THE INFORMATION TECHNOLOGY & INNOVATION FOUNDATION and
THE LONDON SCHOOL OF ECONOMICS AND POLITICAL SCIENCE | APRIL 2013

FEEDING THE PLANET IN A WARMING WORLD

BUILDING RESILIENT AGRICULTURE THROUGH INNOVATION

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TABLE OF CONTENTS

EXECUTIVE SUMMARY

The global agriculture system faces a rapidly growing challenge: in the coming decades it must feed a substantially larger population amidst an increasingly volatile and shifting climate. Already, global food systems are being affected by extreme weather events, including historic droughts, which are leading to higher food prices and greater food insecurity. The negative impacts of global climate change on agriculture are only expected to get worse. Ensuring an expanding, stable, and secure food supply capable of meeting the challenges of climate change requires more resilient crops and agricultural production systems than we currently possess in today's world. This is without a doubt the chief agricultural challenge of our time.

Global food systems are being affected by more frequent extreme weather events, including historic droughts, which are leading to higher food prices and greater food insecurity.

Unfortunately, agricultural resilience policies are plagued by an inadequate paradigm that places undue confidence in the sufficiency of existing technologies to meet new challenges, and a fear of the uncertainty surrounding new technologies. Some have argued that existing technologies are adequate to face the challenge if uniformly diffused and applied, and if global socioeconomic obstacles like poverty are overcome.[1] To be sure, diffusing the best available technologies is important, and the socioeconomic challenges we face are significant. Efforts to deal with them should be encouraged and expedited. But even in the most ideal circumstances, diffusing existing agricultural technologies and practices is not enough to address the challenges we will face in the coming decades.

In light of this, we propose several solutions. In particular, we argue that the critical, game-changing solutions for building global agricultural resilience will come only from expanding the innovation and adoption of next-generation crops and agricultural practices. We need new and improved crop varieties that use less water, deliver increased yields and improved nutrition, and have built-in means for repelling insect pests, resisting disease, and withstanding extreme heat, cold, rain and drought. Agriculture will need every existing tool in the box, as well as the development of new ones, including the use of demonstrably safe crops improved through modern biotechnology, commonly referred to as genetically modified organisms (GMOs) or transgenics.

This report explains why advanced agricultural innovation, including the development and deployment of next-generation transgenics, is an essential response to the growing challenges of food security and climate change. We begin by highlighting the nature and magnitude of the likely impacts of climate change on agricultural production systems. We then discuss the potential of advanced agricultural innovation, including the development and deployment of advanced crop varieties, to meet these challenges by creating improved crops with greater resilience to climate variability. Finally, we outline three policies that should be implemented on global and domestic scales in order to create a more robust agricultural innovation ecosystem capable of producing the next-generation crop technologies needed to feed a rapidly growing population on a warming planet. These policies are:

- **Boost global public investment in advanced agriculture innovation.** Over time, private investments in agricultural innovation have steadily increased, while public investments have stagnated or declined. As a result, the character of agriculture research has shifted to near-term product development, while largely ignoring the early-stage research capable of generating new technology platforms and breakthroughs in next-generation biotechnology. Governments, transnational institutions, and nonprofits need to reverse this trend. For instance, the U.S. Congress should triple its current investments in agricultural research and development (R&D) from roughly $5 billion to $15 billion per year. This would reverse a decades-long decline in public investments to support breakthroughs in genomics, biotechnology, and agronomics that the private sector will not deliver quickly enough on its own—if at all. Delivering these breakthroughs and encouraging continued incremental innovations is critical to boosting crop productivity and climate resilience as well as offering U.S. biotech companies future competitive advantage in a warming world.

- **Governments worldwide should reform GMO regulations.** There is no agricultural policy change that could be adopted with more positive impacts and fewer downsides than drastically reducing regulations applied to crops improved through biotechnology. Foods derived from crops or animals improved through biotechnology have been subjected to more extensive scrutiny than any other agricultural product in human history.[2] Humans and livestock have consumed billions upon billions of meals derived wholly or in part from these improved agricultural varieties for nearly two decades, which have sustained a strong record of safety for humans and the environment.[3] Yet these innovative products, which are developed and brought to market with precise, predictable and safe techniques, are subjected to regulatory obstacles that dwarf those faced by older products and obsolete technologies, some with genuinely problematic legacies.

  Authoritative bodies have repeatedly examined these issues and concluded that the regulatory burdens on advanced biotechnology are not justified by science, data, or experience. These misunderstandings must be challenged, and scientific evidence must be restored to its primacy as the basis for making regulatory decisions about food safety.[4]

- **Create or strengthen institutions to serve as Centers of Innovation Excellence.** Feeding the planet requires a wide array of productive agricultural systems. Climate change is impacting these systems in a variety of ways. Worldwide cooperation to quickly advance and deploy innovative and adaptable agricultural technologies is therefore essential. Just as in the "Green Revolution," agricultural stakeholders around the world must work together to speed the development and deployment of next-generation crop technologies.

  The challenges facing agriculture over the coming decades are so great and complex that they must be met by organizations with commensurate strength and the ability to solve complex problems. Numerous existing organizations at the national and international level have some of the capabilities needed, but none have all that are required. All of these organizations need additional resources to bring their capabilities to the required level and to enable the global networking and cooperative, multidisciplinary approaches that are necessary. National agricultural research systems in a number of countries, colleges and universities, the private sector, and international consortia like the Consultative Group on International Agricultural Research (CGIAR) must all be strengthened and expanded to engage global innovation communities cooperatively and in a realistic way to face the challenges that loom.

GLOBAL FOOD CHALLENGES: RISING FOOD DEMAND AND CLIMATE CHANGE

Since Thomas Malthus' *An Essay on the Principle of Population*, policymakers have debated the challenges of feeding a growing and changing global population.[5] Climate change is the latest challenge, and potentially the most dangerous. According to global bodies such as the United Nations (UN) Food and Agriculture Organization (FAO) and the World Bank, the goal of modern day agriculture policy is to produce a global state of food security in which:[6]

- Food is widely available to all people whether by production or trade.
- Food supply is stable and resilient to system shocks, whether natural (e.g. weather) or man-made (e.g. war).
- Individuals are able to access adequate economic resources to acquire quantities of food sufficient to meet their nutritional needs.
- Food quality is high enough that consumption is safe.

This is already a great challenge. According to Godrey et al, it requires that we "match the rapidly changing demand for food from a larger and more affluent population to its supply; do so in ways that are environmentally and socially sustainable; and ensure that the world's poorest people are no longer hungry."[7] But global climate change is set to further destabilize the international food security situation, demanding new policy frameworks that directly address all aspects of the problem.

Adequately Feeding a Growing Planet

As illustrated in Figure 1, per capita GDP—a useful proxy for per capita food demand[8]—has increased from $2,232 in 1900 to $10,037 today (both 2012 dollars), while global population has increased from 1.6 billion in 1900 to 7.2 billion in 2011.[9] Together, these trends have driven continuous growth in global food demand.[10] In response, the world's food supply has tripled from an annual cereal crop of 877 million tons in 1961 to 2.4 billion tons today.[11] This base of staple crops feeds both humans and animals and is estimated to account for two-thirds of all human caloric supply and 50 percent of all cultivated cropland.[12]

Even more food supply growth is needed in the coming decades. The UN's most recent projection estimates that global population will grow from roughly 7 billion today to 9.3 billion people by 2050 and 10.1 billion by 2100.[13] According to most mainstream economic forecasts, global wealth will also follow a consistent upward trajectory. HSBC estimates that global GDP will triple in real terms by 2050, far outpacing population growth rates.[14]

It is historically recognized that population and economic growth drives increases in food demand. One recent study projected that global demand for crop calories will increase approximately 100 percent by 2050, and that demand for protein will grow by 110 percent.[15] Another recent review published in *Science* estimates that the world will need 70 percent to 100 percent more food by 2050 to meet global demand.[16] FAO estimated that overall global food production must increase by at least 70 percent by 2050, and almost

In simple terms, a serious effort to both meet the nutritional challenge posed by population growth and combat existing food supply deficits necessitates at least a doubling of the global food supply by 2050.

double in developing countries.[17] While the exact growth in food demand is uncertain, it's clear that the world needs to roughly double its present level of food production to keep up with population and economic growth. This implies an increase in cereal production from 2.2 billion tons in 2010 to 4.5 billion tons by 2050.[18]

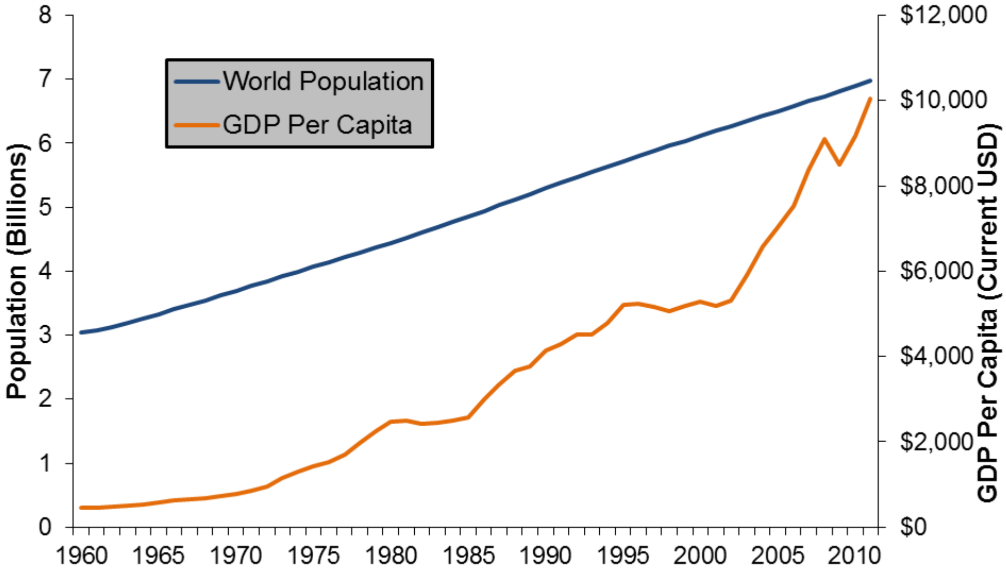

Figure 1: Global population and GDP per capita in current U.S. dollars; 1960-2011[19]

Compounding the difficulty of ensuring global food security is the reality that the global agricultural system already fails to provide adequate nutrition to the global population. According to the latest FAO figures, 870 million people currently do not have enough food to eat, and 98 percent of them live in developing countries.[20] If we aspire not only to meet the demands of population and economic growth, but also to improve human welfare and prosperity by alleviating present and future malnutrition, we will likely need to produce even more food than most agricultural assessments predict. In simple terms, a serious effort to both meet the nutritional challenge posed by population growth and combat existing food supply deficits necessitates at least a doubling of the global food supply by 2050.

Building Resilience to Climate Change

Feeding a growing planet is itself a monumental task. But as a recent Department of Agriculture (USDA) report demonstrates clearly, over the next several decades climate change will compound this challenge by increasing the volatility and severity of extreme environmental conditions.[21] Climate change directly impacts agriculture in two broad ways: (1) by rendering local environmental conditions less conducive to crop growth (e.g., by shifting temperature or precipitation patterns), and (2) by increasing the frequency and severity of extreme weather events such as storms, droughts and floods.[22] Already, agricultural production is influenced strongly by variations in weather conditions, from unexpected late-season frosts to the natural El Nino Southern Oscillation (ENSO), which is responsible for 15 to 35 percent of historic global crop yield variation.[23] Without a doubt, the state of the global climate and its local and regional impacts have vast implications for countries, regions, and farmers worldwide. As increasing concentrations of greenhouse gases in the atmosphere alter global climate patterns, the local impacts will become more variable and in many cases more severe, limiting agricultural yields, crop quality, and the effectiveness of crop planning.[24]

Long-Term Impacts of Climate Change on Agriculture

Studies on climate change and agriculture have focused mainly on how specific climate change impacts will affect agricultural production over time.[25] The scientific literature points to at least three different mechanisms through which these impacts will be felt.

The combination of elevated atmospheric moisture and higher average surface temperatures alters precipitation patterns, decreasing predictability for the 60 percent of the world's food production that comes from rain-fed agriculture.

First, higher concentrations of atmospheric greenhouse gases increase average global surface temperatures. Since the Industrial Revolution, escalating carbon emissions have warmed the earth's surface by an average of 0.8°C. Under the current global CO_2 emissions trajectory, significant additional warming is likely by the end of the century.[26] This warming will gradually increase surface temperatures during growing seasons across the planet, with variable impacts depending on latitude and terrain. Assuming adequate water, crop productivity is generally expected to expand in mid- to high-latitude northern regions, some of which are expected to become more suitable for a wider range of crops.[27] In many other regions, however, higher average surface temperatures will exceed crops' optimal temperature ranges, decreasing yields by reducing individual plant size, the number of grains produced per plant, and the overall quality of food crops.[28] Higher average surface temperatures will also increase levels of evaporation and transpiration, creating a greater need for irrigation and placing additional pressure on already stressed water resources. Regions already facing water shortages are likely to see marked increases in drought conditions and consequent declines in food production.

Second, higher concentrations of greenhouse gases increase the amount of water vapor in the atmosphere and alter global precipitation patterns.[29] By itself, higher humidity might lead to more rain for crops, improving crop productivity and decreasing the need for irrigation. But the combination of elevated atmospheric moisture and higher average surface temperatures alters precipitation patterns, decreasing predictability for the 60 percent of the world's food production that comes from rain-fed agriculture.[30]

Though a clear picture of the expected severity and geographic extent of climate-driven changes in precipitation remains imprecise, it is clear that dramatic shifts will occur.[31] One analysis of precipitation patterns in China found that Northeast China has already become much drier, warmer, and less hospitable to crop growth while Southeast China has become much more agriculturally productive.[32] Another recent study estimates that rising global average temperatures and changing rainfall patterns could increase the need for crop irrigation up to 20 percent worldwide, dramatically escalating already significant pressure on global water resources.[33]

Third, higher concentrations of greenhouse gases will lead to conditions that exacerbate the spread of disease and the frequency and severity of insect outbreaks that damage and destroy crops. Climate influences every stage of the life cycles of pathogens and pests that cause disease, and a large and growing body of scientific literature finds that increased temperatures, changes in precipitation patterns, and higher concentrations of CO_2 could expand the optimal conditions for many crop diseases, increasing the range, frequency, and severity of future epidemics and infestations.[34] Insect pest and pathogen life cycles will accelerate in direct proportion to the degree of warming, commensurately exacerbating their consumption and reproductive rates and amplifying their impacts on plants and livestock.[35] Already, changing rainfall patterns in Sub-Saharan Africa are shifting the migratory patterns of the desert locust, with devastating consequences for local crops.[36] Additionally, several crops have shown changes in susceptibility to disease under higher temperatures, including back shank in tobacco, broomrape in sunflower, and brown rust in wheat.[37] Scientists are also observing that milder winters and higher nighttime temperatures enable pests and diseases to survive winter at a higher rate, increasing the severity of pest and disease infestations during subsequent growing seasons.[38]

Taken together, climate variability and extreme weather events are likely to obviate any benefits that might otherwise result from modest increases in temperature, CO_2, and precipitation.

Impact of Extreme Weather on Agriculture

Even more acute climate change impacts will result from rapid swings in weather conditions and more frequent extreme weather events.[39] According to IPCC projections, higher concentrations of atmospheric greenhouse gases will contribute to increases in frequency, intensity, extent, and duration of extreme weather events.[40] Compared with changes in average climate conditions over time, these events are of greater immediate concern to agricultural producers because they deliver potentially disastrous near-term impacts on a year-to-year and season-to-season basis.

More numerous and severe droughts would strain irrigation and water resources significantly, while increased, extreme precipitation and flooding events could result in crop destruction, delayed crop planting or harvesting, and higher plant disease incidence.[41] Even a modest shift in the amount or timing of precipitation during the growing season, such as that caused by an atypically strong or long heat wave, can lower crop production by as much as 10 percent.[42] For crops such as maize and fruit, higher daytime and nighttime temperatures and extended heat waves during summer growing seasons can accelerate ripening by 10 to 20 days, leading to reduced yields and poorer harvest quality.[43] Extreme temperatures and heat waves can also cause sterility in some grains, depressing crop production.[44] Moreover, severe dust storms, which can accompany extended drought, significantly impact crop productivity by eroding fertile soil and uprooting or smothering young plants.[45]

Taken together, climate variability and extreme weather events are likely to obviate any benefits that might otherwise result from modest increases in temperature, CO_2, and precipitation. On the contrary, they are most likely to impose significant new constraints on global agriculture, adding to the difficulty of expanding agricultural production to meet increasing demand.[46] The combination of higher average surface temperatures and more variable and extreme weather could wreak havoc on all facets of agricultural production and accelerate global food shortages.

WHAT IS NEEDED TO ADDRESS GLOBAL AGRICULTURAL CHALLENGES?

There are two practical ways to increase agricultural output: expand cultivated land area or increase yields on existing lands. The prospects for the former are limited. Though there is some scope for expanding agricultural land area, doing so would involve either using land that is only marginally productive for agriculture or using wild lands that provide ecosystem services of global significance.[47] And even if all such land could be converted to agriculture without destroying vital ecosystem services, there is still nowhere near enough cultivable land to double current agricultural acreage at present yield rates.[48] It is therefore essential to increase yields on existing lands, regardless of whether cultivated land area expands.

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The World Needs More Productive Crops

The world needs to more than double global food supply to meet growing food demand by 2050. Unfortunately, the current annual yield growth rate is not keeping pace with what is needed to feed the planet in a warming world. According to recent projections by Piesse and Thirtle, increasing food production 70 percent by 2050—not even the 100 percent or more that is absolutely necessary—requires an annual yield growth rate of 1.34 percent.[49] This isn't historically impossible; annual yield increases once averaged over 2 percent for several crops, but today they average half that or less, at exactly the time when we need yields to increase faster, not slower (Figure 2). Returning to historically high growth rates of 2 percent will require significant efforts and agricultural change.

The most successful methods for improving crop yields are through improved agronomic practices and seed genetics. Advances in both of these areas were at the heart of the 20th century Green Revolution, and numerous efforts are underway to extend the use of best available technologies to farmers worldwide. Existing precision irrigation techniques, fertilizer applications, and pest and disease control measures can all be very effective in enhancing crop productivity, and continued diffusion of existing technologies is vitally important.[50]

Figure 2: Annual yield growth rates of key US commodities, 1950-1989 vs. post-1990[51]

But while these advanced technologies and practices hold significant potential in developing countries where needs are greatest, they cannot deliver enough productivity enhancement to meet the anticipated need. In addition, significant productivity increases will be required in present agricultural surplus countries as well, where the easiest biotechnological improvements have already been achieved across most major crops.[52]

If we hope to expand global crop yields as the means to address projected growth in food demand, we will need to develop and employ more efficient, productive next-generation biotechnologies.

One example of the kind of innovation we need more of is TALENs, or Transcription Activator-Like Effector Nucleases. TALENs are a type of synthetic restriction enzyme created by fusing a molecule that cuts DNA with another molecule that recognizes a specific sequence as the location to make the appropriate cut.[53] This delivers a powerful and rapid breakthrough that could allow for an almost infinite variety of customized, precise DNA manipulations (e.g., insertions, deletions, and rearrangements) in almost any organism.[54]

TALENs, in concert with modern computer algorithms, make it feasible for the first time to work with new traits in short time frames (years rather than decades or centuries). But in order to identify and disentangle the impacts of one gene from hundreds of others, we need different forms (alleles) of each of these genes. In the past, researchers have had to wait for such alternative forms to appear as a result of the random natural processes of mutation, a long-term and unpredictable process. Since the discovery of ionizing radiation and chemical mutagenesis we have been able to speed this process with mutations produced in the laboratory, but this has remained essentially an inefficient, random and unpredictable process.

The fast and precise process that TALENs provide could be an absolute game changer. It is now possible to produce a complete series of alternate genetic forms (mutant alleles) to help decipher and understand complex physiological pathways on a timescale shorter than the lifetime of the researcher. Though the challenges remain daunting and the work load enormous, this research area has now shifted from “essentially impossible” to “onerous, but eminently doable” because of aggressive investment and research effort.

This is important for a number of reasons. Many of the traits we need to improve in crops and livestock to increase yields and resilience to the stresses exacerbated by climate change are ‘polygenic,’ meaning they are controlled by more than one gene. Some of the most important traits, like drought tolerance, are impacted by hundreds of genes working together in complex and poorly understood ways. TALENs provide a breakthrough research pathway for unlocking these traits and building more resilient crops.

The World Needs Climate Resilient Crops

A farmer faces many challenges from seed to harvest, and then from harvest to market. The most critical challenges, which together make up the greatest constraints on production, are three-fold: competition with weeds for nutrients and moisture, pre-harvest losses due to pests (e.g., plant diseases and herbivorous insects), and inadequate water. All of these challenges are exacerbated by global climate change.

Resilience to Weeds and Pests

Modern approaches to plant improvement have yielded highly effective tools to reduce losses caused by weeds and insects in a handful of major crops (e.g., soybeans, corn, and cotton). Using recombinant DNA techniques, researchers have improved these crops by installing genes encoding the structures of specific proteins that serve useful, crop-preserving functions. For crops with improved weed control, for example, the newly imparted proteins break down chemical herbicides that kill weeds, thus protecting the crop against the herbicides that would kill them too but for the presence of the protein.[55] By reducing competition from weeds, this technology increases the soil resources that the crop can convert to food products. It not only increases crop yields, but also enables shifts to improved agronomic practices (e.g., no-till agriculture) that deliver further economic, environmental, and social benefits.[56]

More than doubling global agricultural production by 2050 cannot mean doubling water use for agriculture—there simply isn't enough fresh water available in many of the places it will be most needed.

Similar techniques have been used successfully to improve pest resistance in crop plants. In any particular crop, scientists can control disease by inserting a gene encoding for a specific protein that conveys protection. This has been achieved with a papaya strain genetically modified to resist papaya ringspot virus, a technological development that has helped rescue Hawaiian papaya production.[57] Other pests can be controlled by inserting into plants a gene encoding a protein derived from a common soil bacterium, *Bacillus thuringiensis* (Bt). This protein is benign to non-target species, but certain insect pests metabolize this protein into a form that is lethal to them.

Over time, the effectiveness of these protections will erode with greater use, as pests and diseases adapt and become resistant in the same way bacteria become resistant to antibiotics after extensive exposure, and some have complained that to use biotechnology in this way merely substitutes a "gene treadmill for a chemical treadmill."[58] But given the vast, untapped reservoirs of genetic variation among living organisms, this represents an advantage and dramatic improvement over the status quo ante. Continued use of genetic approaches is expected to produce similar solutions in the future, particularly when coupled with improvements in agronomic practices such as resistance management.[59] Accelerating these innovations and their deployment is critical, as climate change compounds and expands weed, pest, and disease issues worldwide.

Resilience to Changing Water Conditions

The challenge is different, and much more difficult, in the case of providing crops with adequate water. Of the fresh water used by humans, some 2,700 cubic kilometers (70 percent of the total) is consumed by agriculture each year (Figure 3).[60] At present, it takes roughly 3,000 liters of water to meet the daily food requirements necessary to sustain one person.[61] More than doubling global agricultural production by 2050 cannot mean doubling water use for agriculture—there simply isn't enough fresh water available in many of the places it will be most needed. According to the International Water Management Institute, "Without further improvements in water productivity or major shifts in production patterns, the amount of water consumed by evapotranspiration in agriculture will increase by 70%-90% by 2050."[62] Already, drought-prone regions in North Africa, North China, India, North America, and elsewhere are dealing with rapidly declining groundwater stocks. Clearly, improvements in water-use efficiency (WUE) are essential.

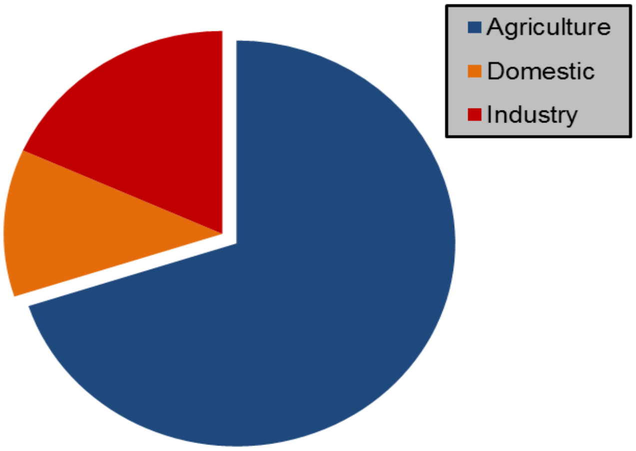

Figure 3: Global annual freshwater withdrawals, 2011[63]

Each of the several physiological systems with which a plant manages its water use is a multi-step process, and each is mediated by one or several enzymes under genetic control. This means there are many genes involved in the way a plant manages water, by some estimates more than 300.

Crop WUE can be increased in two ways: by reducing the amount of water a plant transpires, or by increasing the amount of plant dry-matter that results from the consumption of a unit of transpired water. The former is difficult to accomplish by any means other than closing a plant's stoma, the pores through which water evaporates to create the differential water pressure that drives most plant metabolic activity. When a plant closes its stoma and ceases transpiration, photosynthesis is shut down or dramatically reduced. For this reason, many scientists argue that the most promising way to increase WUE is to increase the plant dry matter produced per unit of water consumed.[64]

The amount of dry matter produced per unit of water consumed is determined by complex, multivariate interactions within plants. Plants deal with water stress (i.e., drought or superabundance) in many ways. Some increase root proliferation to extract more water from the soil, while others reduce leaf surface area to limit transpiration. Every aspect of the way plants absorb water, move it from one internal location to another, and eventually release it back into the atmosphere, has led to plant adaptations that increase water use efficiency. Each of the several physiological systems with which a plant manages its water use is a multi-step process, and each is mediated by one or several enzymes under genetic control. This means there are many genes involved in the way a plant manages water, by some estimates more than 300.[65]

To date, the commercial successes of biotech crops have involved relatively simple traits under the control of just one or two genes that exert simple, direct effects. There are no genes involved in plant water use efficiency that would make the targeted trait respond with comparably large impact to such simple transgenic approaches. Improving WUE requires managing hundreds of independent variables and their interactions, rather than transplanting a single gene of major effect.

Currently, several approaches hold potential. New, widely available genomic technology has led to an explosion in research focused on genes and gene expression that could impact WUE. This approach holds great promise, but mapping the most direct path for crops to use less water and produce higher yields is an extraordinarily complex problem, much more so than conferring herbicide tolerance or pest resistance. In order to maximize the chances of succeeding in this, all possible paths to a solution will need to be pursued, genetic and otherwise.

At this point there are some reasons for optimism. Plant breeders have gained powerful new capabilities through the recent development of marker-assisted selection (the use of biological, genetic, and molecular indicators to locate hard-to-quantify genetic traits), as well as high-performance computing and data analysis techniques to track the enormous numbers of different markings and genes.[66] It may in fact become feasible to leverage these advances to accelerate the development of plants that both produce significantly higher yields and consume less water than their predecessors. For example, Monsanto is preparing to bring to market a new corn crop varietal that it hopes can grow with 30 percent less water.[67]

This is just one example, but it illuminates what may be the most important truth about the transformations needed in our system for producing agricultural innovations: previously used technological solutions will not be sufficient or feasible to produce the food supply the world needs. We require nimble, adaptive research and development that applies coordinated, multidisciplinary approaches to quickly solve complex problems and further the technological breakthroughs we have already achieved.

THE CURRENT APPROACH TO AGRICULTURAL INNOVATION POLICY IS BROKEN

The fruits of our past and present agricultural research system have been remarkable.[68] However, the dramatic productivity increases in major commodity crops during the 20th century resulting from the Green Revolution began to taper off in the 1980s.[69] The Green Revolution's successes were largely the result of increasing yields through genetic modification by age-old breeding techniques to change simple traits controlled by one or a few genes. While similar approaches can still be used to benefit minor crops, future yield increases and climate resilience will have to come from new techniques and technologies that can be used to improve more complex traits controlled by many genes, as in the example of water use efficiency. Unfortunately, the global agricultural innovation system comprised of universities, government institutions, nonprofit organizations, and private industry is currently ill-equipped to produce the advanced innovations necessary.

Policymakers Assume Agricultural Innovation Will Magically Appear

Agriculture and earth systems analysts rely on the Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios (SRES) to provide plausible future scenarios that can be used to anticipate the potential impacts of climate change and compare the outcomes of different policy approaches. A typical agricultural assessment models the future effects of climate change on crop productivity (e.g., temperature, soil conditions, *Between 1951 and 1969, public agricultural R&D spending in the United States grew by an average of 4.2 percent per year. From 1970 to 1989, growth slowed to an average of 1.6 percent per year. Between 1990 and the present, growth has slowed even further to an anemic 1 percent per year.*

crop yields, crop quality, and precipitation) using each of the scenarios presented in SRES. Though the SRES scenarios are carefully constructed in view of the best available scientific evidence, they make overly optimistic assumptions about "baseline" agricultural innovation that obscure the scale of the agricultural production challenge and the importance of a concerted, innovation-centric response.

These unrealistic assumptions permeate the climate and agriculture literature. For example, Tubiello and Fischer use SRES scenarios to conclude that in the absence of climate change and assuming business-as-usual policy, global cereal production would double by 2080 and the number of people at risk of hunger would decrease by almost 33 percent, even accounting for the growing population.[70] Similarly, the 2007 IPCC report on Impacts, Adaptation and Vulnerability assumes that global crop production will increase 80 percent by 2050 absent additional policy. It further asserts that the number of undernourished people in the world will fall from 800 million to 300 million as a result of baseline economic growth and innovation.[71] And Ewert et al. find that European crop productivity would increase 25 to 163 percent depending on the SRES scenario due to "new technology development."[72]

The problem with these assumptions is that they posit significant future agricultural system improvements without specifying where these improvements will come from.[73] In assuming that such improvements will appear absent policy changes, these analyses suppress a critical discussion of how the world will increase crop productivity and food supply.[74] Though they acknowledge that a significant technological gap exists between our current agricultural systems and the more productive and resilient systems we need, they fail to understand that the considerable technological innovation and growth needed to create this improved system will require significant, concerted effort and policy change. The notion that sufficient innovation will occur on its own is naïve, complacent, and contradicted by a long history of breakthrough technologies, such as the Internet, hydraulic fracturing, GPS, and microchips. Ultimately, creating the necessary improvements in agricultural production systems will require strategic, evidence-based policy and investment decisions.

Governments Under-Invest in Agricultural Innovation

Over the last one hundred years, a variety of support systems for agricultural research have evolved at the national and international level. Most nations directly dependent on agriculture have established some type of national agricultural research system (NARS). Historically, these institutions have managed a significant percentage of total global agricultural research and development (R&D), driven by domestic economic imperatives and sustained public investment. Those from Australia[75], the Netherlands[76], the United Kingdom[77], and the United States[78] have risen to particular international prominence, wielding influence and exerting impacts far beyond their own borders.

In addition, a number of international bodies have been active in conducting agricultural research and coordinating efforts to support agricultural growth in developing nations as part of larger economic development agendas, including the Consultative Group for International Agricultural Research (CGIAR), the United Nations Food and Agriculture Organization (FAO), and the United Nations Development Program (UNDP), among others.[79] Private philanthropic groups have also played significant roles. For example, the Rockefeller Foundation was a leader during the Green Revolution, and the Gates Foundation's agricultural work has become increasingly prominent in recent years.

While the number of institutions supporting agriculture research has expanded over time, public investments in agricultural innovation have not been sufficient to maintain the levels of annual growth in crop yields necessary to achieve the growth in total crop production needed by 2050. Annual yield growth has collapsed across most key food commodities, both globally and in the United States (refer to Figure 2 for an illustrative example).

By 2009, agriculture R&D fell to a historically low 0.035 percent share of the United States economy, a level far below that which is necessary to boost annual yield increases from their current low levels.

These declines in yield growth rates can result from a variety of non-policy factors, including bad weather, exhaustion of natural resource bases, and macroeconomic forces. But yield growth rates are also influenced strongly by public policies, including changes in regulatory conditions and, crucially, changes in public spending on agricultural R&D. Though public spending on agricultural R&D has remained on an upward trajectory since the Green Revolution, the rate of growth has slowed considerably.

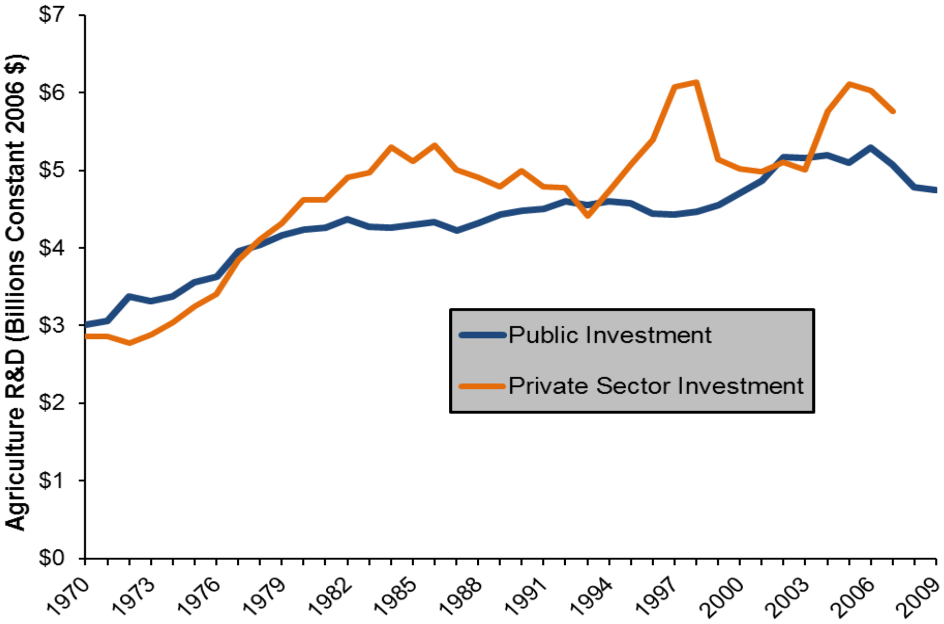

Figure 4: Agricultural R&D funding in the public and private sectors, 1970–2009. Private sector investment data is only available through 2007[80]

Between 1951 and 1969, public agricultural R&D spending in the United States grew by an average of 4.2 percent per year. From 1970 to 1989, growth slowed to an average of 1.6 percent per year. Between 1990 and the present, growth has slowed even further to an anemic 1 percent per year.[81] In 2000, global public investment in agricultural R&D totaled $20.30 billion (2010 dollars). Of this, $4.6 billion (19 percent) came from the U.S. federal government.[82] This represents roughly half of the total U.S. investment in agricultural R&D, the balance of which came from the private sector (Figure 4). As previously mentioned, these public investments have not grown commensurately with the United

States economy; nor are they nearly enough to support the levels of annual yield growth required to meet the projected food demands of 2050 and beyond.

Figure 5 illustrates the steady decline in public agricultural R&D investments as a share of GDP since the early 1980s, as research dollars failed to keep pace with economic growth. In fact, the decline in agricultural R&D outpaces the broader decline relative to GDP in total public funding for all R&D. Through much of the 1990s, a decade marked by economy-wide deterioration in public investments in innovation, agriculture R&D fared well relative to other sectors. Yet, as total R&D investments as a share of GDP reversed course and began increasing again during much of the 2000s, agriculture R&D continued to decline. By 2009, agriculture R&D fell to a historically low 0.035 percent share of the United States economy, a level far below that which is necessary to boost annual yield increases from their current low levels.

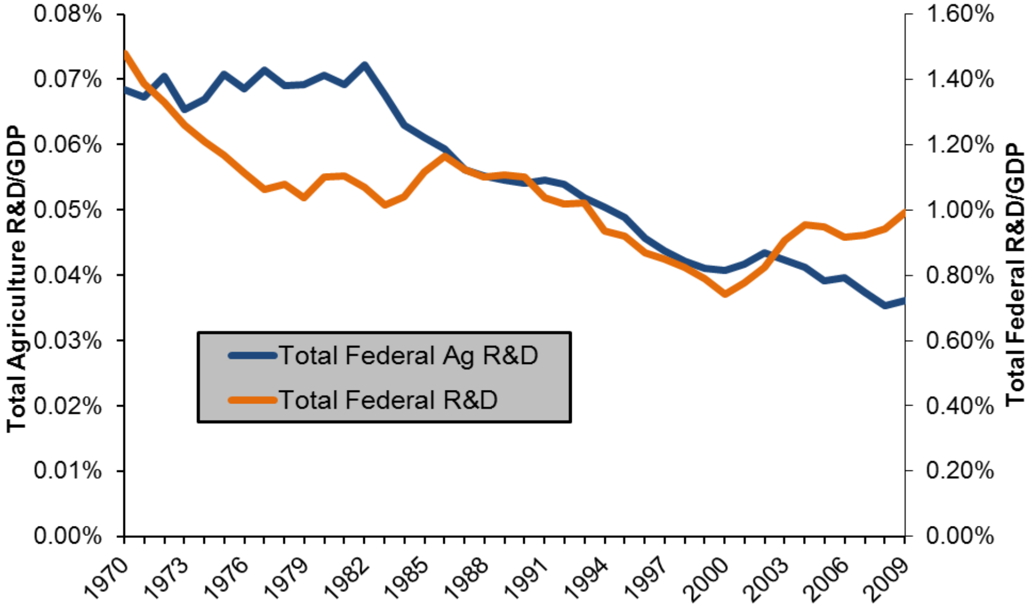

Figure 5: Comparison of public investments in agriculture R&D (blue line) as a share of GDP and total public investments in all R&D (orange line) as a share of GDP, 1970-2009[83]

Moreover, there have been important changes in the administrative and geographic qualities of this research funding. Up until the 1930s, between 40 percent and 60 percent of agricultural R&D funding was administered at the federal level by the USDA, targeted at national-level research priorities in basic crop science and early-stage technological development.[84] The balance was administered on the state level through State Agricultural Experiment Stations (SAESs), research hubs set up by land-grant universities to conduct research into the specific challenges facing individual states and regions. By the mid-1970s, SAESs were receiving roughly 65 percent of public funding, and federal research efforts were receiving the remainder.[85] Since then, the federally administered share of public agricultural R&D investment has remained below 35 percent, at times plunging below 30 percent (though continuing to grow in gross terms).[86]

Though little research has been done on the impact of this transformation on the innovative capacity of the U.S. agricultural R&D system, it stands to reason that shifting investment away from federal research and toward state SAESs would exert qualitative changes on the practices and priorities of the agricultural R&D system. Whereas federally administered funding tends to focus on basic science with broad applicability, state-level research is tailored more toward specific challenges facing individual states and regions. Consequently, when funding shifted away from federal bodies and toward SAESs, it privileged research focused on shorter-term, more localized issues rather than fundamental issues in basic areas of plant science.

The amount of additional land needed to maintain global production at 2010 levels would require an area roughly the size of New York State or equivalent to 8.6 percent of the arable land in the United States.

Industry Investments in Research are not Sufficient

It's clear that the federal government has significantly scaled back support for agriculture R&D at a time when more crop innovation is needed. Increased private sector funding has helped pick up a fraction of the slack, leading to the commercialization of higher yielding varieties of a handful of major crops.[87] But the shift in the global agriculture innovation ecosystem away from a public and nonprofit-based system, and the corresponding slowdown in the growth of public research funding, have serious consequences.

The major private sector players dominating the agriculture innovation ecosystem are large multinational companies that have been active historically in agricultural chemicals. These are sometimes referred to as "the big six": Monsanto, BASF, Bayer CropScience, Dow AgroSciences, DuPont, and Syngenta. Although a host of smaller companies have produced valuable innovations, these six companies have produced the most commercial activity and economic impacts—through products derived from technologies they themselves have developed or applied, or by acquiring smaller companies in possession of innovative intellectual property (e.g., Monsanto's purchase of Calgene, or DuPont's of Pioneer Hi-Bred).

Monsanto, the first major company to move into biotechnology, has a broader and more diverse product portfolio than its competitors, who are now working rapidly to catch up. Figure 6 shows the top 10 institutions that received permits to release new bio-engineered crops and products into the market since 1985, a metric used for evaluating how active individual institutions are in the agriculture innovation ecosystem. The U.S. Department of Agriculture regulates the introduction of most crops improved through biotechnology and requires developers to secure permits for field trials of these new varieties before they enter the market.

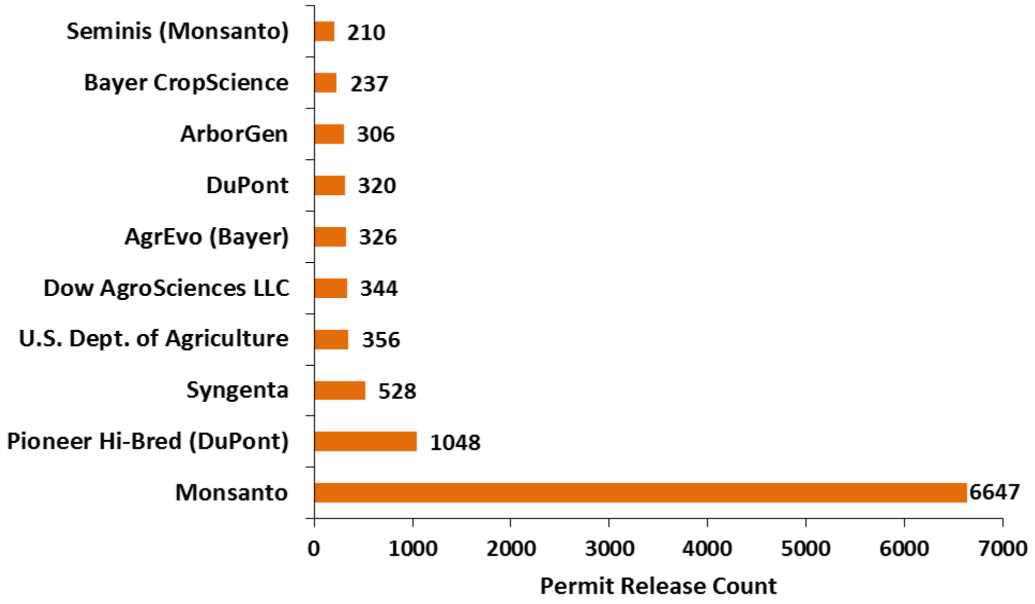

Figure 6: Top 10 permit and notifications for introduction of genetically modified products into the market by institution since 1985. Institution names in parenthesis represent those that purchased the original permit or notification holder.

More important from the perspective of ensuring food security, these developments have boosted crop productivity. One calculation estimates that in the absence of crop biotechnology, maintaining global production levels at 2010 levels going forward would require plantings of 12.6 million additional acres of soybeans, 13.9 million more acres of corn, 7.4 million additional acres of cotton and 0.87 million more acres of canola.[88] Put in perspective, the amount of additional land needed to grow these crops would be roughly the size of New York State or equivalent to 8.6 percent of the arable land in the United States.[89]

However, as research investments have shifted from public-funded projects to industry labs, so too has the character and focus of that research. Industry research is aimed, for the most part, not at basic or fundamental science, but rather at adding recoverable value to seeds by imparting to them the ability to overcome specific problems like disease, pests, or weeds. Industry research has been focused to date largely on major crop species whose seeds are sold in sufficient quantity to provide industry the opportunity to recoup significant R&D costs through sales. Figure 7 highlights the top 10 crop types that received permits to release new bio-engineered crops and products into the market since 1985.[90] The most productive industry investments in innovation have been limited to just four crops: corn, soybeans, cotton and potatoes. Two of the world's most important food crops, wheat and rice, have received much less emphasis. While improved versions of wheat and rice crops are expected soon, particularly in China, these and other important crops still lag far behind the potential enabled by recent technological advances. This has reduced opportunities to improve hundreds of crop species used in agriculture worldwide, even though preliminary research suggests high promise and numerous opportunities.[91]

This is because, amidst the dearth of public sector funding, they have not attracted the support of next-generation private sector product developers, primarily because of regulatory barriers and financially risky long research time horizons.[92]

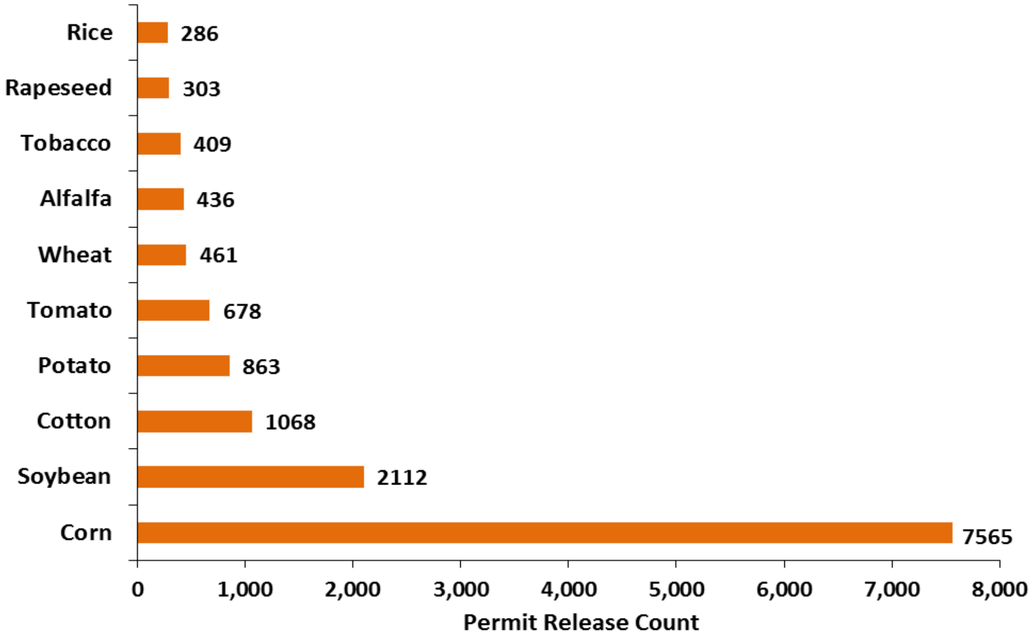

Figure 7: Top 10 permit and notifications for introduction of genetically modified products into the market by crop type since 1985

In fact, the best available science shows agricultural biotechnology is safe and productive, with positive economic and environmental impacts.

Next-generation agriculture research has also suffered from the slowing of public funding for early-stage agricultural R&D. Many fundamental areas of research such as plant breeding, plant pathology, and entomology have lost ground dramatically as funding has shifted toward research aimed at commercializing near-term products. Traditionally, private sector companies have not invested significantly in these areas, as they are high in risk and it is not always clear how basic scientific research will lead to commercially viable technology, or on what timescale. Consequently, many new crop varieties coming from the private sector are delivering only incremental gains, not the breakthrough leaps in crop productivity and climate resilience the world urgently needs.

Today's Global Agricultural Regulatory Regime Stifles Innovation

Early on, agricultural applications of biotechnology became a battlefront in the culture wars over science, technology, and society. Opponents of biotechnology emerged quickly, and described recombinant DNA applications in pejorative terms, claiming inordinate unknowns and apocalyptic potential.[93] Authoritative bodies found no basis for such claims, noting strong and essential similarities with known hazards already being managed in agriculture, such as the evolution of insecticide resistance in pests or weeds adapting to tolerate herbicides.[94] Nevertheless, a precautionary approach was taken, and regulatory oversight was put into place.[95] A vast body of experience has since accumulated.[96] No novel risks emerged,[97] and the overwhelming scientific opinion, reinforced by a vast body of research and experience, is that crops and foods improved through biotechnology are just as safe as other crops and foods, and sometimes safer.[98]

A cautious research, regulatory, and policymaking approach was appropriate during the dawn of modern biotechnology. Since then, researchers, regulators, and policymakers have accrued a vast body of experience in the United States and around the world. Humans and livestock have consumed billions of meals without a single case of harm attributable to the biotechnology-derived nature of the material consumed. Nevertheless, a handful of advocacy organizations have continued to oppose the technology, often conflating it with other issues about which they are concerned but which are, in fact, unrelated to—or even ameliorated by—biotechnology. Such fears include the potential for negative impacts on biodiversity[99] or the potential for increased toxins in foods.[100] In fact, the best available science shows agricultural biotechnology is safe and productive, with positive economic and environmental impacts.

Herbicide tolerant crops provide a telling example. Herbicides—chemicals that kill weeds—have been a huge and widely beneficial advance in agronomic practice. It has largely replaced backbreaking hand-weeding and plowing that is massively disruptive to soil microbial ecosystems. Instead, no-till methods of weed control bring numerous environmental, stewardship, and ergonomic benefits. Virtually all plants are tolerant to some herbicides (and susceptible to others) and herbicides have been used since long before the advent of biotechnology in agriculture. Crops that tolerate herbicides through random genetic mutations developed over hundreds of millions years—which by definition are imprecise, crude, clumsy, and difficult to predict—are essentially unregulated. Yet modern crop varieties made tolerant to herbicides through the most precise, predictable tools of modern biotechnology must clear numerous costly and time consuming regulatory hurdles in every major industrial nation even though they present no novel or unfamiliar risks, despite an unblemished safety record.

For instance, many experiments require prior approval from an institutional review board. Field trials almost always need permits from USDA, and often from EPA as well. Each USDA field trial permit requires submission of the Animal and Plant Health Inspection Service (APHIS) Form 2000 which requires detailed data (applications are routinely hundreds of pages long, sometimes thousands) to answer questions on important characteristics of the new crop variety and its antecedents.[101] Answering these questions requires tests and trials that take years and cost millions.[102] Growing biotech-improved varieties on a commercial scale demands several years of field trials, each requiring one or more permits, and then a major review in far greater depth by USDA before the new crop variety can be grown commercially.[103] Yet the very same phenotype (e.g., herbicide tolerance), produced through far less precise and less predictable methods of random mutagenesis coupled with classical hybridization, is subject to zero federal review and no regulatory approval. In many other countries, and in particular within the European Union, the process is even more difficult and costly to navigate. Faced with political interference rooted in special interest politics, many innovative companies have abandoned their efforts to develop new biotech-improved crop varieties or relocated to other countries.[104]

These regulatory policies add years and millions of dollars to the cost of developing next-generation crops, narrowing research focus to a handful of major commodity crops that can be grown at a large enough scale to allow the recovery of regulatory and R&D costs.[105]

According to the numerous authoritative scientific bodies that have examined these issues, these regulatory burdens are not justified by scientific evidence or experience.[106] While regulation to ensure the safety of new crop varieties is necessary, in a world facing burgeoning demands on agriculture from population growth, economic growth, and climate change, overregulation is an indulgence we can ill afford.

Given growing agricultural challenges related to climate change such as worsening droughts and the impacts of extreme weather, policymakers should go further and triple investments in agriculture R&D to $15 billion per year.

Despite this, many international advocacy groups continue to spread misinformation on the health and safety implications of biotechnology, reinforcing unnecessary regulations.[107] But increasingly, some environmentalists have reconsidered their opposition to biotechnology, and are now in favor of expanding its use. Mark Lynas, formerly one of the most strident opponents of genetically engineered crops and food, has recently apologized for his errors and joined the global scientific community in recognizing the enviable record of safety and delivered value that biotech innovations have amassed.[108] He concluded in a 2013 speech at the Oxford Farming Conference that "the environmental movement has done more harm with its opposition to genetic engineering than with any other thing we've been wrong about…We've starved people, hindered science, hurt the natural environment and denied our own practitioners a crucial tool."[109]

As Lynas has recently realized—and as the scientific community has known for some time—it is past time for governments to revisit policies that were adopted in the name of precaution, as they impede innovation and compel continuing reliance on technologies that are inadequate to meet the challenges we face.

POLICIES FOR CLIMATE RESILIENCE: STRENGTHENING THE AGRICULTURAL INNOVATION ECOSYSTEM

Past success in agricultural innovation does not guarantee future success, and old orthodoxies should not serve as barriers to future change. The agriculture innovation ecosystem requires significant reform if it is to continue to deliver past levels of productivity growth in the face of the unprecedented food demand and climate challenges of the 21st century. Specifically, three groups of reforms are needed as part of any climate adaptation or agriculture legislation: (1) increased global public investment in breakthrough agriculture R&D; (2) substantial changes to key parts of the enabling infrastructure, especially biotechnology safety regulations; and (3) creation or strengthening of the international collaborative research ecosystem to revive centers of excellence in innovation.

Increase Global Public Investments in Agricultural R&D

If we hope to meet the agricultural challenges posed by climate change, population growth, and the rise of a global middle class, the world needs myriad agriculture breakthroughs on par with those of the Green Revolution.[110] But as discussed above, public investments in agricultural innovation have not kept pace with the growth in global GDP, and private sector investments fail to advance the sorts of high risk, high reward research that hold the most promise for building a truly resilient and plentiful agricultural system. A top priority of national and international policymakers should be to reverse this trend by ensuring that the agricultural innovation ecosystem is funded, staffed, and supported on a scale commensurate to the challenges we face. In 2000, global agricultural R&D totaled $20.3 billion, split evenly between developed and developing countries. All countries and regions can contribute more. Even in the United States, which contributed 19 percent of R&D investment in 2000, there is much room for expansion. As a share of the country's total economy, public investments in agriculture peaked in the early 1980s at roughly 0.070 percent of GDP, double the share of investments today. At the very least, U.S. policymakers should double current investments in agricultural R&D, from roughly $5 billion to $10 billion per year, restoring it to its previous share of .070 percent of GDP. This would ensure that breakthrough innovations in next-generation biotechnology accelerate and expand further than the top three or four staple crops.

Arguably, given growing agricultural challenges related to climate change such as worsening droughts and the impacts of extreme weather, policymakers should go further and triple investments in agriculture R&D to $15 billion per year. This would provide scientists and engineers with the ability to rapidly and simultaneously pursue multiple pathways to climate resilient crops that the private sector is not willing to invest in aggressively.

In particular, the increased funds would strengthen flagship research programs at the USDA—the principle agency in charge of agriculture R&D—such as the National Institute of Food and Agriculture (NIFA) and the Agricultural Research Service (ARS). The ARS and NIFA are the major grant giving R&D programs within the USDA that invest across the agricultural innovation lifecycle—basic science through field trials—in a number of research disciplines, including biotechnology, pest management, and plant science. Substantially increasing the budgets of these programs would allow the USDA to offer more high risk, high reward competitive grants to universities, foundations, and industry in order to aggressively tackle the climate resilience issues outlined here.

Just as the United States should scale up its agricultural R&D investment, so too should other countries. The optimal level of investment will ultimately depend on a confluence of factors, including availability of skilled labor to conduct research, demand for research funding, and fiscal situations facing individual governments. However, it is likely that most governments, particularly in the developed world, have scope to increase their agricultural R&D funding and research capacity to soak up productively enhanced research funding.

Governments Worldwide Must Reform GMO Regulations on the Basis of Best Available Scientific Knowledge

Of all the policy changes that must be made to improve the efficiency of agricultural research, none will yield more rapid and less costly returns than regulatory reform. Regarding the types regulatory reforms needed to boost innovation and accelerate much needed breakthrough crops into market, a growing number of experts point to four principles that must be honored in any scientifically defensible regulation.[111] These principles are not new; indeed, they are rooted in a vast body of practical experience around the world, and are very similar to the rules codified under the World Trade

Organization SPS Agreement.[112] We present them below as principles for reform in the United States and abroad.

- The trigger for regulatory review should be the novelty of the introduced trait (regardless of how or when it was derived), and *not* the process used to introduce the trait;
- The severity of regulatory control should be directly related to the actual, relative risk associated with the novel characteristic (phenotype);
- Phenotypes with a history of safe use should be exempted from regulatory review regardless of the methods used to produce them;
- Regulators must recognize that gene flow is a natural phenomenon, one that is not intrinsically hazardous. The potential for gene flow via the movement of pollen is a natural phenomenon. Regulatory authorities must stop treating gene flow as if it were intrinsically hazardous (it is not), and shift their focus to appropriate risk management/mitigation in the rare cases where genes so disseminated could, in fact, present a genuine hazard.

In practice, this means existing international regulatory systems designed specifically for GMOs should be reviewed, and those triggered by the use of recombinant DNA techniques should be set aside in favor of regulations that focus on the characteristics of the crops and foods themselves (which are in fact the determinants of risk). All crops are genetically modified through one means or another and that fact conveys nothing informative about the level of hazards they may pose.

For example, biotechnology regulations at the three oversight agencies in the United States—the USDA, Food and Drug Administration (FDA), and Environmental Protection Agency (EPA), which are the primary regulators of plant, medical, and pesticide biotechnology respectively—should be reviewed. For instance, care should be taken to ensure that the Coordinated Framework for Regulation of Biotechnology[113]—the codified regulation of biotechnology in the United States—is properly interpreted and follows the principles outlined above.[114]

Such a review is not unprecedented and in fact would be a natural extension of reforms enacted in previous decades. For instance, in 1997, the USDA, FDA, and EPA simplified the APHIS oversight procedures for most GMOs to create a more efficient and open process.[115] Unfortunately, some of this simplification was reversed over time as regulatory agencies applied regulations to biotechnology differently in reaction to public concerns over GMO-based products. Such regulatory barriers are even more stringent elsewhere. Using these fundamental principles as a starting point, it’s time to reconnect biotech regulatory oversight with the best available science.

Create or Strengthen Institutions to Serve as Hubs for Agricultural Innovation

The research approaches used to boost crop productivity during the last century are vastly different than those needed to solve today's agricultural challenges.[116] The proven solutions of yesterday largely focused on using plant breeding to create improvements of traits controlled by only a few genes. These techniques are no longer sufficient. Today, the traits that need to be improved—drought tolerance and water use efficiency, tolerance to extremes of heat and cold, and so on—are controlled by multiple genes, sometimes a great many, each of small, inextricable effect.

What is important in influencing these traits is the dynamic interaction of all of these genes as part of a complex, multivariate system. As a result, these traits cannot be managed with the same approaches that were so fruitful in the last century, and research methods and techniques must change accordingly. In effect, today's research institutions must become vehicles for coordinating reticulated networks, using many different disciplines and tools to solve complex biotechnology problems.

Building climate resilient agriculture in addition to doubling crop productivity is one of the chief social, economic, and technological challenges of our time.

Fortunately, there are positive examples of next-generation agricultural research to use as models. For instance, Monsanto and the Gates Foundation have partnered to create a unique collaboration to address water and crop resource issues in Africa.[117] And the USDA's National Institute for Food & Agriculture (NIFA) has taken great strides in conducting multidisciplinary R&D in partnership with industry.[118] But instead of one-off research projects and programs, more dedicated, institutionalized collaboration is needed to move agriculture into the 21st century.

The advances that laid the foundation for the Green Revolution would not have occurred without consistent, multi-disciplinary research. Norman Borlaug, supported by the Rockefeller Foundation, founded the International Rice Research Institute (IRRI) in 1960 and the International Center for the Improvement of Maize and Wheat (ICIMW) in 1963 to advance the myriad crop improvements Borlaug and others had been working on since the 1940s. By 1971, these led to the establishment of a worldwide network of innovation hubs—the Consultative Group on International Agricultural Research (CGIAR)—which is today sponsored by the United Nations Food and Agriculture Organization (FAO), the International Fund for Agricultural Development (IFAD), the United Nations Development Programme (UNDP), and the World Bank, and supported by a network of more than 60 donors and members.[119] Its 15 research centers are distributed around the world, located in the regions where the problems on which they are focused are most acute.

But like agricultural research investment generally, the CGIAR network has been a victim of its own success. While hunger and famine have been reduced since its inception, funding for the CGIAR has also not kept pace with economic growth in member countries, leading to steady retrenchment and leaving many potential advances unfulfilled.[120]

What the world needs are next-generation versions of CGIAR. Broadly, policymakers have two options: (1) reform and increase funding for the existing CGIAR infrastructure to focus on next-generation transgenics for climate resilience and crop productivity, or (2) create and fund a network of Advanced Agricultural Innovation Hubs. In both cases, increased funding would be part of the tripling of public R&D funding discussed previously. A useful model for both options can be found in the United States Department of Energy's Innovation Hubs—a network of five multi-disciplinary institutions created to spur and help bring to market key breakthrough clean energy innovations.[121] This approach was modeled after past research institutions like those used during the Manhattan Project, the Lincoln Lab at MIT, and AT&T's Bell Labs. Each hub is tasked with supporting research and enabling multidisciplinary efforts aimed at solving a specific problem by bringing together universities, national laboratories, and industry. For example, a new Battery Innovation Hub was recently created to bring together the best research across sectors to create a new generation of battery technology that is a fraction of the cost of today's lithium batteries, but at least five times more energy dense. Similarly transformative innovation is needed in agricultural technology.

A good first step in creating Agricultural Innovation Hubs (or reforming the existing CGIAR) is for international policymakers to convene a series of working groups made up of leading academic, government, and industry stakeholders to distill what the major research and technology barriers are to climate resilient, productive crops. The goal of the working groups would be to produce a series of actionable research topics and questions that policymakers can build hubs around, so that public investment is directed at the highest priority research issues. In particular, four areas the international community should pay particular attention to are water use metabolism, pest/weed/disease control, methods for managing flowering time and maturation, and methods for reducing post-harvest losses. Each are critically important to boosting crop resiliency to climate change, and each could benefit from more advanced research and technology development.

CONCLUSION

The projected growth in human population means that in order to maintain the status quo, agriculture will have to produce more food over the next 40 years than the combined total of all food produced from the dawn of agriculture to the present day. Adding to this monumental task, climate change is increasing the severity and volatility of weather patterns and environmental constraints around the world. Increasing crop productivity isn't enough. Building climate resilient agriculture *in addition to* doubling crop productivity is one of the chief social, economic, and technological challenges of our time.

The task ahead is easier said than done. The global agricultural innovation ecosystem is currently ill-prepared to quickly and aggressively meet this challenge. The robust system that spurred the Green Revolution and saved billions of people from starvation is marred by underfunded research budgets, scientifically indefensible regulatory barriers, and a lack of vision for the kinds of next-generation innovations needed to continue feeding a growing world. Strengthening and rebuilding this ecosystem requires significant policy attention in the United States and abroad and the three policy recommendations described in this report aim to do just that. Let there be no mistake: the world needs not just a second Green Revolution to feed the planet; it needs the equivalent of many Green Revolutions to meet the demands of a growing, hungry population in a volatile, warming world.

ENDNOTES

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10. Tim Dyson, "World Food Trends and Prospects to 2025," *Proceedings of the National Academy of Sciences* 96 (1999): 5929-5936.
11. United Nations FAOSTAT database (productions: crops; accessed October 9, 2012), http://faostat.fao.org/site/567/default.aspx#ancor.
12. Dyson, "World food trends and prospects to 2025."
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17. United Nations Food and Agriculture Organization, "How to Feed the World in 2050."
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22. There are a number of ways to categorize climate impacts on agriculture. For example, Schmidhuber and Tubiello, “Global Food Security Under Climate Change,” categorizes impacts by the four characteristics of food security as well as by mean impacts compared to extreme weather impacts. Another example is in William Easterling et al., *Climate Change 2007: Impacts, Adaptation and Vulnerability* (London: Cambridge University Press, 2007); Chapter 5, “Food, Fibre and Forest Products: Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change,” categorizes impacts according to specific climate variables (e.g., precipitation, temperature, extreme weather, and CO2). While no method is more correct or incorrect than the other, the categorization method used for this report serves best to illustrate the inherent range and uncertainty of these impacts as described in the academic literature as it pertains to policymaking.
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