (GMOs). "Genetic modification" 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 to produce offspring with random mixes of genes from the parent plants. Breeders continue this process until they can reliably produce plants with the desired traits.

Although plant scientists have bred crops with a wide variety of genetically modified (GM) features, two traits currently dominate the market. One is resistance to a particular herbicide, glyphosate. This trait allows farmers to spray glyphosate—originally effective against virtually all weeds—directly over crops that the herbicide would otherwise kill. The second common trait is the production of a natural insecticide from the bacterium *Bacillus thuringiensis* (Bt), which is particularly effective against insect larvae such as the corn rootworm and the corn borer. Bt traits are used predominantly in maize and cotton.

To date, the majority of GM crop traits are in just four high-value crops: maize, soybeans, canola, and cotton. Of the 190 million hectares annually planted in GM crops—approximately 12 percent of global cropland[18]—the vast majority are in Argentina, Brazil, Canada, China, India, and the United States.[19]

Subject of great debate

The GMO debate focuses on four issues: (1) food safety, (2) toxicity and pest resistance, (3) crop yield effects, and (4) shift of profit and control to major corporations. Most of the debate focuses on glyphosate-resistant crops and Bt crops.

Food safety

Fear that GM crops are not safe for human consumption drives much of the public opposition to GMOs. At this time, there is no evidence that GM crops have actually harmed human health.[20] The vast majority of studies have found no adverse health effects,[21] and even GM critics mainly argue that the risks have been insufficiently studied.[22] The most alarming study of GM crops claimed to find a large increase in rat cancers. However, the sample involved only 10 rats of each gender, and food safety institutes criticized it for a high likelihood of random error.[23]

Any breeding has some potential to create unintended health consequences. Nevertheless, the U.S. National Research Council has agreed that genetic modifications using genes from diverse species pose a greater risk of producing unexpected effects than conventional cross-breeding of same- or related-species varieties.[24] This greater risk justifies mandatory safety studies, and there is room for reasonable debate about the proper scope of such studies. But even conventional breeding may carry some risk.[25] Conventional breeding includes methods of encouraging and experimenting with mutations whose potential for unintended consequences approaches that of genetic engineering.

Overall, there is scientific consensus—among entities such as the National Research Council, the European Joint Research Centre, the American Medical Association, and the American Academy for the Advancement of Science—that although GM crops should undergo safety screening, food safety does not justify rejecting genetic modification outright.[26]

Toxicity and pest resistance

Because both glyphosate and Bt are less toxic than other pesticides, researchers have generally argued that the overall toxicity of pesticides for glyophosate-resistant crops has declined, and both the toxicity and volume of pesticides have declined for Bt crops.[27] Some studies, however, have arrived at contrary conclusions.[28]

Measured by sheer volume rather than toxicity, the quantity of pesticides used in the United States increased gradually from 1996, and then jumped in 2011.[29] Much of that growth was in glyphosate and probably resulted from increasing resistance in weeds that farmers tried to overwhelm by using more glyphosate. The overall increase in pesticide use is important because glyphosate—like many other herbicides—is a hormone disruptor and its widespread use in high volumes is a concern even if its acute and chronic toxicity is lower than other pesticides.[30] Hormone disruptors appear to lower sperm counts and may be responsible for a range of health effects.

In contrast, Bt crops appear to have reduced the use of insecticides, particularly in China and India, although there is disagreement about the degree of that reduction.[31] In some places, Bt crops have led to an increase in "secondary" pests. Reducing the secondary pests, in turn, can require more pesticide use. But some studies show that Bt crops can also contribute to reductions in secondary pests,[32] and can even promote beneficial insects that reduce pests on neighboring maize, peanut, and soybean fields.[33]

The strongest counterargument against the notion that Bt crops have contributed to a drop in pesticide use focuses on the pesticides naturally created by the Bt crops themselves. Bt crops express Bt proteins throughout the entire crop, not merely at the roots that are most vulnerable to pests. If all this crop-generated Bt counts as a pesticide, then Bt crops are increasing total pesticide use.[34] This argument merits concern, although Bt is less toxic than other pesticides, and avoiding spraying should reduce effects on non-targeted species.

Much of the environmental criticism of these GM crops acknowledges the advantages of reduced toxicity in the short term, but argues that they may lead to greater toxicity in the long term. An increased reliance on individual pesticides can lead to more rapid development of resistance by weeds or invertebrate pests, which could eliminate the usefulness of less toxic pesticides such as glyphosate and Bt. There are examples of crop infestations by insects that are resistant to one Bt protein, but no evidence of Bt resistance to crops with a broader range of Bt proteins. Breeding multiple Bt proteins into crops should reduce the likelihood of resistance, because even genetic mutations that lead to resistance to one Bt protein will not give those pests an advantage as they will remain vulnerable to the other Bt proteins.[35]

In contrast, glyphosate resistance is developing rapidly and has now spread to 24 weeds.[36] In some areas, glyphosate-resistant weeds have become an expensive problem,[37] and trying to overwhelm resistance has led to a large rise in the total quantity of glyphosate applied.[38] In part because of this resistance, chemical companies are trying to develop crops that are resistant to even more toxic pesticides, such as 2,4-D, which would be applied along with glyphosate. This approach, however, would reduce—if not eliminate—the low-toxicity benefit of using glyphosate-resistant crops. The risk that weed resistance to relatively benign pesticides could lead to increased use of more toxic pesticides requires attention.

The new focus on breeding crop resistance to more toxic pesticides also highlights that nothing inherent in GM technology leads to lower pesticide toxicity. Breeding probably originally focused on glyphosate partly because its lower toxicity was likely to lead to its greater use, but GM technology can also be used for more toxic pesticides. In other words, GM technology—like most technologies—is a tool whose merits depend on how it is used.

Crop yield effects

Whether glyphosate-resistant and Bt crops have led to yield gains is open to debate. On the one hand, 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 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. This drag effect eventually disappears for a particular GM gene,[39] but the insertion of new genes will repeat the drag effect in the future.

On the other hand, yields improve not only when maximum potential yields increase, but also when farmers are better able to control stresses, such as pests, on their crops. The easier management of weeds because of the use of glyphosate-resistant crops, or the greater control via Bt of insects that attack crop roots, could boost yields in the real world. In addition, greater profitability because of reduced losses from pests may lead farmers to make other investments to improve overall yields. The question, therefore, is: What net effects on yields have GM crops produced in the real world?

In the United States, the National Research Council has concluded that the net effect on yields of glyphosate-resistant crops has been modest, although the reduction in farm labor and management intensity has been large.[40] It also concluded that Bt has led to 5–10 percent yield gains for cotton[41] and perhaps smaller gains for maize.[42] Other studies have found no yield gain for most GM varieties.[43]

In warmer developing countries where pest pressures are naturally greater and pesticide use is less common, the gains may be different. India 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.[44] 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.[45] Overall, the evidence tends to justify claims that Bt cotton helped to significantly increase yields, although improved management of cotton overall probably played an even larger role.[46]

Fundamental methodological challenges make it difficult to resolve these differences in research findings. To be fair, studies such as Shi et al. (2011) that compare test plots of well-managed GMOs with well-managed alternative plots are less likely to recognize the potential for real-world gains from the greater ease of pest management that GMOs may allow. Conversely, comparisons of real-world yields between those who adopt and those who do not adopt GMO crops are confounded by the fact that early adopters tend to be farmers already achieving higher yields, and farmers who pay more for GMO seeds are likely to plant them on better fields and pay more attention to them.[47] Similarly, studies based on country comparisons tend to ignore the fact that countries adopting GM crops already had high and rising yields.[48] Conversely, the higher profitability of GM crops may help explain the larger efforts farmers are making to grow them.

Overall, the weight of the evidence supports some yield gains, particularly for Bt crops, but the extent of those gains is uncertain.

Shift of profit and control to major corporations

A fourth concern with genetic engineering is expense. Farmers must buy new seeds annually instead of harvesting their own seeds, and GM seeds cost more. Thus the farmer must surrender some revenue and depend on purchasing external seed supplies. Conversely, farmers would not buy hybrid or GM seeds unless the payoff exceeded the cost—suggesting that a boost in yields or a reduction in other costs can justify the higher GM seed costs. In other words, although it may entail surrendering some revenue to companies, farmers may choose GM seeds if they offer a greater net profit. Some studies have found such benefits for small farmers.[49]

Higher seed costs can increase pressures on small farmers more than on large farmers because small farmers 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 than larger farmers to balance these added losses in bad years with the greater benefits in good and average years, even though small farms can be as or more productive overall as large farms in many farming systems.[50]

This problem is the same as any increase in input costs caused by technological advances: How does one ensure that small and poorer farmers can capture the benefits of technological change? One solution is for public researchers to contribute to the technological advancement, in this case GM seeds. The concern about higher seed costs would then be less. Although annual seed purchases by farmers would probably still be necessary, the seed costs would not include payments to a private patent holder.

The concern about shifting profit and control to major corporations is not unique to GM seeds: it holds for conventionally bred hybrid seeds that dominate the world's maize production. Some farmers resist hybrid seeds because of their expense.

What is the Future Role for Genetically Modified Crops?

Although claims both for and against GMOs have been overstated, GM technology could play a role in maintaining and improving yields in real-world conditions. But breeding pesticide resistance directly into major crops is probably not the most promising opportunity. Instead, the most immediate opportunities lie in breeding disease-resistant traits into crops under serious 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 into the papaya itself, generating a kind of plant immune response.[51] Because of public resistance to GMOs, this variety has not spread much to the developing world.[52] Genetically modified cowpeas and plantains could be useful in Africa against various diseases,[53] and recent advances indicate the potential for reducing potato blight worldwide.[54] Disease threats are only likely to grow as regional and global trade increases, and as more farmers use a limited number of high-yielding varieties susceptible to the same diseases. Genetic engineering approaches may sometimes offer an effective response.

GM technology may also contribute to yields through improved drought resistance, although improving drought resistance is complicated because of the large number of genes involved. Traits that lead to more resistance to some kinds of droughts will increase damage in other kinds of droughts and could hold down yields in wet years. The challenge, therefore, is finding the right mix that generates overall net gains across different years.[55] It is too soon to determine if drought-resistant crop varieties emerging in the United States will contribute to yield gains over multiple years.

In the longer run, GM technology may lead to fundamental improvements. A recent paper cites the potential to increase traits that resist aluminum toxicity or high salt concentrations in soil, and that increase the plant's uptake of phosphorus and nitrogen.[56] Some researchers are trying to develop cereals that fix their own nitrogen, just as soybeans and other pulses do. Nitrogen-fixing cereals would probably assist production in some regions, although plants typically extract an energy cost for fixing nitrogen, which may hold down yields.[57] Researchers at the International Rice Research Institute are attempting to develop a "C4" rice variety—one that shares the basic photosynthetic biology of maize and sugarcane—which permits higher growth in a number of conditions.[58] Even more ambitious efforts would reengineer fundamental properties of photosynthesis to increase its rate. These improvements could have dramatic benefits for yield growth. Even if successful, these changes will take time, generally decades, but the scope of the challenge requires these kinds of explorations.[59]

Much of the interest in genetic engineering lies in the recent, vast improvement in genetic techniques. So far, breeders have mostly used techniques such as a "gene gun" or a bacterium that inserts a gene into existing DNA at unknown locations and in unknown ways. These techniques rely on large-scale trial and error. A variety of new techniques allow the precise placement or replacement of existing genes in particular locations. These finer techniques—which rely less on massive, random testing—can be cheaper and are likely to lead to greater benefits.[60] Other techniques may permit moving genes around within a genome, or may change plants by suppressing the expression of some genes, therefore avoiding consumer concerns about GM plants that contain foreign genes.

Despite these promises, the gains from GMOs are often overstated, which has research implications. The ability to patent new genes, thereby generating income for the breeders, can distort research attention away from even more promising breeding methods and areas of focus with fewer financial benefits for breeders. These more promising methods are based on conventional breeding. GM technology generally works for traits controlled by a single gene or a small number of genes, while most traits that lead to higher yields result from a large number of genes and their interactions with environmental factors.[61] It is through conventional methods that breeders can affect such a large number of genes. GM technologies, therefore, are likely to be less important for future global yield gains than conventional breeding techniques, which must remain the first research priority.

POTENTIAL ADVANCES IN CONVENTIONAL BREEDING

Conventional breeding involves changing the genetic makeup of a plant—but without inserting genes from unrelated species—so that a new and better variety emerges. New varieties of plants are bred to grow more densely, to direct more growth into their edible portions, to suit different climate and soil conditions, to cope better with disease or pests, and to use water and nutrients more effectively. In the "low-tech" version of conventional breeding, breeders cross individual plants based on how they perform in the field, not by looking at their DNA. They then select the offspring with the most desired traits for mainstreaming or for subsequent crossing.

For ages, conventional breeding and the careful annual selection of the most favorable plants from the previous year's trials supported the steady advance of crop yields. For instance, the research breakthroughs that increased Brazil's yields for soybeans, maize, and *Brachiaria* grasses for pastures came through conventional breeding techniques that enabled these plants to thrive despite the high levels of aluminum in Brazil's acidic soils.[62]

What are the prospects for increasing the rate of yield gain through conventional breeding? Strategies include increasing the number of test breeding seasons by using controlled environments to grow crops out of their normal growing seasons, and using approaches (such as double-haploid technology) that help to "purify" crop strains faster than conventional breeding over multiple generations.[63] Breeders can also take greater advantage of computer technologies to more rigorously track and share breeding information. Even better prospects, however, focus on the opportunities available through broad technological improvements in genetics that make it easier to understand and track genes (and combinations of genes) that give rise to favorable crop traits.

The Potential of Marker-Assisted and Genomics-Assisted Breeding

Much of the progress in all fields of biology over the past two decades has resulted from the development of faster and cheaper methods of analyzing DNA. Plant breeders have begun to take advantage of these improvements. Most prominently, breeders have developed methods for mapping and marking portions of plant DNA associated with agronomically useful traits. This "marker-assisted" breeding enables breeders to identify through genetic analysis the seedlings that are most promising for further breeding—even before they grow into mature plants. 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 mature to figure out which individuals to cross.[64] Whereas "low-tech" conventional breeding may require a minimum of 7 to 17 generations—depending on the type of crop—to produce a new cultivar, marker-assisted breeding can cut this down to just a few generations.[65]

The International Rice Research Institute demonstrated the potential of this approach in 2009 by introducing a rice variety that could survive underwater submersion. It developed the variety in just three years after it identified the relevant genetic marker for flood tolerance. Since then, the Institute has delivered 10 more varieties that are resistant to monsoon flooding in South and Southeast Asia.[66]

Like genetic engineering, marker-assisted breeding is valuable primarily for simple traits determined by a single gene. Within the past decade, improvements in "genomics" have created opportunities to further increase and accelerate the yield improvements from conventional plant breeding for more complex traits controlled by multiple genes. Genomics applies DNA sequencing methods and genetic mapping to analyze the function and structure of genomes—*the complete set* of DNA within a single cell of an organism.[67] A breeder who wishes to breed-in a large number of traits may now be able to predict through a combination of a DNA map and statistical analysis whether an individual plant has the genes needed to yield the desired traits.

Genomics has the potential to make conventional breeding not only faster but also better. The traditional approach either ignores underlying genes altogether, selecting plants by the traits they show, or requires that breeders use indirect methods to estimate the favorable underlying genes. New genomics-assisted techniques allow breeders to identify and breed for promising gene combinations whose benefits are otherwise hidden because they may not immediately show up in the first few generations of offspring. Knowing that the genes are there, breeders can push forward through continued breeding until the desirable traits are expressed.

Although these modern genetic techniques seem to promise enormous conventional breeding gains, to date they have generated major successes in only a few situations, such as the flood-tolerant rice.[68] Why?

One reason may be the limited facilities and training for using these techniques.[69] Many breeding institutions are still developing these capabilities, and they are particularly undeveloped in critical parts of the world, such as sub-Saharan Africa. To some extent, breeding responsibilities can be shared; for example, globally oriented research institutions can engage in “pre-breeding” by using new techniques to develop promising plant material that still requires extensive local breeding to be useful. Some partnerships between research institutions in developed and developing countries are working this way.[70] However, even this sharing of responsibilities requires a dedication to the crops needed locally, and local capabilities in the new techniques to fully realize opportunities to reduce breeding timelines.

A second reason is more fundamental and turns on the difficulty and complexity of connecting genes and combinations of genes to particular traits. Identifying genes is now easy, but knowing what these genes do—and how they respond to a variety of environmental settings—is hard, time-consuming, and complicated. Scientists need to build understanding of what different genes do. Fortunately, technological advances are creating new capacities in techniques known as “high throughput phenotyping.” They include using remote-sensing devices to monitor attributes of plant growth in the field, and various molecular techniques that serve as proxy indicators for other plant attributes. These techniques allow researchers to determine if new offspring have desirable traits before they complete their growth, and reduce the time and labor needed to analyze them. To do so, the size of the crop population has to be large, the assessment of traits has to be reliable and replicable, and the population under study must be of the same type. Although genomics is very promising, the extent to which scientists can design and execute improved varieties from known gene building blocks remains unclear.

A third reason these modern genetic techniques have not yet lived up to their promise is the simplest: the ability to identify genes rapidly and cheaply in high “throughput” operations is quite new.

Although breeders have yet to fully realize benefits from marker-assisted and genomics-assisted breeding, these techniques will at a minimum reduce the time necessary for conventional breeding of relatively simple traits. Given the magnitude of the crop-yield challenge, additional investments in these technologies are worth the bet.

The Potential of Orphan Crops

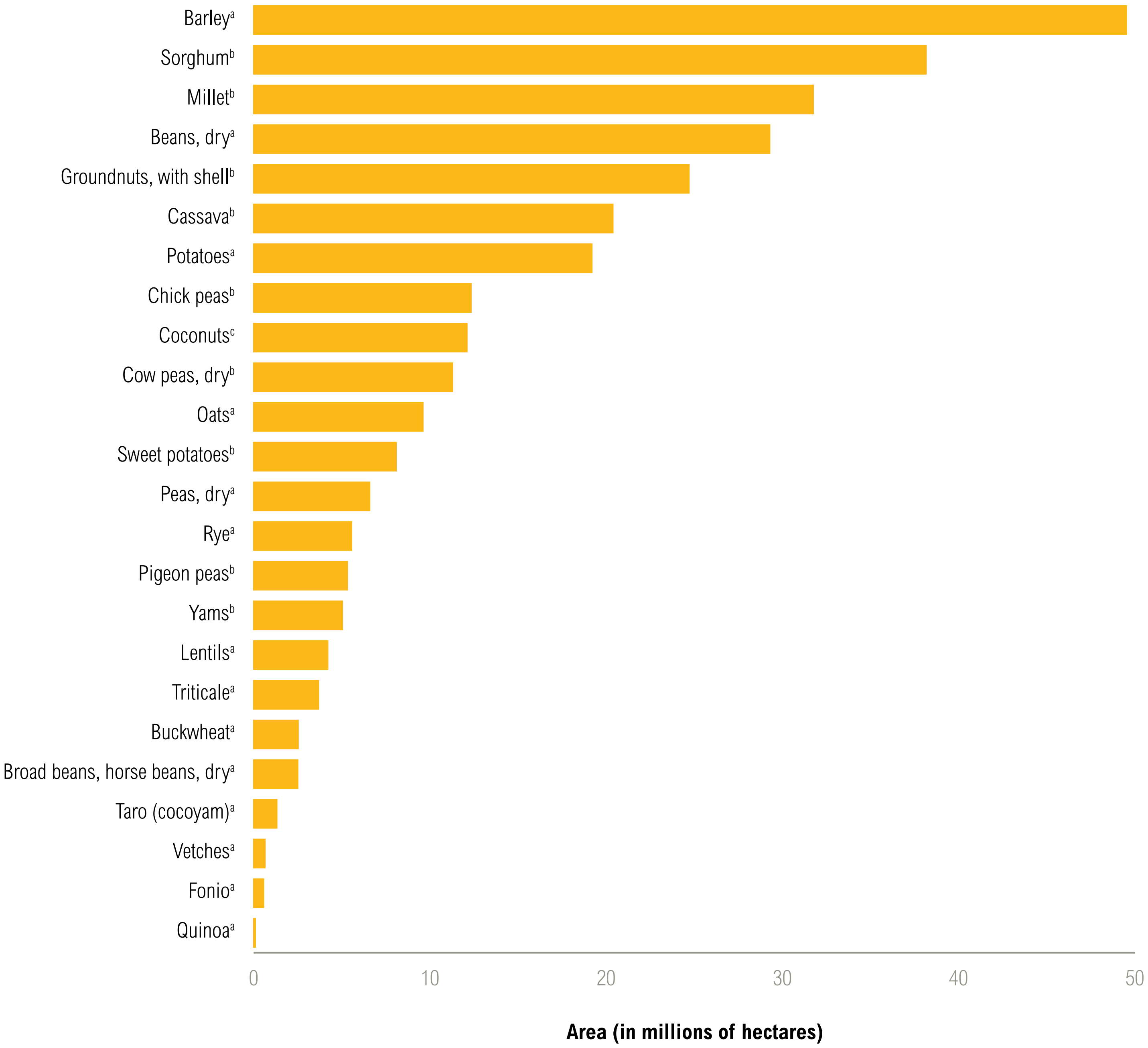
The ability of marker assistance and genomics to speed up breeding supports a case for increasing attention to “orphan crops” in developing countries.[71] The term “orphan crops” generally refers to crops that have received relatively little research attention, despite their importance to food security in less developed regions. Some researchers add that “orphan crops” are those that are not widely traded on global markets.[72]

Orphan, however, does not mean that they are not grown. Twenty-four crops considered orphans occupied 300 million hectares worldwide in 2012 (Figure 2).[73] Many of these orphan crops have special significance for food security because they are adapted to marginal cropland where many of the world’s poor and hungry live. Sorghum and millet are prominent examples, occupying roughly the same area as maize and wheat in sub-Saharan Africa in 2011. Because of their importance to poor smallholder farmers, improving their yield to half of their maximum yield potential would have greater benefits for food security in sub-Saharan Africa than improvements in any other crops, according to an International Food Policy Research Institute study.[74]

Marker assistance and genomics should make it easier to advance breeding quickly in these less-studied crops in two ways. First, they can increase the speed of breeding in general. Second, they make it possible for breeders to understand the gene combinations that have already led to yield gains of the more-studied crops so they can then select for these advantageous gene combinations in the orphan crops.

A projection of crop growth demand through 2050 by the Food and Agriculture Organization of the United Nations (FAO)[75] provides compelling food-security and environmental reasons to focus on orphan crops. The demands for pulses, potatoes, oil seeds, fruits, and vegetables are projected to grow more rapidly than demands for cereals. FAO’s land-use projections assume greatly accelerated yield growth for many of these secondary crops. Unless these high rates of yield growth are achieved, even more land will need to be converted to agriculture to adequately feed the planet by 2050.

Figure 2 | **Twenty-four "Orphan" Crops Occupy about 300 Million Hectares in the World, 2012**



Notes:

Although cacao, common bean, and tef are considered orphan crops by either Naylor et al. (2004) or Varshney et al. (2012), data on area under cultivation is not available from FAO (2013).

a. Naylor et al. (2004) lists this crop as an "orphan" crop.

b. Varshney et al. (2012) and Naylor et al. (2004) list this crop as an "orphan" crop.

c. Varshney et al. (2012) lists this crop as an "orphan" crop.

Source: FAO (2013) using definitions of "orphan crops" from Varshney et al. (2012) and Naylor et al. (2004).

CROP BREEDING TO MEET ENVIRONMENTAL GOALS

To make the greatest possible contribution to global food security, increasing yields—or at least maintaining yields in the face of climate change—should remain the primary goal of crop breeding. However, improving crop breeding to meet environmental goals would help with the "great balancing act" by further reducing agriculture's impact on ecosystems, climate, and water.

One environmental goal should be to increase the nitrogen-use efficiency of crops so that less nitrogen fertilizer needs to be applied on croplands. Nitrogen run-off from excess fertilizer application is a leading source of algal blooms and "dead zones" in coastal waters around the world.[76] In addition, fertilizers probably account for at least 3 percent of global greenhouse gas emissions,[77] and they are now on a course to grow dramatically by 2050.[78]

Crop breeders are attempting to increase the biological efficiency with which crops can absorb and use nitrogen. This characteristic depends partly on the efficiency with which crops take up nitrogen from soils and partly on the efficiency with which crops allocate nitrogen to the harvestable part of the plant. Crops bred for nitrogen efficiency must have a natural variability that allows researchers to select for higher efficiencies. It helps if genes that contribute to higher efficiency in one environment do so in other environments, and if different genes that contribute to higher efficiency work in ways that lead to additive benefits when combined. Efforts to breed higher nitrogen-use efficiency into crops are new; the few breeders working on it report both challenges and the discovery of promising basic plant characteristics.[79]

Other environmentally related crop breeding needs include increased water-use efficiency, increased natural pest resistance, and improvements in cover crops designed to protect soils outside major plant growing seasons by replenishing soil carbon, limiting erosion, and storing nutrients. In addition to environmental benefits, nearly all of these breeding goals would also improve yields. For example, climate change threatens to severely limit potential rain-fed yield growth—even in the U.S. corn belt—which might be partially offset by increasing crop water-use efficiency.[80] However, with the exception of drought-tolerance, the number of breeders and the size of budgets devoted to these environmental goals are extremely small.

HOW TO BOOST BREEDING

The combination of the need for higher yields and new technological options make a strong case for increased dedication to conventional crop breeding. In light of this, we offer five recommendations.

Recommendation 1. Improve and stabilize crop-breeding budgets

Realizing the potential of marker-assisted and genomics-assisted conventional breeding will require substantial investments by a wide range of institutions.[81] The challenge is particularly acute in developing countries since these innovative approaches to plant breeding are still essentially out of reach to most public-sector researchers there. Developing countries need more scientists trained in modern breeding technologies, increased transfer of these technologies from developed countries, and introduction of data management systems and computational tools to support market-assisted and genomics-assisted breeding.

Recent years have seen some good news in agricultural research and development (R&D) funding. After many years of modest growth, global public research spending spurted from $26.1 billion in 2001 to $31.7 billion in 2008,[82] when a food crisis spurred additional spending on agricultural R&D. For example, the Consultative Group on International Agricultural Research (CGIAR)[83] system received funding that pushed its annual budgets from roughly $400 million in 2000 to more than $1 billion in 2013, and China continued to boost its spending by another $2 billion between 2008 and 2010.[84]

Despite this good news, growth has been uneven, and spending in many food-insecure regions remains inadequate. Roughly half of the agricultural R&D growth from 2001 to 2008 occurred in China and India. Similarly, although overall spending on agricultural R&D grew in sub-Saharan Africa from 2001 to 2008, eight countries in that region accounted for 70 percent of all spending, while many African countries saw declining R&D spending.[85] R&D spending in sub-Saharan Africa roughly matches that of Brazil despite the African region's fourfold greater population. Although high-income countries spend 3 percent of the value of their agricultural production on R&D overall, low- and middle-income countries spend only half a percent.[86] This limited funding is compounded by the high volatility in funding for the world's poorest countries, which depend on and therefore respond to the interests of international donors.[87] Breeding requires stable funding because it is inherently a slow and cumulative process.

Private sector research, although growing, only modestly replaces the need for public sector research. Total private food sector R&D reached $20 billion globally in 2010,[88] and in the United States and Europe, the private sector has taken over the task of the localization, steady improvement, and production of seeds. But globally, only $3.7 billion of these private R&D funds were directed at crop breeding, with the remainder spent on food processing, machinery, and chemical inputs.[89] Even in the United States, private sector R&D accounts for only one-third of the annual $3.5 billion spent on research in agricultural production.[90] Furthermore, private sector research is generally directed at the commercial sector and involves crops, such as hybrid maize, for which intellectual property rights are more easily exploited.

This funding landscape leaves enormous areas of unmet research needs that no one institution can satisfy. When the United States Agency for International Development's (USAID) "Feed the Future" program compiled a list of global research priorities and opportunities for agriculture in food insecure regions, it found its research budget could fund only a small portion of them.[91]

Abundant evidence indicates that agricultural R&D generally pays off, with estimates commonly in the range of annual returns of 40 percent.[92] China and Brazil, recent global leaders in agricultural R&D, have seen their productivity increase between 1979 and 2009 by 136 percent in China and 176 percent in Brazil.[93] Unfortunately, we found no thorough study of the extent to which global R&D funding could profitably increase and should increase to address the Great Balancing Act.

As a start, we recommend an initial goal to raise agricultural R&D in low- and middle-income countries from the current 0.5 percent to 1.0 percent of their agricultural output production value. This goal would involve an increase of roughly $15 billion per year. The burden of this growth would have to be shared with high-income countries. The growth should occur in ways designed to guarantee continuity, development of infrastructure, and advancement of partnerships that allow low- and middle-income countries to benefit from newer breeding methods.

Recommendation 2. Leverage new technologies in proportion to their yield-enhancing potential

Greater inputs alone will not secure the rapid yield improvements they delivered in the past. This reality, along with the scope of the crop-yield challenge, makes boosting yields through improved breeding more critical in the future.

Most important is taking advantage of advances in conventional breeding. In particular, this means embracing marker-assisted and genomics-assisted conventional breeding, supported by better data management, sensors, and other tools for more quickly and cheaply identifying what different genes do.

Breeding not only advances the maximum yield potential of crops, but also the ability to achieve those yields in real-world conditions where crops face chemical and biological stresses. The importance of GM technology has often been exaggerated, and there is a debate about the balance of toxicity effects of Bt and glyphosate-resistant crops. But those traits represent only a few of the technology's potential uses. Breeding disease-resistant traits into crops under serious threat is an immediate need for which genetic engineering might provide solutions.

Recommendation 3. Increase research attention to orphan crops

Researchers at universities, government agriculture agencies, agricultural companies, and independent research institutions should broaden their scope beyond the most intensely researched crops—maize, wheat, rice, and soybeans—to give increased attention and funding to orphan crops.

Some movement in this direction is underway. In 2003, CGIAR launched a 10-year Generation Challenge Programme to improve crops in drought-prone and harsh environments via genetic diversity and advanced plant science. From 2009 to 2014, the program focused on drought tolerance for nine crops, six of which are orphan crops: beans, cassava, chickpeas, cowpeas, groundnuts, and sorghum.[94] In addition, CGIAR has launched a new research partnership initiative on grain legumes.

Furthermore, the African Orphan Crops Consortium[95]—consisting of companies, nongovernmental organizations, and international institutes—is undertaking an effort to sequence the genomes of 100 food crops in Africa. Although promising, the research dollars involved are still small. The Consortium has raised $40 million per year from developed countries, with a promise of $100 million more from African countries.[96] More orphan crop efforts and more research funding are needed.

Recommendation 4. Increase attention to breeding for environmental goals

Breeders should increase efforts to breed food crops that use nitrogen more efficiently and use less water, and for cover crops that more effectively prevent erosion and sequester carbon. Doing so requires incorporating these goals into other breeding programs and requires sharing basic research across different crops. Agriculture funders should collaborate on supporting networks of researchers focused on these critical traits.

Recommendation 5. Support sharing of genomic advances

Universities, government agricultural research centers, and companies can accelerate yield enhancements by developing and publicizing basic genomic data and methods. The GOLD genome online database[97] is designed for such a purpose. Private sector involvement is also important. For example, recognizing its own interest in promoting cocoa improvements, 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.[98] Making such foundational genomic information widely available to breeders everywhere could help accelerate advances in yields, especially for orphan crops, because it enables more researchers to work on identifying improvements.

CONCLUDING THOUGHTS

Although crop breeding has always been critical for feeding the planet, its importance going forward will be even greater. Unprecedented increases in crop yields will be necessary to meet projected food needs, advance agriculture-led economic development, and reduce pressures on natural resources and the environment. Because of resource constraints or environmental impacts or both, increasing crop yields in the future will have to rely less on increased inputs and more on improved knowledge and management. Crop breeding that uses the latest technological advances will be necessary to achieve the needed yield increases, and is an important item on the menu for a sustainable food future.

ENDNOTES

1. Evenson (2003).
2. Several studies are summarized in section 1.5 of Tischer et al. (2013).
3. Nelson et al. (2010).
4. Searchinger et al. (2013) p. 18 and note 29.
5. Millennium Ecosystem Assessment (2005).
6. Searchinger et al. (2013).
7. Searchinger et al. (2013).
8. Different crops (such as corn, beans, and lettuce) have very different yields and different projected rates of demand. There is no fixed way of combining different crops to estimate one average "growth rate" for crops. Our method derives the "one third," or 32 percent to be more precise, estimate the following way. First, we calculated that if each crop categories' yields were frozen, 790 million hectares of additional harvested land would be necessary to meet crop needs in 2050. If yields grew at their historical rates for each crop (their linear rates from 1962–2006), 192 million more hectares of harvested land would be needed each year. In such a scenario, expansion would provide 24 percent of the projected needs (192 Mha/790 Mha), and yield gains would provide 76 percent. By this rationale, yield gains would have to grow 32 percent more (24.4/75.6) to meet projected global food needs by yield improvements alone. This approach weights each crop increase by its yield (such that a growth in a crop demand of 40 tons with a yield of 4 t/ha/y is equivalent to the growth in demand for another crop of 20 tons with a yield of 2 t/ha/y), and then weights the need for yield growth by the relative growth rate of that crop.
9. Searchinger et al. (2013).
10. World Bank (2012) ; IPCC (2014).
11. IPCC (2014).
12. IPCC (2014), Searchinger et al. (2013).
13. Searchinger et al. (2013), Foley et al. (2011).
14. Alexandratos and Bruinsma (2012).
15. See Winterbottom et al. (2013) for further elaboration on strategies for improving land and water management practices.
16. Evenson (2003).
17. Tischer et al. (2014)
18. CFS (2014).
19. Editors of Nature (2013); FAO (2012).
20. NRC (2004).
21. Snell et al. (2012).
22. 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 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/.
23. Séralini et al. (2011).
24. NRC (2004).
25. Ronald (2011) gives an example.
26. NRC (2004); NRC (2010); EU Joint Research Centre (2008); AMA (2012); AAAS (2012).
27. NRC (2010).
28. NRC (2010).
29. Benbrook (2012).
30. Gasnier et al. (2009).
31. Benbrook (2012).
32. Krishna and Qaim (2012).
33. 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).
34. Benbrook (2012).
35. NRC (2010).
36. International Survey of Herbicide Resistant Weeds (2014).
37. For example, the weed palmer amaranth, which can grow three inches a day and can release 1 million seeds from a single plant, has begun to overrun cotton fields in south Georgia and, once established, is almost impossible to eradicate (Charles 2012).
38. Benbrook (2012).
39. NRC (2010).
40. NRC (2010).
41. NRC (2010).
42. Fernandez-Cornejo and Wechsler (2012).
43. Shi et al. (2011).
44. Stone (2012).
45. Gruere and Sun (2012).
46. Supporting this judgment is the fact that studies that have tried to control for selection bias or use methods that should not reflect selection bias still find significant yield gains (Crost et al. 2007; Kathage and Quaim 2012; Gruere and Sun 2012), and the fact that the overwhelming majority of peer-reviewed studies, biased or not, do find yield gains.
47. 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.
48. 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.
49. Kathage and Quaim (2012), Smale et al. (2009).
50. Wiggins (2009) provides a good summary of the debate about the productivity and advantages and disadvantages of small versus larger farms in developing countries.
51. Gonsalves et al. (2007).
52. Davidson (2007).
53. Witty et al. (2013).
54. McGrath (2014).
55. Gurian-Sherman (2012).
56. Schroeder et al. (2013).
57. Foresight (2011).
58. Von Caemmerer et al. (2012). C4 plants convert carbon and sunlight into tissue and energy differently from C3 plants that leads to more abundant plant growth under conditions of drought, high temperature, and nitrogen limitation.
59. Hall and Richards (2012).
60. Lusser et al. (2012).
61. Hall and Richards (2012).
62. Cremaq (2010)
63. Gates Foundation (2013) provides an excellent list of methods for speeding up the pace of conventional crop breeding.
64. Hall and Richards (2012), Jannink and Lorenz (2010), Nakaya and Isobe (2012).
65. Shimelis and Laing (2012).
66. Information about the International Rice Research Institute monsoon-resistant rice variety was gathered from Higgins (2014).

67. National Human Genome Research Institute (2010).
68. Varshney et al. (2012).
69. Varshney et al. (2012).
70. Varshney et al. (2012).
71. Varshney et al. (2012).
72. Naylor et al. (2004). Naylor et al. 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'."
73. The African Orphan Crop Consortium lists about 100 orphan crops, including many perennials and tree crops. See http://www.mars.com/global/african-orphan-crops.aspx.
74. Nelson et al. (2014).
75. Searchinger et al. (2013).
76. Selman and Greenhalgh (2009).
77. Author's estimates from various sources. FAOSTAT (2014), for example, identifies ~0.9 gigatons of CO_2e from nitrous oxide from synthetic fertilizer and manure applied to soils as of 2011. The International Fertilizer Association has estimated fertilizer production and distribution emissions at roughly ~0.5 gigatons. (International Fertilizer Association 2009). These numbers would amount to ~3 percent of global emissions from all sources. However, there are substantial uncertainties about both these numbers, including some higher estimates for fertilizer production emissions in China and different global estimates of the percentages of nitrogen that turn into nitrous oxide.
78. Searchinger et al. (2013).
79. McAllister et al. (2012); Bingham et al. (2012).
80. Ort and Long (2014).
81. Nelson et al. (2014).
82. Beintema (2012). 2008 is the most recent year with available global figures.
83. Formerly the Consultative Group on International Agricultural Research.
84. Beintema (2012).
85. Beintema (2011)
86. Beintema (2012), p. 10.
87. Beintema (2012).
88. Fuglie et al. (2011).
89. Fuglie et al. (2011), table 1.1
90. Pardey and Beddow (2013), figure 4, p. 14.
91. U.S. Government (2011).
92. Alston et al. (2000).
93. Fuglie (2012).
94. See GCP (2014).
95. 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.
96. Howard Shapiro, personal communication, May 15, 2014. Shapiro was a founder of the Consortium.
97. U.S. Department of Energy and the University of California (2014).
98. Nieburg (2013): Motamayor et al. (2013).

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ACKNOWLEDGMENTS

The authors would like to acknowledge the following individuals for their valuable guidance and critical reviews: Nourollah Ahmadi (Institut National de la Recherche Agronomique), Jean-Marc Bouvet (CIRAD), Keith Fuglie (U.S. Department of Agriculture), Jean-Christophe Glaszmann (CIRAD), Charles Godfrey (Oxford University), Janet Ranganathan (WRI), Richard Waite (WRI), and Robert Winterbottom (WRI). The authors also thank all of those who reviewed an earlier version of this paper that was published as part of *Creating a Sustainable Food Future: Interim Findings* including Eija Pehu, Robert Townsend, and Chris Delgado of the World Bank.

The authors would also like to thank Jenna Blumenthal for valuable research to support this working paper.

We thank Emily Schabacker for style editing and Mary Paden for copyediting and proofreading. In addition, we thank Carni Klirs, Bill Dugan, Hyacinth Billings, and Jen Lockard for publication layout and design.

For this working paper, WRI is indebted to the generous financial support of the Norwegian Ministry of Foreign Affairs, the United Nations Development Programme, the United Nations Environment Programme, and the World Bank.

This working paper represents the views of the authors alone. It does not necessarily represent the views of the World Resources Report's funders.

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ABOUT WRI

WRI is a global research organization that works closely with leaders to turn big ideas into action to sustain a healthy environment—the foundation of economic opportunity and human well-being.

Our Challenge

Natural resources are at the foundation of economic opportunity and human well-being. But today, we are depleting Earth's resources at rates that are not sustainable, endangering economies and people's lives. People depend on clean water, fertile land, healthy forests, and a stable climate. Livable cities and clean energy are essential for a sustainable planet. We must address these urgent, global challenges this decade.

Our Vision

We envision an equitable and prosperous planet driven by the wise management of natural resources. We aspire to create a world where the actions of government, business, and communities combine to eliminate poverty and sustain the natural environment for all people.

Our Approach

COUNT IT

We start with data. We conduct independent research and draw on the latest technology to develop new insights and recommendations. Our rigorous analysis identifies risks, unveils opportunities, and informs smart strategies. We focus our efforts on influential and emerging economies where the future of sustainability will be determined.

CHANGE IT

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

SCALE IT

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