# Agricultural Innovation: The United States in a Changing Global Reality

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April 2013

Study commissioned by the
Global Agricultural Development Initiative
Catherine Bertini and Dan Glickman, Cochairs

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Printed in the United States of America.

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Philip Pardey joined the Department of Applied Economics at the University of Minnesota in early 2002 as professor of science and technology policy and directs the University of Minnesota's International Science and Technology Practice and Policy (InSTePP) center. Prior to that Philip was a senior research fellow at the International Food Policy Research Institute (IFPRI) in Washington, DC, (one of the 15 international research centers that form the Consultative Group on International Agricultural Research, or CGIAR), where he led the institute's Science and Technology Policy Program. He is a graduate of the University of Adelaide, Australia, and obtained a doctoral degree in agricultural and applied economics from the University of Minnesota in 1986. Before joining IFPRI in 1994 he was a senior research officer at the International Service for National Agricultural Research in The Hague, Netherlands.

His research deals with the finance and conduct of R&D globally, methods for assessing the economic impacts of research, and the economic and policy (especially intellectual property) aspects of genetic resources and the biosciences. He is a fellow of the American Agricultural Economic Association and a distinguished fellow and past president of the Australian Agricultural and Resource Economics Society.

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Jason Beddow is a fellow in the International Science and Technology Practice and Policy (InSTePP) center at the University of Minnesota, a visiting scientist with Australia's Commonwealth Scientific and Industrial Research Organization, and an affiliated scientist with the International Livestock Research Institute's Biosciences eastern and central Africa (BecA) hub. He has worked for the HarvestChoice project since 2006. His research focuses on understanding the spatial, biological, economic, and historical contexts of agricultural production, productivity, and food security, with the overriding goal of promoting development in international agriculture. Jason is a graduate of Texas Tech University, the Virginia Polytechnic Institute and State University, and the University of Minnesota, where he received his doctoral degree in applied economics in 2012.

# Foreword and Acknowledgments

In the next 40 years, the global agriculture and food system will be asked to increase production by 60 percent to ensure people have enough nutritious food to eat. It will have to do so in the face of significant challenges posed by rising temperatures, resource scarcity, and the increased frequency of extreme climatic events. Agricultural research is a necessary vehicle for equipping the agriculture and food sectors to overcome these challenges.

In response to these trends, The Chicago Council on Global Affairs supported this independent assessment of global trends in public and private agriculture research and development funding. The data and conclusions presented in this paper were developed solely by the authors. The paper explores the implications of the increasingly influential roles of global business, Brazil, China, and India in agricultural research and the limited national research capacity of developing countries. It concludes that to meet future challenges, the international system has to take a more comprehensive perspective on the entire world's innovative capacity—both public and private. The Consultative Group on International Agricultural Research plays a role in this global approach, but more needs to be done. The paper presents new measures of global spillover potentials to help guide research and development decisions in the United States and globally.

## Acknowledgments


The Chicago Council would first like to thank the report's authors Philip G. Pardey and Jason M. Beddow. Their great wealth of knowledge and insights, tireless data collection and analysis, and dedication to the issue of agricultural research have made this report one of the leading definitive assessments of the state of agriculture and food research globally available today.

The Chicago Council extends its appreciation to the cochairs of the Global Agricultural Development Initiative, Catherine Bertini and Dan Glickman, for supporting the commissioning of this paper and providing valuable insights through its development.

The Chicago Council and the authors acknowledge and thank Connie Chan-Kang and Steve Dehmer for sharing their yet largely unpublished work concerning the various research and development estimates. Michelle Hallaway provided significant support in the efforts that led to this report. Without implication, the authors are also grateful for the help with data and ideas received from Gary Alex, Julian Alston, Ali Bittinger, Denyse Faulkner, and Martin Van Weerdenburg. The data collection on which this report is based was partly supported by the University of Minnesota and the Bill & Melinda Gates Foundation by way of the HarvestChoice project.

Several members of The Chicago Council staff played key parts in bringing this report into fruition. Lisa Eakman, executive director, Global Agriculture and Food, provided leadership and guidance. Meagan Keefe and Maggie Klousia, assistant directors for Global Agriculture and Food, oversaw the day-to-day management of the editing and publication process. Catherine Hug and Duane Nelsen of the Chicago Creative Group provided editing and design support.

Finally, The Chicago Council would like to express its deep appreciation to DuPont; Quaker Oats Company, a division of PepsiCo; and the Bill & Melinda Gates Foundation for the generous support that made this report possible.


Marshall M. Bouton
President
The Chicago Council on Global Affairs

# Executive Summary

Over the past half century, the world has witnessed dramatic gains in agricultural productivity, a long-term decline in agricultural prices, and increasing supplies that have outstripped the growth in demand. There are signs, however, that this trend may be reversing. Continued population and food demand growth, increasing environmental concerns such as climate change, tightening water supply, and degrading soils are placing ever greater strains on global agriculture. With global agricultural demand expected to increase by more than 60 percent between 2005-07 and 2050, a new wave of productivity increases will be needed to sustainably meet this demand.

Agricultural research and innovation have been pivotal to increasing productivity. Yet the global agricultural research and innovation landscape has been changing, with funding trends shifting dramatically. Besides a drop in the share of research and development (R&D) investments made by high-income countries, especially the United States, investments have shifted away from a focus on farm productivity improvements in staple crops and been redirected to a wide variety of other issues. Further, many national research programs fail to take full advantage of the vast stocks of knowledge that exist around the world and that could be tapped to spur innovation elsewhere.

A new, internationally oriented way of thinking about agricultural investments and innovation is likely to enhance the efficiencies of R&D investment at all levels, from the local to the global level. The lag between research investments and commercial use is exceptionally long, underscoring that decisions taken now will have consequences for decades to come. To help move decision making in the United States and the world toward this global approach, this paper provides new evidence on research investment trends worldwide and offers novel measures of accumulated knowledge stocks for each country and the potential for this knowledge to "spill over" across national boundaries.

## The nature of agricultural innovation

Agricultural innovation requires patience and persistence. It is a long, cumulative process with distinctive biological and site-specific attributes. A better understanding of the innovation implications of these unique characteristics calls for new approaches to investing in agricultural R&D.

### The benefits of investments in research and development are large

In the United States over the past half century, every dollar invested in public agricultural R&D returned benefits valued at between 20 to 30 dollars. Changes in US corn production illustrate how investments in research and development have paid off in productivity gains. US corn production grew from 2.7 billion bushels in 1900 to just under 12.4 billion in 2011, or 36 percent of the entire world's output, while over the same period the amount of land under corn production decreased. A sizeable share of the growth derived from use of technological innovations (notably, new hybrid varieties of corn) resulting from investments in research.

### Innovation is inherently an international and cumulative endeavor

Much of today's gricultural production uses genetic material and knowledge that had its source hundreds or even thousands of miles away. The magic of science stems from the slow and steady accretion of new knowledge. Differences in the accumulation of research results over the long haul account for a sizable share of the differences in agricultural productivity observed around the world. This is one of the reasons why sustained, long-term funding of research is so important.

### Striking the right mix of local, national, and international research is critical to addressing the intrinsic site specificity of agriculture and optimizing spillover potentials

Locally targeted research programs are indispensable parts of the innovative process in agriculture. But R&D findings have the potential to spill both into and out of local areas, some requiring adaptation to different economic and agroecological environments. This spillover potential should be taken into account when forming agricultural investment policies, including the support for and structure of international research and the composition of national and international research.

### Both the public and private sectors have critical roles to play

Changes in the scope of intellectual property protection have been associated with a rise in agricultural innovations coming from the corporate sector. While increasing investments in innovation by private firms have obviated the need for some public research, much of the private research stands squarely on the shoulders of publicly performed research. In addition, 89 to 94 percent of private agricultural research takes place in high-income countries. While private investment will be indispensible to agricultural development and increased productivity worldwide, public research will remain the principal source of agricultural innovations for many of the world's (poorer) farmers for many years to come.

### Lag time between research and uptake of technologies is typically long

It can take decades for the productivity impacts of R&D investments to be realized via adoption and use of new technologies. For example, it took 20 years (and arguably longer) before initial research into hybrid corn resulted in significant commercial planting of new varieties and 20 more years before the adoption process had run its course in the United States. Decades of slowing growth in agricultural R&D investment by the United States foreshadowed substantial slowdowns in the rate of growth of US agricultural productivity. To make up lost ground, preserve gains that have already been made, and move toward meeting the productivity demands of the future, renewed attention must be given to agricultural R&D and innovation policy.

## The shifting structure of US and global research and development

Funding patterns for agricultural R&D have undergone substantial shifts in recent years. What research, done by whom, and how has potentially profound productivity consequences. Getting a better handle on the changing US and global structure of R&D is a critical first step in revamping agricultural R&D policies to meet the changing demands of the 21st century.

### The patterns of overall global research and development spending in science are shifting

Real global spending on science has increased threefold since 1980. In 2009 US spending accounted for one-third of the world total, and high-income countries accounted for 77 percent of the world's spending. Low-income countries, which support 11.7 percent of the world's population, accounted for just 0.4 percent of global R&D spending. The greatest spending growth occurred in middle-income countries (including Brazil, India, and China), which increased by 12.5 percent per year between 2000 and 2009. Spending grew at just 3 percent per year in high-income countries during that time.

### Global public spending on food and agricultural research and development has shifted geographically, and the US share has declined significantly

High-income countries accounted for 48 percent of total public spending in agricultural R&D in 2009, down from 56 percent in 1960, with the United States dropping from a 21 to a 13 percent share. Spending by middle-income countries surpassed the high-income total in 2009, with China's share growing from 13 to 19 percent of the world's spending. Comparing agricultural research expenditures to the size of a country's agricultural economy reveals that "research intensities" have increased in the United States and high-income countries from $0.56 of agricultural R&D for every $100 of agricultural output in 1960 to $3.59 in 2009.

### Overall US food and agricultural research and development spending growth is slowing

Over the past several decades, the real rate of growth of US funding for public agricultural R&D has gradually slowed and in more recent years spending has actually decreased. Funding for productivity-enhancing research has also fallen from 65 percent of total public spending in 1976 to 56 percent in 2009. Private spending has increased to 58 percent of total public plus private spending, up from a roughly equal share through the end of the 1980s. Spending shares between federal versus university research have shifted from roughly equal shares around the middle of the 20th century to nearly three-quarters conducted by universities in recent years.

### The structure and orientation of international research has shifted

The Consultative Group on International Agricultural Research (CGIAR), a consortium of international research centers, receives only a small, and of late, declining fraction of global agricultural research dollars—just 1.6 percent of the global public-sector total in 2009. The US share of funding for the CGIAR declined from a peak of 29.3 percent in 1983 to 12.8 percent in 2010. In addition, funding has shifted away from unrestricted funds, which are spent at the discretion of a research center's management, toward primarily restricted funds to be used for specific projects. Restricted funds rose from 10.2 percent of total funding in 1970 to 67.1 percent in 2010. This is a massive change in how and by whom decisions are made about the deployment of resources. While reforms in the funding and operations of the CGIAR are under way, the outcome is still unclear and significant challenges remain.

## Rethinking global agricultural research and development

To safeguard the hard-won agricultural productivity gains made over the past half century and to meet the future challenge of feeding two billion more people by 2050 will require revitalizing the institutions and investments that promote productivity growth in global and poor-country agriculture. A more comprehensive perspective on the world's innovative capacity in food and agriculture is needed to effectively tap local knowledge stocks for the benefit of agricultural producers worldwide.

### Estimating accumulated knowledge stocks and spillover potentials

This paper quantifies the stocks of productive knowledge in countries around the world through measures of "home-grown" knowledge and "other people's" knowledge, along with the potential of that knowledge to spill across national borders. National spill-in potentials are measured based on the agroecological and production similarities among countries. For example, given their agroecological similarities, countries in the middle northern latitudes might benefit most from US research (and vice versa). Taking production similarities into account, countries such as Mexico and South Africa could benefit from US research. A metric of the amount of knowledge that could potentially spill in to each country was then calculated by averaging the potential spill-ins from these two measures.

The analysis reveals that, on average, countries with smaller shares of the world's stock of knowledge have greater potential to benefit from R&D spill-ins. While most Sub-Saharan African countries have above-average spill-in potentials, all countries have sizable spill-in potentials.

### Leveraging spillover potentials as part of domestic (and global) research decision making

The extent and pattern of potential spillovers should be integral to decisions on how much and what types of research to fund and where in the world is best to conduct or target the research. For example, for certain types of commodity research, a regional or multicountry approach may be more appropriate than if individual states or countries conducted uncoordinated, unproductively repetitive, possibly competing programs of research. In the decades ahead, substantial reform of research institutions may be necessary to achieve efficient jurisdictions for agricultural R&D, especially in light of the rapidly changing structure of agriculture and changes in communication, bioinformatics, transportation, and the conduct of science itself.

# Introduction

Recent trends in farm productivity and food prices raise concerns about whether the era of global agricultural abundance is over. Anxieties over affordable access to food have resurfaced in reaction to recent food price volatility, projected population growth, and longer-term environmental concerns, including changes in climate, ever-tighter supplies of water for irrigation, and degradation of soil and other natural assets that sustain global agricultural production. With an estimated two billion *more* mouths to feed by 2050 and comparatively limited scope for increasing the land used in agriculture, future increases in agricultural output will be even more reliant on sustained increases in agricultural productivity than they were in the past.[1] Agricultural research and development (R&D) is a crucial determinant of agricultural productivity and production and, therefore, of the world's global food prospects.

Research is a particularly powerful instrument for promoting international and domestic economic growth and development. Perhaps less appreciated is the importance of R&D in simply maintaining productivity gains that have already been achieved, as environmental challenges and coevolving pests and diseases progressively undermine those gains. At the same time, the global R&D investment environment that yielded so much progress in the past is undergoing seismic shifts, including a decline in the share of investments made by the United States and other high-income countries. If the world is to meet the productivity challenges before it, those making decisions that affect agricultural R&D must be better informed about the changing nature of agricultural innovation processes worldwide and how to best leverage R&D investments for the benefit of all countries—rich and (especially) poor.

Domestic research policies and institutions have often failed to take full advantage of the enormous stocks of agricultural knowledge that exist internationally—developed in other countries and through international research centers—and that could be adapted to fit local economic and environmental circumstances. In addition, as in the case of the United States, policymakers in some countries have sometimes failed to fully appreciate the potential of their own knowledge stocks to aid development in other countries. Consequently, a more comprehensive perspective on the world's innovative capacity is needed to increase efficiencies.

This report looks at the processes of agricultural innovation and the role of R&D in increasing agricultural productivity. It presents new evidence on investment trends in public and private food and agriculture research in the United States and worldwide and discusses the implications of these trends for global agricultural productivity. This assessment goes beyond simple notions of R&D spending to also consider more pertinent and newly constructed country-by-country measures of the accumulated stocks of agricultural knowledge and of research "spillover" potentials on the premise that the changing international interconnectedness of agricultural innovations—and the R&D systems supporting these innovation processes—should be part of a new way of thinking about global economic development prospects for the 21st century. It typically takes decades for R&D to do its magic, principally by way of improved productivity and sustainable economic growth. Decisions taken and especially the R&D investments made (or not made) now—even in these tight fiscal times—will have profound domestic and global consequences through the middle of this century and beyond.

# CHAPTER 1
# The Nature of Agricultural Innovation

With global agricultural demand expected to increase about 62 percent between 2005-07 and 2050, increasing crop yields will be pivotal to meeting global demand at prices that people can afford.[2] The dramatic rise in agricultural productivity and the long-run decline in real (inflation-adjusted) agricultural prices that have characterized the past half century may be in danger, as signs of a reversal in this pattern follow several decades of slowing growth in agricultural R&D spending by the United States and other countries.[3] This section looks at how R&D investments impact productivity and at the nature of agricultural innovation to guide new thinking in the approach to R&D policies and investments required to help meet the global food and agricultural challenges ahead.

## Investments in research and development are a primary driver of agricultural productivity growth

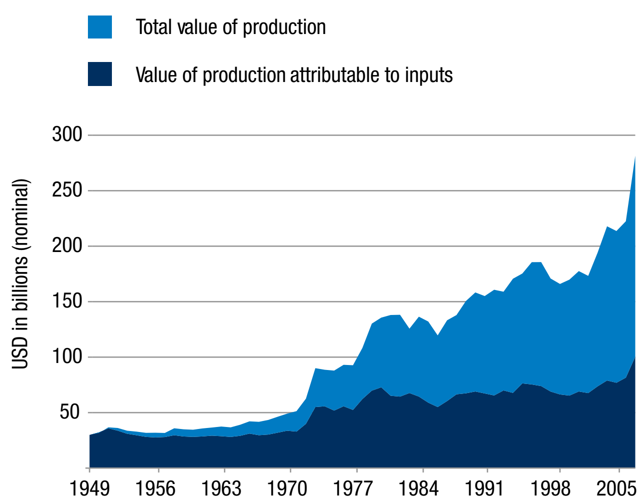
Over the past century, the productivity of agriculture in the United States has grown dramatically. For example, US corn production increased from 2.7 billion bushels in 1900 to just under 12.4 billion bushels in 2011, or about 36 percent of the entire world's output of this crop.[4] During that time, the amount of land used for corn production fell,[5] revealing that increases in output came from increasing corn yields (output per acre). US corn yields grew from an average of just 28.1 bushels per acre in 1900 to 147.2 bushels per acre in 2011, a growth rate of 1.49 percent per year.[6] While some of the yield growth resulted from increases in the *quantities* of inputs used by farmers—such as fertilizers, herbicides, seeds, machinery, fuel, and irrigation—a sizable share of the measured growth in productivity reflects changes in the *quality* of inputs—such as the development of new varieties of corn, especially hybrid varieties stemming from investments in R&D.[7]

Figure 1 graphically illustrates the power of such investments. The upper line shows the total value of US agricultural output from 1949 to 2007, which grew from $29.9 billion to $281.5 billion. The lower line shows what the value of US agricultural production would have been if the same inputs and technology from 1949 had been used from that point forward. Thus, the darker shaded area represents the output attributable to productivity growth since 1949, a benefit worth $219.6 billion in 2007 alone.[8] Yet total US public and private investment in agricultural research was only $11.1 billion in 2007, and the returns on this investment are large.[9]

### Importance of sustaining research

The historically high crop yields and productivity levels now evident for US agriculture represent hard-won gains by yesteryear's public and private researchers and farm innovators. But these past and present gains are by no means to be taken for granted, let alone be counted on to sustainably increase the productivity of US (and global) agriculture. Cutbacks in agricultural R&D spending (see

**Figure 1 – Value of US agricultural output attributable to productivity growth, 1949-2007**




*Source: Pardey, Alston, and Chan-Kang (2012), an updated version of figure 12.1 from Alston et al. (2010).*

chapter 2) are bound to eventually slow the pace of productivity growth and may even claw back past productivity gains as economic and environmental circumstances change to undermine those gains. Indeed, the slowing growth (now cutbacks) in inflation-adjusted spending on US public agricultural R&D since the 1960s is associated with a dramatic slowdown in multifactor productivity (MFP) growth in US agriculture since about 1990. MFP growth almost halved from 2.12 percent per year for the period 1949 to 1990 to just 1.16 percent per year for the period 1990 to 2007.[10]

Many of the traits incorporated into new varieties of crops, for example, are designed to protect them from the ravages of pests and diseases and the competitive pressures of ever-evolving weeds. Yet nature continually adapts to these changes, presenting new and evolving challenges. Changes in climate can also contribute directly (via heat, drought, or floods) or indirectly (via the evolution of biotic stressors on plants) to the downward pressure on productivity.

A vivid illustration of these continually evolving natural agricultural challenges is a renewed threat to the world's (including the US) wheat crop posed by stem rust, a potentially devastating fungal disease of wheat. The disease can kill wheat plants, but more typically it reduces foliage, root growth, and grain yields. In the United States prior to the 1960s, crop losses from stem rust were sizable—almost 24 percent of the country's wheat production was lost to the disease in 1935, and losses in the 5 to 10 percent range were also not uncommon (figure 2a). Breeders developed varieties that were resistant to the disease, but after years of successes in keeping the rust at bay, new virulent races (collectively referred to as "Ug99") have emerged with the potential to infect much of the world's wheat.[11] Like all crop-pathogen interactions, wheat and its stem rust pathogens are locked in a coevolutionary Darwinian dance. Wheat varieties with resistance to contemporary races provide the selection pressure for the evolution of new races of rust that overcome that resistance. Wheat breeding successes can be short- or long-lived, but by their very nature sow the seeds for their own failure.

The reemergence of stem rust as a real threat to wheat yields in the United States and elsewhere coincides with a rundown in spending on US agricultural research in general and stem rust research in particular.[12] Pardey et al. estimated that the economically justifiable spending on stem rust research was around $51 million per year, a seemingly paltry amount, but more than double what has been spent on an annual basis over the past decade or so.[13] An investment strategy that supports sustained research programs in crop-pest systems subject to these coevolutionary pressures is critical to identifying and addressing these ever-evolving pest and disease threats.

The stakes are substantial. Around two-thirds of the world's wheat area is climatically suitable to support the growth of stem rust, and the fungus will persist interseasonally on about 11 percent of the wheat acreage worldwide (figure 2b). The potential problems posed by the disease vary from location to location. For example, in Sub-Saharan Africa, 83 percent of the wheat acreage is suitable for the disease, which will persist on about 61 percent of the region's wheat acreage, a much more pressing problem than revealed by the global averages. Failing to increase and sustain investments in rust-resistance research is tantamount to accepting an increase in the risk of yield losses on one of the world's food staples and severely undermining the livelihoods of poor wheat farmers in Africa and other low-income areas of the world.

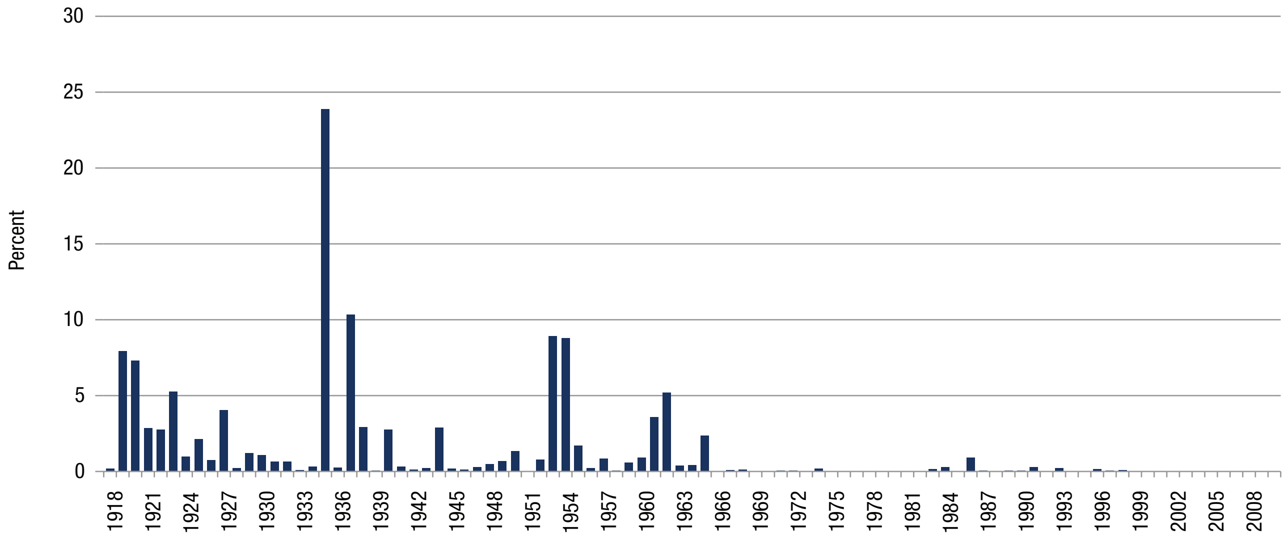
Beyond the need to maintain spending on research to protect the productivity gains that have already been made, research investments will be critical to developing the innovations needed to sustainably meet future growth in demand.

## Agricultural innovation is inherently an international and cumulative endeavor

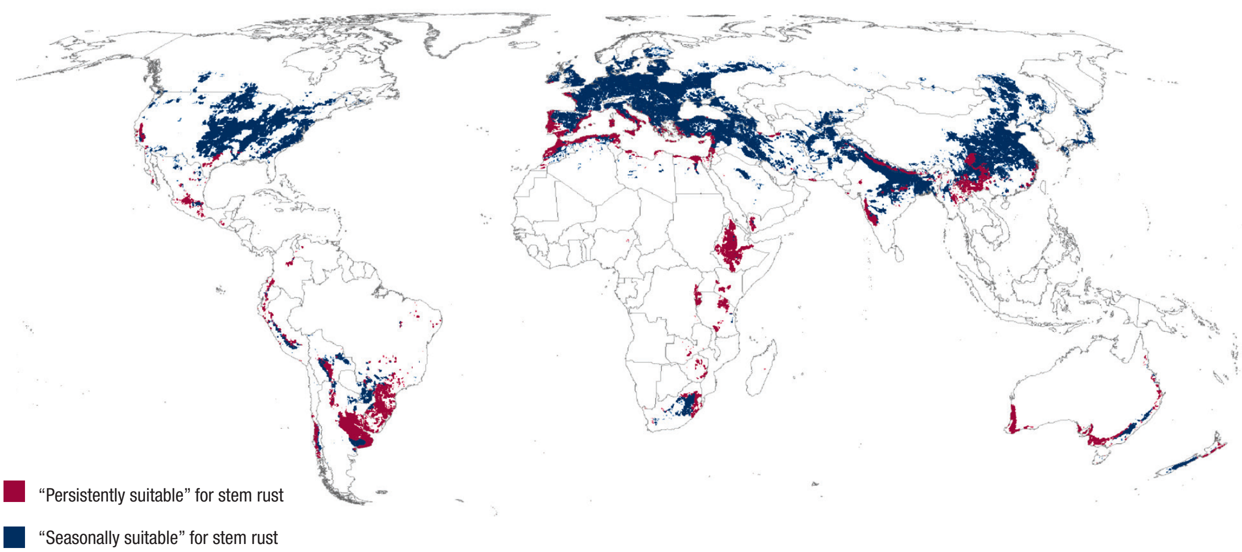
Progress in agriculture has always been an inherently international affair, a fact that is often underappreciated. Most agricultural production today uses genetic material that had its source hundreds or even thousands of miles away. After thousands of years of slow development, slow improvement, and gradual movement of plants and animals, the rate of change has accelerated in the past 500 years. The "Colombian Exchange" that was initiated when Columbus first made contact with native Americans in the "New World" was an early catalyst.[14]

## Figure 2 – The challenge of stem rust

### 2a – US wheat losses attributed to stem rust (percent production loss per year)




### 2b – Modeled global climate suitability for stem rust




*Source: Pardey et al.,* Right-Sizing Stem Rust Research (2013)*; and Beddow et al.,* Measuring the worldwide spatial occurrence and probabilistic consequences of stem rust *(2013, in press).*

Before the modern scientific age, many of the advances in American agricultural productivity resulted from the efforts of plant prospectors who imported new and improved crop varieties from foreign lands. Walter Burling of Mississippi imported a new cotton variety from Mexico in 1806 that would become the mainstay of the early American cotton industry. Agoston Haraszthy helped transform the California wine industry by importing several hundred grape varieties from across Europe, North Africa, and the Middle East in the 1860s. In addition to the efforts of private citizens, the US Department of Agriculture (USDA) sent its scientists to the far corners of the globe in search of better plant varieties.[15] These efforts were particularly fruitful in introducing varieties of wheat and other crops suitable for the relatively arid and harsh conditions on the Great Plains.

Most of the commercial agriculture in the United States today is based on crop and livestock species introduced from Eurasia (e.g., wheat, barley, rice, soybeans, grapes, apples, citrus, cattle, sheep, hogs, and chickens), though with significant involvement of American species (e.g., corn, peppers, potatoes, tobacco, tomatoes, and turkeys) that are also distributed throughout the rest of the world.[16]

Along with the international movement of plants and livestock, there was also much direct transfer of European farming techniques, practices, and materials to the New World and the (colonial) tropics. The global diffusion of agriculturally significant plants and animals and the tools and techniques used in agricultural production—collectively known as "spillovers"—have been a pivotal part of the history of agricultural innovation.

Science is also a cumulative endeavor, with a snowball effect. To many, technological progress appears to happen by a series of breakthroughs, be it the invention of tractors, hybrid corn, bioengineered pest- or herbicide-resistant crops, or drip irrigation. While the occasional genius does make a great leap forward, the real magic of science stems from the slow and steady accretion of new knowledge.

Today's scientists stand firmly on the shoulders of those who went before them. While investments in research give rise to new ideas, know-how, and innovations in the near term, these innovations draw directly on the efforts of past research. Innovations beget new ideas and further rounds of innovation or additions to the cumulative stock of knowledge. It is the *accumulation* of research results over the long run that accounts for the differences in agricultural productivity observed around the world.

The mutually beneficial effects of accumulating and exchanging ideas is why lone innovators have largely given way to institutional approaches to research, why scientific disciplines formed professional organizations and spawned journals to capture and carry forward findings, and why scientists seek out other scientists and their ideas at conferences, via the Internet and other venues. This is one of the reasons why sustained, long-term funding of research is important.

## Development of international research centers

Most of the world's public agricultural R&D takes place in national agencies largely funded (and often operated) by each country's respective government. More formal forms of international collaboration in the development and diffusion of agricultural innovations, designed to more readily take advantage of cumulative knowledge and enhance the international spillovers of technologies and techniques for the benefit of all countries, crystallized in the first half of the 20th century.

Baum as well as Culver and Hyde attribute the original idea of providing rich-country research assistance to developing country agriculture to Henry A. Wallace, who founded the Pioneer Hi-Bred International Company in 1926 and served as US secretary of agriculture from 1933 to 1939 and as vice president in the Roosevelt administration from 1940 to 1944.[17] In 1940 before being sworn in as vice president, Wallace spent a month traveling through Mexico. Wright observed that on "[r]eturning to Washington, however, Wallace found a [US] federally funded Mexican agricultural program to be politically infeasible. Government funds were committed to national defense. Where else to turn? In 1941 there was no FAO [Food and Agriculture Organization], no USAID [US Agency for International Development], no Marshall Plan to copy, and no World Bank. The paucity of alternatives makes it less surprising that Wallace turned to the Rockefeller Foundation for help in raising corn, wheat, and bean yields in Mexico, even though the Foundation was not experienced in conducting agricultural research."[18]

As a result, the first venture in international collaboration in agriculture was the Mexican Agricultural Program, a cooperative program between the Mexican government and the Rockefeller Foundation, established in 1943 to conduct crop improvement (mainly wheat) research, which later, in 1966, became the International Maize and Wheat Improvement Center (CIMMYT). Another notable international collaboration was the rice research program at Los Baños in the Philippines that led the Rockefeller Foundation, in partnership with the Ford Foundation, to establish the International Rice Research Institute (IRRI) in 1960. Closely following these developments came

BOX 1

## Wheat varietal spillovers

In 2005 the hard red winter wheat variety Jagger was the most widely planted variety in the United States, occupying 11 percent (i.e., 5.5 million acres) of the total US wheat area and more than 25 percent of the area in states such as Kansas and Oklahoma. Released commercially in 1995 as a joint product of the Kansas agricultural experiment station and the USDA's Agricultural Research Service (USDA-ARS), Jagger was one of a number of important wheat varieties grown throughout the US wheat belt in the mid-2000s (Sears et al. 1997). Others included Jagalene, grown widely in Kansas and Nebraska, and Reeder, a popular variety in North Dakota and Montana.

The pedigree (or family tree) starkly reveals the cumulative nature of agricultural innovation processes and also shows the intrinsically international nature of modern crop breeding efforts (figure B1). The breeders who developed Jagger drew on genetic material from all over the world and throughout the United States. Jagger was formed by crossing the breeding line KS82W418 (developed by the Kansas agricultural experimental station) with the variety Stephens (developed jointly by the Oregon agricultural experiment station and USDA-ARS). In turn, these two varieties stand firmly on the shoulders of the investments in scientific crop breeding over the past century and the eons of selection and seed-saving efforts of farmers since wheat was first domesticated around 10,000 years ago. Jagger's ancestry includes varieties like Turkey Red from Russia, Noe from France, Federation and Purplestraw from Australia, Yaqui from Mexico, and Etawah from India.

Tallying up the number and origin of the known nodes in the genetic lineage (or pedigree) of Jagger reveals that almost 70 percent of the antecedent varieties come from places and breeding efforts outside the United States (table B1). Around 8 percent of the known nodes were developed by scientists at the International Wheat and Maize Crop Improvement Center (CIMMYT), located in El Batan, Mexico, that is supported in part with funds from the United States.

The international collective action that constitutes crop breeding is further evident in table B1, with almost one-quarter of the known nodes in Jagger's pedigree coming from the developing world and almost 37 percent of the material spilling in from other rich countries.

**Table B1 – Number and share of pedigree nodes by origin**

| | Number | Share (%) |
|---|---|---|
| CIMMYT | 25 | 8.4 |
| Low & middle income | 70 | 23.5 |
| USA | 94 | 31.5 |
| Other high income | 109 | 36.6 |
| **Total** | **298** | **100** |

*Source: Pardey and Chan-Kang (in process).*

the establishment of the International Institute of Tropical Agriculture (IITA) in Ibadan, Nigeria, in 1967 and the International Center for Tropical Agriculture (CIAT) in Cali, Colombia, in 1968. The further development of international agricultural research centers took place largely under the auspices of the Consultative Group on International Agricultural Research (CGIAR), established in 1971 as bilateral and multilateral donors bought into the model.[19]

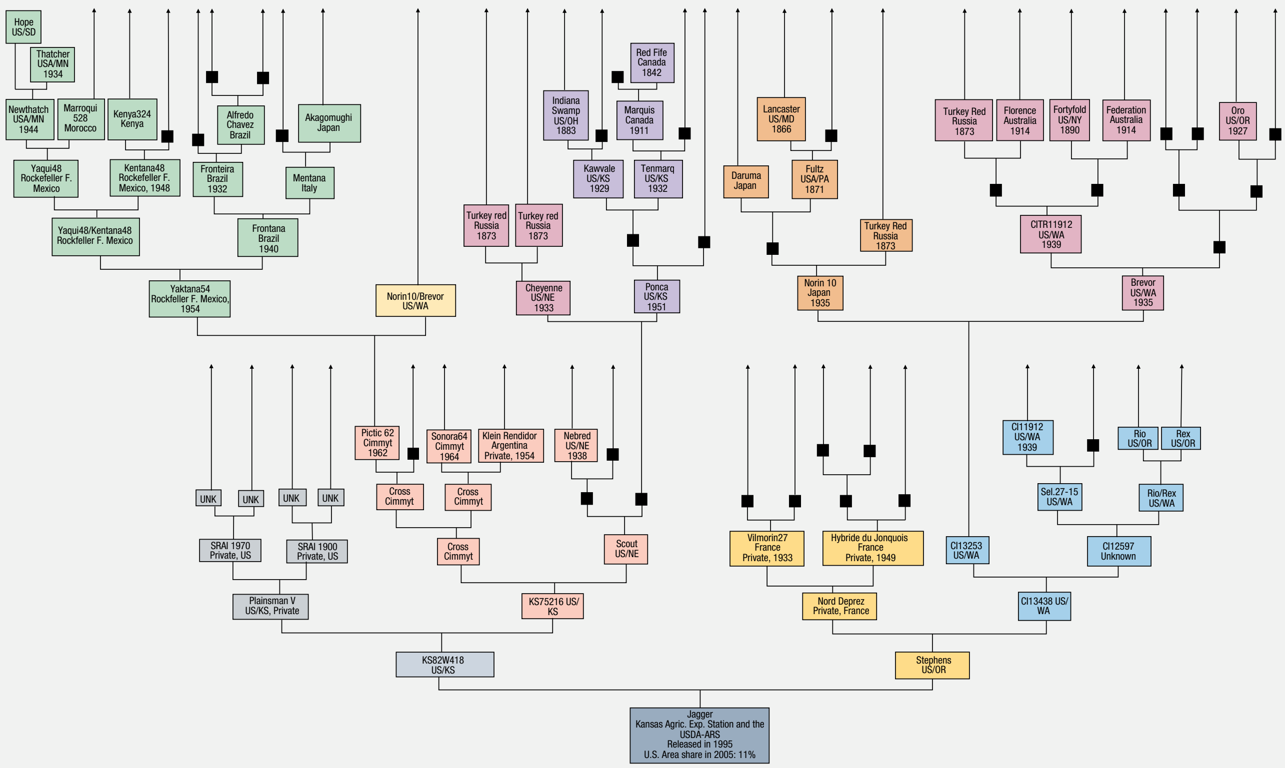
The accomplishments of the Green Revolution of the 1960s and 1970s are attributable to the development and international transfer of new crop varieties and associated innovations that were enabled by the CGIAR and its antecedent activities.[20] For example, the use of improved wheat varieties with CIMMYT ancestry by India and Pakistan contributed to a doubling of wheat production in the two countries from 1967 to 1971.[21] From 1961 to 2000 rice production in the developing countries of Asia grew 170 percent, with 83 percent attributable to growth in yield. In Latin America rice production doubled from the mid-1960s to 1995, allowing the region to become largely self-sufficient in rice.[22]

### The importance of spillovers

A myopic view of innovation policy would consider only recently and locally performed R&D. A more nuanced approach is to recognize that the findings from local research spill across national borders (typically in both directions, in and out of a country) and to be explicit about these spillovers when forming innovation policies, particularly when deciding how much to invest in agricultural R&D and who should pay for it.

From an economic perspective, when R&D in one political jurisdiction (e.g., a state or a country) results in spillover benefits in another political jurisdiction—whose residents have not participated in the choice about what R&D to do and have not contributed to the costs of the R&D—an interjurisdictional externality exists.[23] As with exter-

**Figure B1 – Partial pedigree of Jagger**




*Source: Pardey and Chan-Kang (in process).*

nalities among individuals, externalities among jurisdictions involve efficiency losses. It thus makes economic sense, for example in the United States, to fund public US agricultural R&D with a mix of federal and state funding because states typically underfund locally performed research to the extent benefits spill out and accrue to producers and consumers in other states (that is, decision makers in the state consider all of the R&D costs, but only the portion of the benefits that is captured locally). So too would countries underinvest in agricultural R&D from a global perspective to the extent that the results of research done in (and paid for by) one country spill over and realize benefits for those residing elsewhere in the world. This provides an economic motivation for international, regional, or other forms of collective (cross-country) action in agricultural R&D in addition to local research.

R&D spillovers from international sources, including the international research centers, are still of substantial if not increasing economic importance to US agriculture. For example, foreign entities accounted for 64 percent of all the plant varietal rights in the United States in 2008, compared with just 21 percent in 1984.[24] By the early 1990s, about one-fifth of the total US wheat acreage was sown to varieties with International Maize and Wheat Improvement Center (CIMMYT) ancestry, and in 1993 virtually all the California spring wheat crop was grown with varieties from CIMMYT or CIMMYT-based ancestors.[25] The US reliance on wheat varieties from CIMMYT and elsewhere in the world persists, as illustrated in box 1. The CIMMYT spill-ins to the United States are an example of the payoffs of US support for these centers—promoting productivity growth among American wheat farmers as well as poor smallholder wheat producers throughout the world. Few other forms of US development aid have such profound payoffs worldwide while also realizing direct economic benefits for the US economy.

The reliance on R&D spillovers goes well beyond wheat varieties. A comprehensive study by Alston et al. of the state-by-state returns to *all* the state-level investments in agricultural R&D performed in the United States estimated that, on average, one-third of the economic benefits from research-induced productivity gains in agriculture in each state were attributable to spill-ins from research done in other states or by the federal government.[26]

R&D spillovers are especially important to low-income, developing countries. With limited capacity and resources for domestic R&D, these countries are more reliant on research done elsewhere to help boost agricultural development and productivity. Nonetheless, locally targeted research programs are essential parts of the innovative process in agriculture. Agriculture is inherently site specific, with myriad local factors such as climate, soil, pests, cultivation practices, and markets affecting productivity and production.[27] National programs of research are often carried out with specific local problems in mind. For example, corn varieties (be they bred conventionally or by more modern methods) must be tailored to local production realities that affect the performance of the plant. Thus, new technologies with spillover potential for other areas of the world still require further research to enable local adoption and uptake.

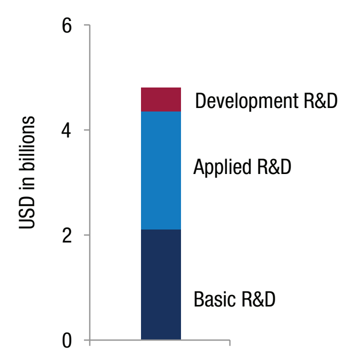
## Both the private and public sectors have critical roles to play

Changes in the scope of intellectual property protection have been associated with a rise in agricultural innovations coming from the corporate sector. For example, legal forms of plant varietal rights have been on offer in the United States since 1930 and the corporate share of the rights issued has risen from 55 percent in the 1930s and 1940s to 82 percent of the rights in more recent times.[28] The intellectual property landscape evolved hand-in-hand with important changes in the genetics and genomics sciences that support crop varietal development. The legislative and legal changes that gathered momentum in the 1980s preceded a substantial rise in the amount of private research oriented towards biological innovations during the subsequent two decades by firms such as Monsanto and Pioneer-Dupont.[29] In addition, the share of food processing, beverage, and tobacco research in total food and agricultural R&D has continued to be a big part of the private R&D effort over the past 50 years (averaging 43 percent of the private US total over the past two decades) as industry has sought to respond to changing consumer demands, including an increase in the share of food and beverages consumed away from home and a growing demand for prepared foods and those packaged in more convenient forms.[30]

While the increasing investments in innovation by private firms have obviated the need for some public research, much of the private research stands firmly on the shoulders of publicly performed research. For example, public and private roles were closely intertwined in the crop varietal technologies described in box 2 and the development of the new disease-resistant wheat varieties described earlier. The complementary role of public and private research is unlikely to change, although the details of what research is done in the public versus private sectors will surely change as intellectual property policies and practices continue to evolve along with the scientific and market realities that shift the incentives and comparative research advantages of each sector.

The different roles played by public and private research are revealed to some extent by the substantial differences in the composition of the research performed by both sectors. Figure 3 shows that around 44 percent of the food and agricultural research performed by the US public sector

### Figure 3 – US public agricultural research and development by type, 2007-2009




*Source: Developed by authors from USDA, Current Research Information System (CRIS), various years.*

**BOX 2**

# Crop varietal technology timelines

The timelines below illustrate the lengthy innovation processes typical of agriculture. They also reveal the complementary roles of the public and private sectors and the complex interactions between them in going from a new idea to a marketable innovation. Some of the innovations were put in the public domain, some were protected by intellectual property rights.

In these timelines the circles represent innovative events that occurred somewhere in the public sector, the square nodes are private R&D efforts. The dark shaded nodes are commercial events or innovative effort subject to intellectual property protection undertaken by either the public or private sectors.

**Figure B2 – Timeline of scientific and commercial events to develop new crop traits and varieties**

**Hybrid Corn**

| | | |
|---|---|---|
| 1877 | ○ | Beal conducts first controlled crosses/hybrid vigor |
| 1905-1912 | ○ | Shull developed correct understanding of inbreeding and cross breeding |
| 1918 | ○ | Jones developed double cross-hybrid |
| 1922 | ○ | Iowa State station began corn in-breeding program |
| 1933 | ■ | First commercial planting of Hybrid Iowa 939 developed by Merle Jenkins |
| 1936 | ○ | First release of a widely popular double-cross hybrid developed at Purdue University |
| 1960 | ● | Vastly improved in-breds led to shift to single-cross hybrids |
| 1960 | ■ | 95 percent of U.S. corn acreage in hybrids |

**Bt Corn**

| | | |
|---|---|---|
| 1901 | ○ | Bacillus thuringiensis (Bt) discovered in Japan (and 1911 in Germany) |
| 1950s | ○ | Bt used as a control agent and registered |
| 1986 | ○ | Cry1Ab gene sequence published |
| 1986 | □ | Cry1Ab cloned into root colonyzing Pseudomonas bacteria |
| 1992 | ■ | YieldGard insect protected corn event Mon810 produced by "gene gun" |
| 1996 | □ | FDA, USDA & EPA approvals for YieldGard |
| 1997 | ■ | Bt corn (corn borer protection) commercialized in U.S. |
| 1998 | ■ | Stacked with other traits (e.g. herbicide tolerance) |
| 2004 | ■ | U.S. patent issued to Monsanto for Mon810, a Bt construct |
| 2008 | □ | Regulatory approval in 20 countries |

**Roundup Ready Soybean**

| | | |
|---|---|---|
| 1970 | ■ | Glyphosate shown to have herbicidal activity |
| 1976 | ■ | Roundup herbicide commercialized in U.S. |
| 1980 | □ | Identification of three mechanisms to infer glyphosate tolerance |
| Late 1980s | ■ | Several genes encoding glyphosate insensitivity isolated |
| 1987 | ■ | First soybean transformation achieved |
| 1990 & 1991 | □ | Glyphosate tolerant seeds evaluated |
| 1996 | □ | Roundup Ready Soybeans commercialized |

○ = Public R&D efforts

□ = Private R&D efforts

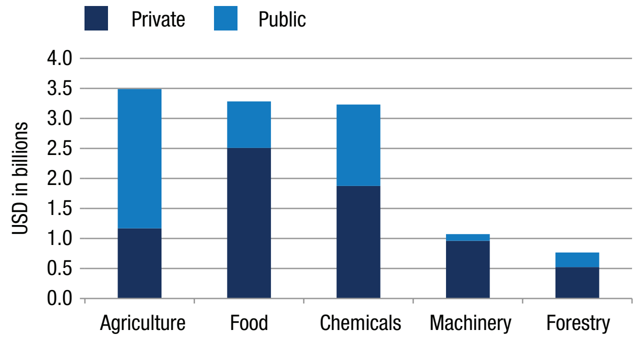
● OR ■ = Commercial events or innovative effort subject to intellectual property protection

*Source: Alston, Pardey, and Ruttan (2008) and Alston et al. (2010).*

is considered "basic" research, where the notional objective is the pursuit of new knowledge or ideas without *specific* applications in mind.[31] The insights gained through basic research feed into the development of future innovations and technologies that increase productivity and economic growth over the longer run.[32] Another 47 percent of public research is classified as "applied," or research done to meet a specific need. Only 9 percent is deemed "developmental" and directed towards the production of specific products and processes with nearer-term commercial potential. By contrast, the National Science Foundation reports that US private research is overwhelmingly "developmental" in nature, intended to develop prototypes, new processes, or products for commercialization. Overall, 63 percent of private US R&D was of this type in 2009, with only 18 percent of private research considered applied and 19 percent considered basic.[33]

Figure 4 shows US food and agriculture R&D broken down into five subsectors. Once again the composition of the research varies markedly between the public and private sectors. Food research is the largest component of private research, accounting for 35.7 percent of the total when averaged over the three years from 2007 to 2009. With 83.9 percent of the value of 2010 US food sales accruing to postfarm activities, this is to be expected.[34] Chemicals and pharmaceuticals research, designed to develop new herbicides, pesticides, fungicides, and veterinary medicines, accounts for the next largest share of private research, followed by agricultural R&D (which includes biological research intended to develop new crop varieties) and research on new farm machinery and equipment. The public sector does negligible machinery research, accounting for only 2.3 percent of total public plus private research in this area. The largest share of public research is in agriculture. This includes research on plant and animal growth processes; disease and reproductive systems; crop, livestock, and natural resource (e.g., soil and climate) management issues; and so on. Food-related research in the public sector includes new and improved food processing technologies and food products as well as human and animal nutrition, food storage, and safety issues.

**Figure 4 – US public and private food and agricultural research and development by economic sector, 2007-2009**




*Source: Developed by authors from USDA, Current Research Information System (CRIS) (2012) database and Dehmer and Pardey,* Private Food and Agricultural R&D *(in process).*

Most of the world's private food and agricultural R&D is conducted in and targeted toward rich-country markets. The more limited private-sector participation in agricultural research done in or for developing countries stems from several factors, many of which are likely to persist for some time (except perhaps in countries experiencing relatively rapid economic growth such as Brazil, China, and India). A significant share of food produced in developing countries is consumed by the household that produced it. Even when commodities enter the marketing chain, they are often purchased in less processed forms for preparation and eating at home. Consequently, a much smaller share of the food bill in developing countries accrues to postfarm food processing, shipping, and merchandising activities, areas where the incentives for private innovation are relatively pronounced.

Likewise, on the supply side, purchased inputs (such as herbicides, insecticides, improved crop varieties or animal breeds, and all sorts of agricultural machinery) constitute a comparatively small share of the total costs of production in many agricultural market segments in many parts of the developing world. While this is likely to change as incomes rise and infrastructure improves, the pace of change will be gradual in the poorest areas, where (semi-)subsistence farming still predominates. The cost of doing business in places with small and often remote farms subject to poor market access, lack of farm credit, and limited communication services also undercuts private participation in agribusiness, in turn reducing the private incentives to invest in R&D targeted to these markets. In addition, a plethora of regulations, many times inefficiently enforced, combined with an uncertain and incomplete legal environment (especially related to contract law and intellectual property protection) make it difficult for local and multinational private interests to profitably penetrate agricultural markets with new seed, chemical, or other agricultural technologies in substantial parts of the developing world.

Private investment will increasingly be critical to agricultural development and increased productivity in the developing world. However, the current obstacles to investment make clear the importance of public investments, which can make private investment in these areas more attractive. Publicly performed R&D continues to play a pivotal, and typically complementary, role to private R&D in the rich countries, and will remain the principal if not sole source of agricultural innovations for many of the world's (poorer) farmers for many years to come.

## Lag time between research and uptake of technologies is typically very long

While investments in agricultural R&D yield substantial returns, it typically takes a long time for R&D to affect agricultural output. Getting innovations into the hands of farmers requires much more than just lab bench science, which itself takes time. In addition to the persistence it takes to generate new technologies that pass commercial muster, extensive field testing and adaptation of the primary (crop) innovation to variable local agroecologies are required before these technologies spread across farmers' fields.[35] In some cases, such as for transgenic crop varieties like Bt corn and Roundup Ready soybeans, additional testing for allergenicity and other safety factors and for weediness and other environmental effects may be required or done voluntarily before the technologies gain regulatory approval for commercial use. Then when released commercially, it often takes a long time for the technology to be adopted. All told, the generation and uptake of new technologies often takes decades, thus demanding a long-term perspective on investments in R&D.[36]

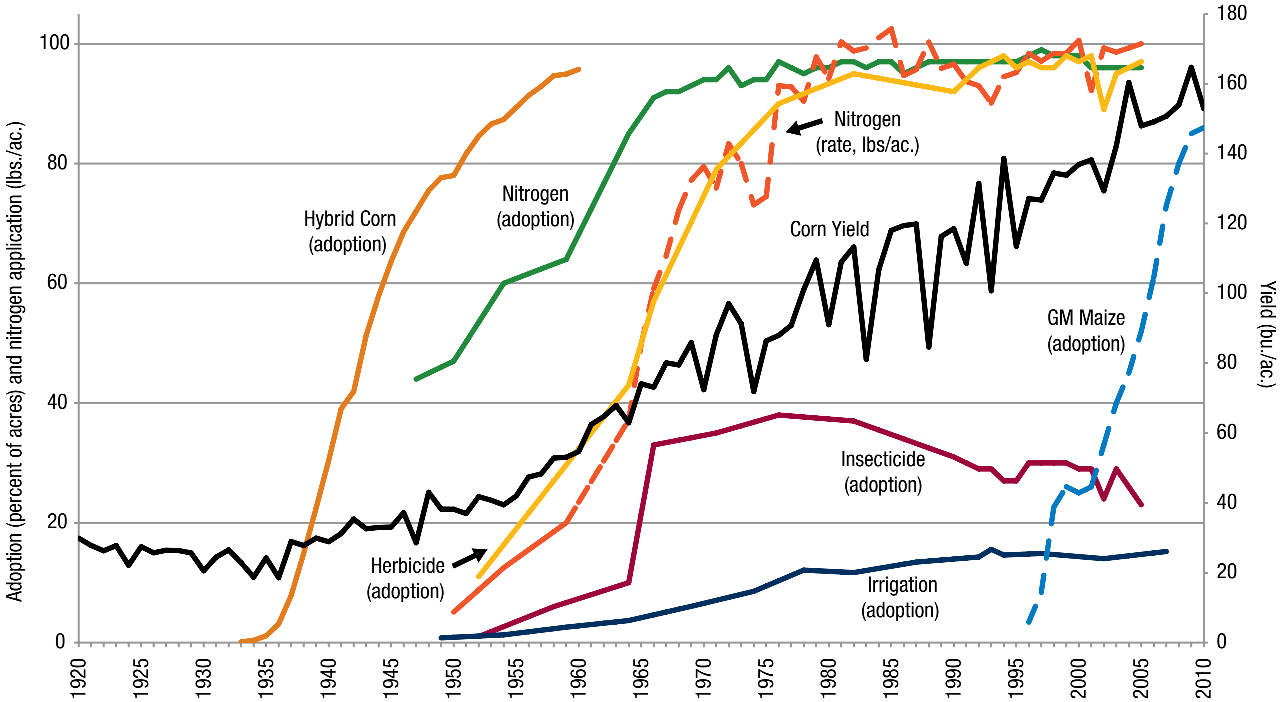
The timelines in box 2 illustrate the lengthy innovation processes typical of agriculture. While the history of crop varietal improvement goes back thousands of years to the beginning of agriculture, even if we focus on the modern scientific era and the applied research that produced hybrid corn, for example, the relevant R&D story began at least 20 years before commercial planting of hybrid corn became significant and 40 years before the adoption process had been completed (in the sense that the percentage of corn planted to hybrids had reached a stable maximum).[37]

The more applied research stage can be dated to around 1918 when Donald F. Jones, working at the Connecticut Agricultural Experiment Station, developed the double-cross method (crossing two single inbred lines of a particular crop variety) as a practical and effective means of realizing hybrid vigor in corn that George Shull and Edward East had begun pursuing using single-cross methods a decade earlier.[38] Through an expanding number of inbreeding projects at various state agricultural experiment stations (SAESs), research conducted by the USDA's Bureau of Plant Industry, and efforts by private firms, seeds developed with this technology were gradually bred for various local agroecologies and began spreading among the various states in the early 1930s, beginning in Iowa. Thus the R&D (or innovation) lag was at least 10 years and likely took 20 to 30 years.

The lag in getting the technologies into farmers' fields was at least as long. The adoption curve for hybrid corn can be seen in figure 5, which shows the share of the US corn acreage planted with hybrid varieties over time. Iowa had 10 percent of its corn acreage planted to hybrids in 1936, rising to 90 percent just four years later. It took until 1948, however, before Alabama—a state with a distinctive agroecology—had 10 percent of its corn acreage planted with hybrids.[39] This delay reflected lags in the availability of hybrid seed suitable for the agroecology of that state and in the uptake or acceptance of the technology once suitable seed became available. Nevertheless, by 1950, 80 percent and by 1960 almost all of the corn grown in the United States was sown to hybrid varieties.

In total, if we think of the entire research, development, and adoption process for hybrid corn varieties as having begun as late as 1918, then the total

## Figure 5 – Uptake of innovations for corn in the United States




Note: Yield is plotted on the right axis; all other variables are plotted on the left. Nitrogen use is in pounds per harvested acre of corn and the adoption variables represent the percentage of harvested corn acres on which the technology was adopted in each year.

*Source: Beddow (2012, figure 3).*

process that had been accomplished by 1960 took place over a period of at least 40 years and arguably decades longer. Despite the long lag times, the success of hybrid corn R&D is undisputed, as shown by the dramatic increases in corn yield achieved as a result (figure 5). Hybrid corn continues to be grown today in the range of 100 years since the focused research that led to those initial innovations began to take hold.

Contrary to popular perceptions, modern crop varietal technologies also take many decades to develop and diffuse. The first commercial use of *Bt* corn (a genetically engineered form of corn that produces proteins that control pests, especially European corn borer) began in the United States in 1997. However, the scientific lineage of this technology dates back to at least the early 1900s with the discovery of the soil-dwelling bacterium *Bacillus thuringiensis* (*Bt*), whose spores and insecticidal proteins have been used to control crop pests since the 1920s.[40] Getting these proteins to express themselves in corn plants took a good deal of science—most actively during the 1980s and 1990s—before the technology passed regulatory scrutiny and was deemed suitable for commercial use (box 2). From commercialization to 80 percent of the maximum level of adoption took 12 years (figure 5). Likewise, herbicide resistant (e.g., Roundup Ready) varieties of soybeans took decades to develop and seven years before reaching 80 percent of its ceiling level of adoption following the first commercial use of this technology in 1996.[41]

Figure 5 also shows the successive waves of uptake of other new technologies by US corn farmers during the 20th century—in addition to improved corn varieties—that gave rise to historically unprecedented increases in corn yields. The figure shows the extent of the uptake of these new technologies, or the percentage of corn acreage to which the technologies were applied, and the associated lag times. Productive as these technologies ultimately proved, the lag times from first commercial release to the ceiling (or maximum) levels of adoption were considerable. It took decades, not

BOX 3

## The role of economic factors in uptake of new technologies

Economic factors that affect the extent and pace of diffusion of new technologies are just as important as the availability of technologies per se. Linking farms to input and output markets is a big part of that picture. The ease with which farms can be linked to markets can measured in travel times between farms and the nearest city with a population of at least 50,000 (a medium-sized city).* On average, a given acre of Sub-Saharan African cropland is over twice as far from the nearest medium-sized city as is cropland in the United States (5.5 hours versus 2.7 hours, respectively) (table B3). About 30 percent of Sub-Saharan Africa's cropland is more than six hours from the nearest medium-sized city (versus 5.3 percent in the United States and 12.5 percent worldwide), with serious implications for farmers' ability to cost-effectively get (perishable) products to market and improved inputs onto farms.

Table B3 – Proximity of cropland to a city

| | % of cropland by time to nearest city of at least 50,000 people | | |
|---|---|---|---|
| | < 2 hours | 2 - 6 hours | > 6 hours |
| Sub-Saharan Africa | 15.5 | 54.5 | 30.0 |
| United States | 41.9 | 52.8 | 5.3 |
| World | 41.9 | 45.6 | 12.5 |

*Source: Calculated by the authors using data from Nelson (2008).*

*The travel time incorporates information on not only the distance between two locations, but also considers the mode of transport (e.g., road, rail, or water-based), slope, delays in border crossings and other factors that influence how long it takes to reach a market (see Nelson, 2008). Thus, the travel time is a proxy for the cost of traveling between locations and therefore the cost of transporting inputs and outputs and of transferring knowledge (e.g., by interacting with extension agents and company sales representatives).

years, before the 80 percent ceiling level of adoption was reached.

Part of the impediment to the uptake of these technologies is the intrinsic site specificity of agriculture. For example, corn varieties (be they bred conventionally or by more modern methods) must be tailored to local production realities involving soil, climate, pest, and other location-specific attributes that affect the performance of the plant. These constitute an ecological constraint to technology adoption in agriculture.

Economic constraints are another important component in the lag times associated with (or impediments to) the adoption of new technologies (box 3). Farmers must deem new technologies more profitable than their existing production practices before it pays for them to switch.[42] Balancing the costs of getting new seeds, fertilizers, machinery, and such onto farmers' fields with the additional revenues realized from selling the increased output into local and international markets is the economic essence of the decision farmers face when choosing whether or not to use new technologies. The 20th century rural landscape in the United States had an infrastructure makeover that went hand in hand with the revolution in agricultural technologies.[43] Transportation, communication, electrification, and other infrastructure lowered the costs of getting new technologies onto farms and delivering the added output to markets.

As illustrated, it typically takes decades for the fruits of R&D to show up in farmers' fields as new, productivity-enhancing technologies. These considerable innovation and adoption lags mean that it will be decades before the economic and environmental benefits of the R&D policies and investment decisions made now will be fully realized.

# CHAPTER 2
# The Shifting Structure of US and Global Research and Development

With a significant share of supply growth stemming from productivity-enhancing investments in R&D, a more comprehensive understanding of past and prospective R&D investment trends is critical to understanding global food prospects. It is the magnitude and nature of R&D spending to which we now turn our attention.

## The patterns of overall global research and development spending in science are shifting

Increasingly, innovations—in areas like genomics or precision agriculture and other informatics technologies—that affect agricultural productivity arise from R&D done in or for sectors other than agriculture. To place food and agricultural R&D in this broader innovation landscape, this section begins with a brief look at new data on the changing global structure of science spending in general for both the United States and the world.

### Large spending differences between high- and low-income countries

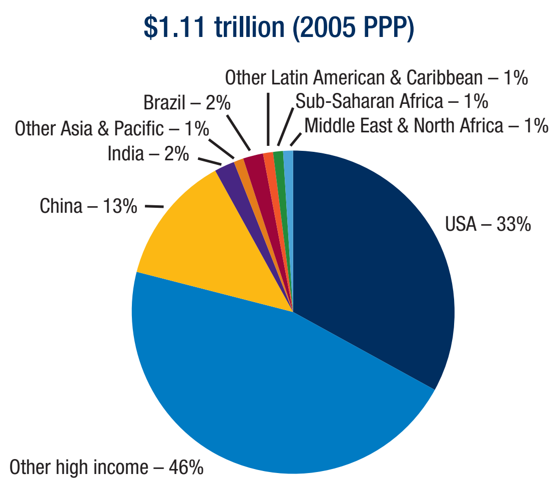
Estimates indicate that the world spent a total of $1.1 trillion (2005 PPP prices) on *all* types of public and private science R&D in 2009.[44] This is roughly a threefold increase (in inflation-adjusted terms) over the global R&D spending back in 1980. Yet the global divide in this spending is stark. Seventy-seven percent of the world's 2009 science spending was performed in just 20 high-income countries, with the United States alone accounting for 33 percent of the world total.[45] The 142 remaining countries of the world accounted for the remaining 23 percent of global spending. Notably, the middle-income countries of Brazil, India, and China (the BICs) accounted for 74 percent of this rest-of-world total. Most worryingly, the low-income countries (those 32 countries with GNP per capita averaging less than $1,005 per person and striving to support 11.7 percent of the world's population) accounted for a mere 0.4 percent of the world's science spending in 2009.[46] To underscore the magnitude of these spending differences, in 2009 the high-income countries invested $866 per person (2005 PPP prices) in R&D, while the middle-income group spent $50 per person and the low-income group committed just $6 per person.

The huge regional differences in the amount of investment in public and private R&D are plainly evident in figure 6. While China accounted for 13 percent of the world's R&D spending in 2009, the rest of Asia & Pacific (including India) had a global market share of just 3 percent—the same share as Latin America & Caribbean (including Brazil)—while sub-Saharan Africa accounted for less than one percent of the total.

### Greatest spending growth in middle-income countries, especially China

While the United States and other high-income countries still make up by far the largest share of global science R&D spending, there are signs of

**Figure 6 – Global public and private research and development spending, 2009**




Note: Eastern European and Former Soviet Union countries are excluded. Asia & Pacific includes China and India; Latin America & Caribbean includes Brazil. High-income countries are excluded from each geographical region. For example, Asia & Pacific excludes Japan and Singapore; Middle East & North Africa excludes Qatar and United Arab Emirates.

*Source: Data underlying Dehmer and Pardey,* Global Science Spending *(in process).*

an inexorable shift in the global R&D landscape. Growth in real spending in high-income countries from 2000 to 2009 was the lowest of all income groups, at just 3 percent per year. Spending in low-income countries grew by 6.9 percent per year during this same period (from a small base), while real R&D expenditures in middle-income countries grew by a staggering 12.5 percent per year.

The shifting patterns of investment in science spending overall are also reflected in spending on food and agricultural R&D more specifically, as shown in the next section. Moreover, the enormous geoeconomic differences in investments in scientific innovation worldwide will likely have a huge impact on the innovation potential for food and agriculture, especially to the extent that the sectoral and disciplinary boundaries of R&D are blurring and new ideas developed for one application or by one scientific discipline spill over and affect scientific or commercial activity in other sectors or disciplines.

## The geographical footprint of public spending on food and agricultural research and development is also shifting, and the United States is losing significant global share

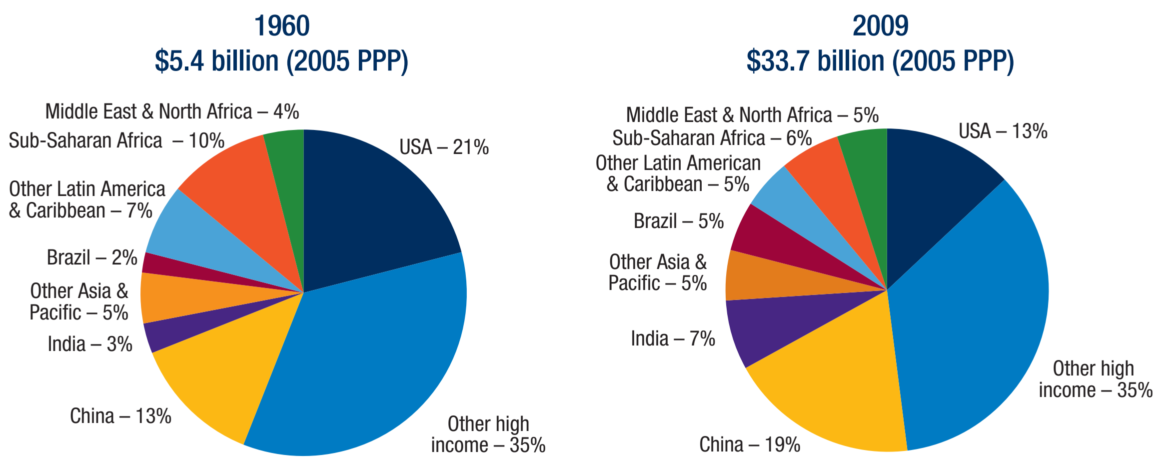
Over the past half century, and especially during the past decade or so, the global pattern of public agricultural R&D spending has also undergone a seismic shift.[47] While spending increased at an average, inflation-adjusted rate of 3.4 percent per year from $5.4 billion (2005 PPP prices) in 1960 to $33.7 billion in 2009 (figure 7), there have been significant, and of late accelerating, geographical shifts in the location of this R&D.

### Spending by middle-income countries now surpasses high-income countries

In 1960 the high-income countries—classified according to their average per capita incomes in 2009—accounted for 56 percent of the world's total. Almost 50 years later in 2009, that share had dropped to 48 percent.[48] This 8-point drop is accounted for entirely by a corresponding drop in the US share of spending, from 21 percent of the total in 1960 to just 13 percent in 2009.

Sub-Saharan Africa has also lost market share, declining from 10 percent of the world's total public-sector agricultural R&D in 1960 to 6 percent in 2009. So too has the Latin America & Caribbean region, although Brazil's share increased from 2 percent to 5 percent, while the rest of that region lost ground relative to the rest of the world. The notable expansion in market share was in the Asia & Pacific region, which grew from 21 percent of the world's public agricultural R&D in 1960 to 31 percent in 2009. China's share grew from 13 percent in 1960 to 19 percent in 2009—now surpassing the US share—while India's grew from 3 to 7 percent. China now spends more than any other country on public-sector agricultural R&D, including the United States.

**Figure 7 – Global public food and agricultural research and development spending, 1960 and 2009**

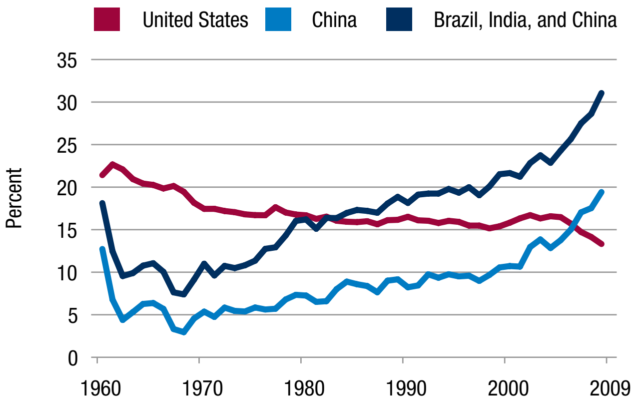



Note: See figure 6 for details on country coverage and groupings.

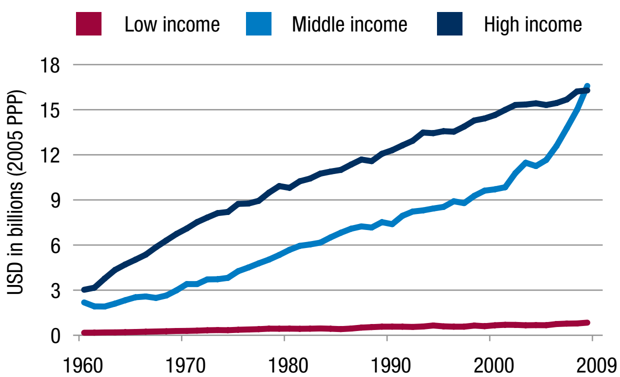
*Source: Pardey, Chan-Kang, and Dehmer (in process).*

## Figure 8 – Public agricultural research and development spending by income class, 1960-2009

### 8a – Countries as share of total global public agricultural research and development



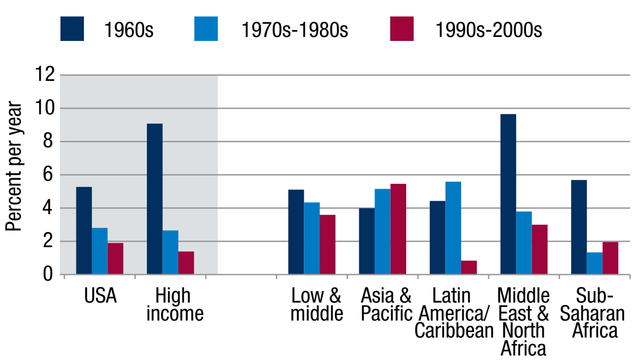

### 8b – Countries grouped by 2009 per capita incomes




Note: Countries are grouped into income classes using contemporary World Bank (2011, p. 305) schema and each country's 2009 per capita income.

*Source: Pardey, Chan-Kang, and Dehmer (in process).*

## Figure 9 – Rates of growth in public agricultural research and development spending by decade, 1960-2009




Note: Eastern European & former Soviet Union countries are excluded. All growth rates were calculated using the least-squares method (i.e., as the slope of a regression of logarithms of variables against trend). See figure 6 for details on country coverage and groupings. The 1960s indicates the period covering 1960 to 1970 and likewise for other decades.

*Source: Pardey, Chan-Kang, and Dehmer (in process).*

Figure 8a highlights the drop in the US share of the world's spending compared with the increase in spending by the middle-income countries, driven by China.[49] The US trend reflects the declining share of spending for today's rich countries as a group and for many of the countries within this group (specifically 20 out of 33 countries).

Figure 8b plots real spending from 1960 to 2009 by country income category. Again, the rapid increase in agricultural R&D spending over the past decade by today's middle-income group of countries, including Brazil, India, and China, is clearly visible, with spending now slightly surpassing the high-income countries.[50] Both groups spent around $16 billion dollars on public agricultural R&D in 2009. Over this same time period, the 28 countries in today's low-income group (of which 24, or 86 percent, are in Sub-Saharan Africa) made little headway vis-à-vis the rest of the world. In 2009 they collectively spent just $0.8 billion (2005 PPP) on agricultural R&D, less than 5.2 percent of the corresponding high- or middle-income totals that year.

Figure 9 shows the average rate of spending growth by decade since 1960 for the United States, the high-income countries as a group, and the low- and middle-income countries as a group further split into four regions. Reflecting the trends above, the rate of spending growth of the rich-country group (and of 29, or 88 percent, of the 33 countries in this group) has slowed markedly over the years and is now well below the low- and middle-income rate (1.4 percent per year versus 3.6 percent per year from 1990 to 2009). Among the low- and middle-income countries of the world, the increasing rate of spending growth in the Asia & Pacific region as compared with the slower pace of growth in Latin America & Caribbean and Sub-Saharan Africa is especially evident. From 1960 to 2009 the Asia & Pacific region sustained a 5.1 percent rate of growth per year, compared with 3.8 percent for Latin America & Caribbean and 1.8 percent for Sub-Saharan Africa. The 1990s was an especially dismal decade for Sub-Saharan African research, with less spending on agricultural R&D in 1999 than at the dawn of that decade.[51] Moreover, the more recent recovery in Sub-Saharan Africa appears fragile and was not widespread—over half the increase in spending from 2000 to 2009 came from just two countries (Nigeria and Angola).

**BOX 4**

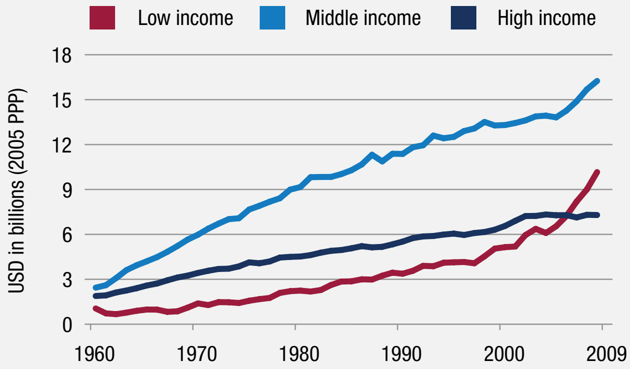
# The shifting geoeconomic order of public agricultural research and development investments

Over the past half century, the geoeconomic order of public agricultural R&D investments shifted, with the historically richer countries ceding ground in more recent years to those with rapidly rising per capita incomes. Table B4 shows the ranking of the top 10 countries in terms of spending in 1960–62 and in 2007–09. In the early 1960s the first-ranked United States spent almost three times more than the second-ranked China. By 2007–09 China was spending more than the United States. Germany dropped in the ranking, as did the United Kingdom (5th in 1960 versus 13th in 2009). By 2007–09 Australia had also dropped out of the top 10 (down to 16th). New entrants into the top 10 are Brazil (11th in 1960–62, 5th in 2007–09), Spain (31st to 9th), and South Korea (14th to 10th). India also moved markedly up the ranking from 8th to 4th.

Notably, spending on agricultural R&D has become more concentrated among the top 10 countries. In the early 1960s the top 10 countries ranked by public agricultural R&D spending accounted for 62 percent of the world's total spending; by 2007–09 this share had increased to 67 percent.

A similar trend can be seen in figure B4. Here countries are grouped into income classes according to their 1960 per capita income levels (versus their 2009 per capita income levels as in figure 8b). From this perspective, the 1960 middle-income category—which included France, Japan, South Korea, and Spain, all of which are now high-income countries—spent substantially more on agricultural R&D in 2009 than the corresponding 1960 high-income cluster.* Similarly, the 1960 low-income group includes China and India (now both classified as middle-income countries) and that group also spent more than the high-income cluster on public agricultural R&D in 2009. This once again shows the shift in spending toward countries with rapidly rising per capita incomes.

### Figure B4 – Public agricultural research and development spending by 1960 per capita incomes, 1960-2009




Note: Countries are grouped into income classes using contemporary World Bank (2011, p.305 ) schema and each country's 1960 per capita income.

*Source: Pardey, Chan-Kang, and Dehmer (in process).*

**Table B4 – Top 10 countries in public agricultural research and development spending, 1960s versus 2000s**

| Rank in 1960-62 | | | Rank in 2007-09 | | |
|---|---|---|---|---|---|
| Country | USD in millions (2005 PPP) | Rank in 2007-09 | Country | USD in millions (2005 PPP) | Rank in 1960-62 |
| 1. United States | $1,213 | 2 | 1. China | $5,767 | 2 |
| 2. China | $433 | 1 | 2. United States | $4,487 | 1 |
| 3. Germany | $339 | 6 | 3. Japan | $3,223 | 4 |
| 4. Japan | $310 | 3 | 4. India | $2,071 | 8 |
| 5. United Kingdom | $268 | 13 | 5. Brazil | $1,473 | 11 |
| 6. South Africa | $205 | 24 | 6. Germany | $974 | 3 |
| 7. Canada | $197 | 7 | 7. Canada | $871 | 7 |
| 8. India | $162 | 4 | 8. France | $867 | 12 |
| 9. Australia | $157 | 16 | 9. Spain | $795 | 31 |
| 10. Argentina | $137 | 19 | 10. South Korea | $792 | 14 |
| **Top 10** | $3,422 | | | $21,320 | |
| **Top 20** | $4,298 | | | $26,479 | |
| **Bottom 100** | $958 | | | $4,258 | |

*Source: Authors' calculations based on data from Pardey, Chan-Kang, and Dehmer (in process).*

Box 4 shows the top countries in terms of their public agricultural R&D spending for both 1960-62 and 2007-09. The geoeconomic order of agricultural R&D has markedly changed, with Brazil, France, Spain, and South Korea moving into the top 10 by 2007-09. Spending by countries according to their 1960 per capita income is also highlighted, revealing that the low-income countries of the early 1960s have recently surpassed the high-income countries in terms of R&D spending.

## Private sector making a significant contribution in high-income countries

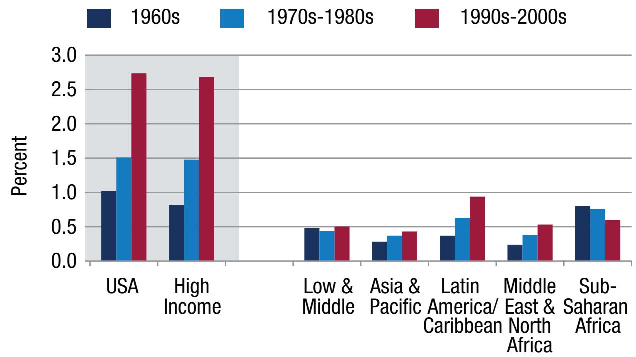
While our empirical handle on private investments in food and agricultural research is far from certain, the available evidence indicates that (a) the private share of global food and agricultural R&D is in the 35 to 41 percent range, (b) the lion's share of that research (89 to 94 percent) took place in the high-income countries, and (c) for the rich countries, almost one-half of that research was concerned with producing off-farm, primarily food processing, innovations.[52]

## Another view of spending—research intensities

Countries with larger (smaller) agricultural economies are likely to invest more (less) in agricultural R&D simply because of a congruence effect.[53] For this reason, looking at a country's agricultural research expenditures compared with the size of its agricultural economy provides one measure of the intensity of research spending. The research intensity ratios summarized in figure 10 are (weighted) averages by decades of the amount of public agricultural R&D spending relative to agricultural GDP.

By this measure, the United States and the high-income group have progressed steadily over the past 50 years towards an ever-more research-intensive mode of agricultural production. From just 56 cents for every $100 of agricultural output in 1960, these countries invested an average of $3.59 per $100 of output in public agricultural R&D in 2009 (figure 10). However, this increasing R&D intensity has occurred even as the rate of growth of agricultural R&D spending has slowed, an indication of an even more pronounced slowdown in the rate of growth of agricultural output in these countries.

### Figure 10 – Agricultural research intensities by region and income class, 1960–2009




Note: Agricultural research intensity indicates food and agricultural R&D spending relative to agricultural GDP.

*Source: Pardey, Chan-Kang, and Dehmer (in process).*

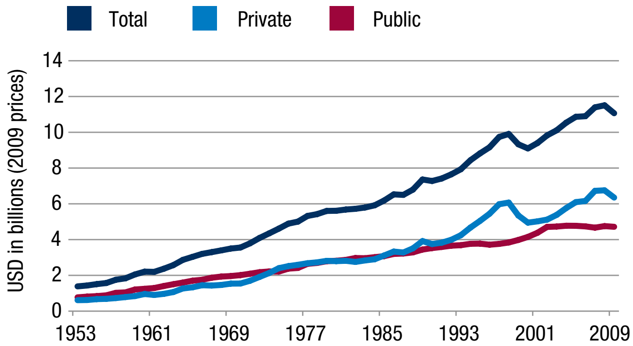
The intensity at which the Asia & Pacific region invests in agricultural R&D has grown much more modestly, from 0.40 percent of agricultural GDP in 1960 to 0.54 percent in 2009. While this region has sustained growth in agricultural R&D spending at a comparatively rapid pace, averaging 5.1 percent per year since 1960, agricultural output has grown at a rapid rate as well (3.8 percent per year). Thus, while the growth in spending on agricultural R&D outpaced the corresponding growth in the value of output, the growth rate differences were comparatively modest such that the region's research intensity only inched up over time, although increasingly so after the mid-1990s.

In distinct contrast to the other developing-country regions of the world, research intensities in Sub-Saharan Africa have been slipping, especially over the past couple of decades. According to data from Pardey, Alston, and Chan-Kang, 20 of the 43 countries in Sub-Saharan Africa had lower research intensities in 2009 than they did in 1980.[54]

## US food and agriculture research and development spending growth is slowing

Systemic shifts in the pattern of investment in agricultural R&D in the United States (and elsewhere in the world, especially among the high-income

## Figure 11 – US private and public agricultural research and development trends, 1953–2009




*Source: Public agricultural research series (exclusive of forestry research). Private food and agricultural research series (also exclusive of forestry research) from Dehmer and Pardey (in process). Implicit GDP deflator from Bureau of Economic Analysis (2012) used to deflate all R&D spending series.*

countries) give cause for concern. Notably, the pace of growth in real (inflation-adjusted) public plus private investment in US agricultural R&D slowed considerably over the past several decades, from 3.8 percent per year during the 1950s and 1960s, to 2.7 percent per year during the 1970s and 1980s, to just 1.2 percent per year during the years 1990 to 2009.[55] In the very recent past, US funding for public agricultural R&D (i.e., intramural spending by the US Department of Agriculture, USDA, and the state agricultural experiment stations, or SAESs) has transitioned from an extended period of slowing down to one of stagnation or even negative growth.[56] After adjusting for the rising costs of R&D, public agricultural R&D spending in the United States declined in all but one year after 2004, and by 2009 real spending was 7 percent below what it was in 2004.[57] If recent trends continue, the US market share of public agricultural R&D worldwide will continue to shrink.

Moreover, as other agricultural R&D agendas such as research on health, nutrition, the environment, and biofuels have gained ground, the share of SAES research directed to enhancing the productivity of US farmers—or simply sustaining past farm productivity gains via so-called "maintenance" research—has declined from an estimated 65 percent of the total in 1976 to only 56 percent in 2009. Available estimates suggest that between 35 and 70 percent of all agricultural R&D must be invested in maintenance research just to prevent productivity from falling.[58]

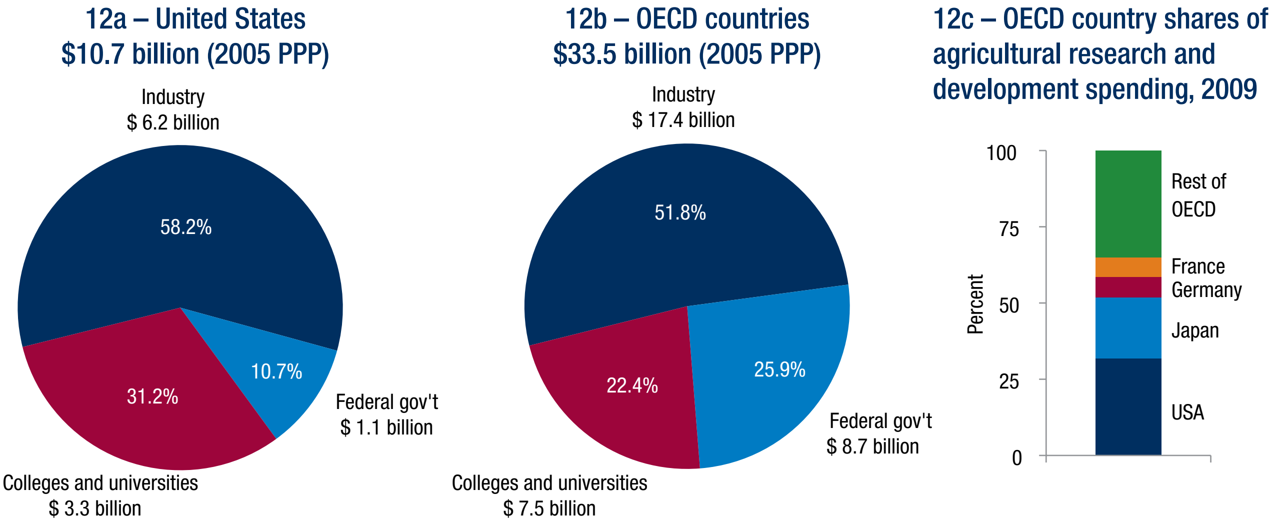
## Share of private funding has increased as public sector funding has faltered

Of total US agricultural R&D investments, the majority (58 percent in 2009) were made by the private sector, with the remaining 42 percent made by public agencies.[59] Although the private sector now spends more than the public sector on agricultural research in the United States, this has not always been the case (figure 11). According to Dehmer and Pardey, private food and agricultural R&D grew at an average rate of 8.6 percent per year over the past half century (or 3.2 percent per year after deflating by a purpose-built US agricultural R&D price index), from $90.4 million ($1.3 billion in 2009 dollars) in 1953 to $6.3 billion in 2009.[60]

The public and private agricultural R&D sectors in the United States generally grew hand in hand over the past 50 years.[61] Nonetheless, during the 20-year period after 1953 (the first year of data reported in figure 11), public spending exceeded private spending on agricultural R&D. Private and public spending were then very similar until the late 1980s, after which private spending exceeded public spending in all years. From an average of 44.1 percent in the three-year period from 1953 to 1955, the private share of agricultural R&D grew to 58.4 percent over the 2007 to 2009 period. This is still substantially less than the 78 percent of *all* R&D (i.e., agriculture, health, engineering, and so on) performed by private firms in the US economy in 2007 to 2009. Agriculture's share of total private R&D in the United States has fluctuated between 1.4 and 3.0 percent since 1953, with an overall declining trend since 1977.

Figures 12a and 12b juxtapose total (i.e., public and private) US spending on food and agricultural R&D against 24 high-income, OECD countries, including the United States. The United States accounts for around one-third of this high-income country spending (figure 12c). In the United States, a larger share of the total (58.2 percent) is spent by the private sector compared with the high-income average (51.8 percent, or 48.8 percent if the United States is excluded). The group average masks a good deal of variation among countries. The country with the lowest private participation rate was Greece (with an 11.3 percent private share in 2009); Switzerland had the highest private share (87.2 percent).

## Figure 12 – US and OECD agricultural research and development spending by sector, 2009




Note: All figures are in nominal US dollars and are inclusive of forestry research. For OECD, government includes R&D performed by the private nonprofit sector. The colleges and universities category of agricultural R&D spending for the United States includes SAES, 1890 Colleges, Veterinary Schools, Cooperating Extension Institutions, and Other Cooperating Institutions in all 50 US states and Washington, DC.

*Source: OECD spending figures are from OECD,* Aggregate Official and Private Flows *(2012). US public agricultural research series were extracted from Current Research Information System (CRIS) data files. Private food and agricultural research series are from Dehmer and Pardey,* Private Food and Agricultural R&D *(in process).*

### Federal research has shrunk relative to university research

Public agricultural research in the United States is conducted by federal agencies and by the SAESs and other cooperating institutions (e.g., veterinary and forestry schools) located throughout the land grant universities. The balance of research effort between local (state) and federal agencies has changed considerably since the mid-20th century. In 2009 one-quarter of US public agricultural research (or 10.7 percent of the public and private sector total) was conducted in federal government labs (mainly intramural research carried out by the USDA), while the rest was performed at the state level by the SAESs. Until the early 1940s, research conducted by the USDA and the SAESs accounted for roughly equal shares of public research spending, after which the SAES share grew to 74 percent of total public spending on agricultural R&D by 2009.

Compared with high-income countries as a whole, the percentage of research conducted by the SAESs located in the land grant universities is quite high. While nearly three-quarters of the public food and agricultural R&D in the United States is conducted by universities, roughly half the public research of the high-income country group is carried out by universities. Once again, behind this group average lies a substantial amount of cross-country variation. In countries such as the United Kingdom, Norway, and France, less than 20 percent of the public research is performed by universities, whereas in Denmark, Sweden, and the United States the corresponding university share is higher than 74 percent.[62]

## The structure and orientation of international research has shifted

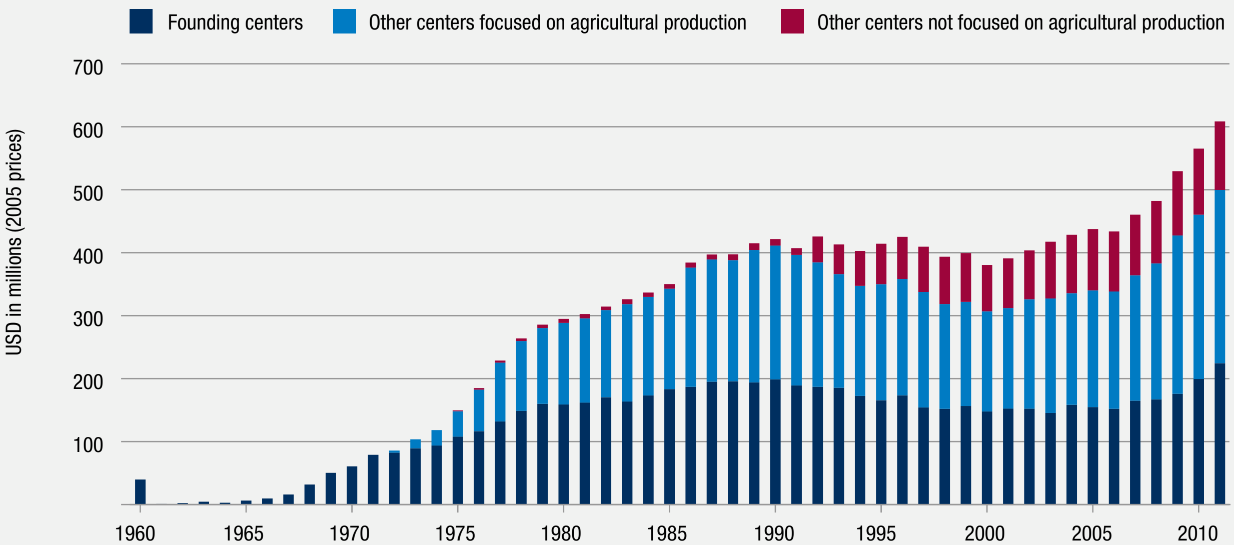
Efforts to develop formal centers of international collaboration began in the 1940s and continued through the 1960s with the founding of four international research centers that would become the core of the CGIAR (see also chapter 1). By 1970 the budgets of the four founding centers totaled US$15 million. With the creation of the CGIAR in 1971, the system began expanding over the next two decades (box 5). The total number of centers increased, as did the funding per center, with funding reaching US$305 million in 1990 ($422 million in 2005 dollars). After an abrupt cessation of growth in funding during the 1990s, funding began increasing again after 2000, reaching $690 million ($609 million in 2005 dollars) by 2011.

BOX 5

## Growth of the Consultative Group on International Agricultural Research, 1960-2011

The CGIAR began modestly. Between 1960 and 1964, of the institutes that would become the CGIAR, only the International Rice Research Institute was operating as such. From a budget of US$15 million for the four founding centers in 1970, the progressive expansion over the next decade involved a tenfold increase in nominal funding to US$141 million in 1980. During the 1980s funding continued to grow, more than doubling in nominal terms to reach US$305 million in 1990. Although the rate of growth had slowed, it was still impressive. In the 1990s two decades of growth came to an abrupt end. The number of centers continued to grow—from 13 to 18 at one point, but now 15—but funding did not grow enough in inflation-adjusted terms to maintain the real funding per center, let alone the rate of growth. In 2000 the CGIAR spent US$380 million (in 2005 prices, or US$338 million in nominal terms), less than the US$422 million (2005 prices) it spent in 1990. Total funding resumed growing after 2000, increasing to $609 million (2005 prices, or $690 million nominal dollars) by 2011.

**Figure B6 – Real expenditures of the Consultative Group on International Agricultural Research, 1960-2011**




Note: Data in US dollars deflated to 2005 prices with implicit GDP deflator from Bureau of Economic Analysis (2012).

*Source: Developed by authors from data underlying figure 5 in Pardey and Beintema (2001), updated by data from CGIAR (2012, and various other years).*

Over time, as agricultural productivity increased and donor priorities began to change, the allocation of funding among centers also changed. Throughout the 1970s and 1980s overall CGIAR spending grew at a substantially faster rate (9.7 percent per year) than the spending by the four founding centers (5.6 percent per year).[63] At the same time there was a broadening of the scope of the system beyond the main staple food crops, which was the focus of the founding centers, to include commodities such as potatoes, livestock, sorghum, millet, bananas, and plantains. Funding was also targeted to agricultural development issues such as food policy and the management of national agricultural research systems. Mirroring domestic agricultural research policy developments in the rich countries that mainly fund the CGIAR, during the 1990s the scope of the system broadened further to encompass forestry, fishery, water, and other issues. As a consequence, CGIAR activities now give less weight to directly enhancing the productivity of the main staple food crops relative to other activities.

The long-run shift in CGIAR priorities has been dramatic. Of the total increase in funding for the CGIAR since 1990 ($158 million in inflation-adjusted 2005 dollars) only 1.3 percent of that increased funding went to the four founding centers (or 34.7 percent if other centers that do research on specific agricultural commodities are also included such as the International Potato Center (CIP), the International Center for Agricultural Research in the Semi-Arid Tropics (ICRISAT), the International Network for the Improvement of Banana and Plantain (INIBAP), and the International Livestock Research Institute (ILRI). The overwhelming majority of the funds (64 percent) were directed to issues other than productivity improvements in rice, wheat, and maize. In 1990 the four founding centers constituted 47.2 percent (almost one-half) of the total CGIAR funding. By 2010 their share had fallen to 34.7 percent (just over one-third).[64]

## The Consultative Group on International Agricultural Research accounts for a declining share of global agricultural research investment

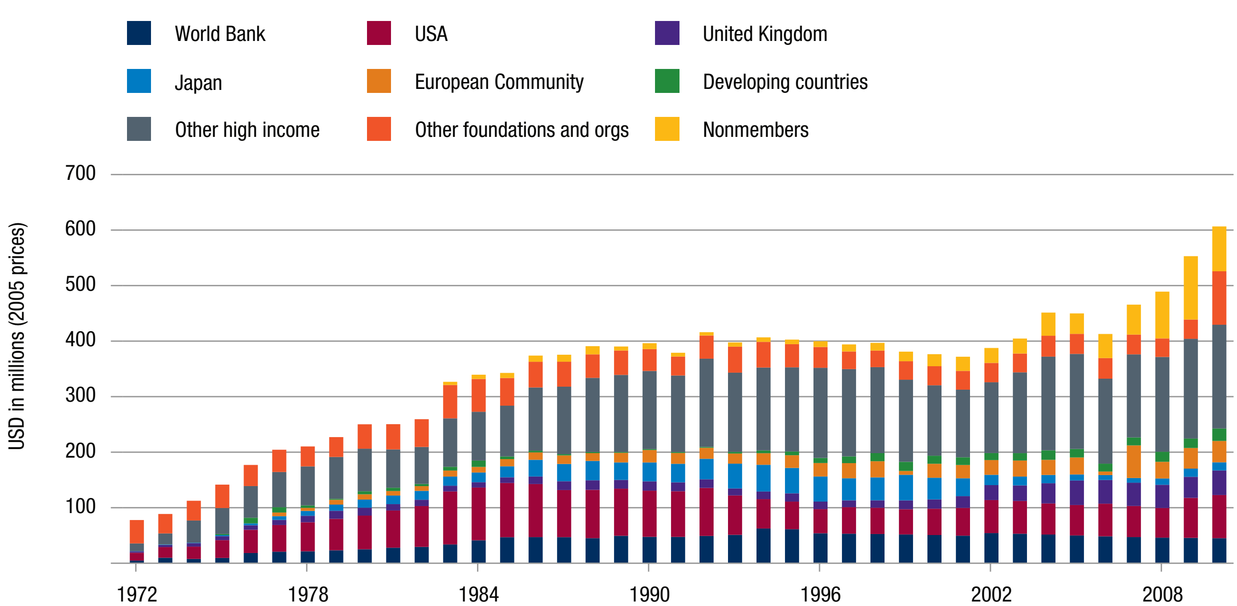
The size and scope of CGIAR activities vis-à-vis investments globally in food and agricultural research has also changed markedly. Although the CGIAR substantially accelerated the spread of new varieties of wheat, rice, and other technologies (commonly called the Green Revolution), it now receives only a small, and of late, declining fraction of the global agricultural research investment dollars. In 2009 it represented just 1.6 percent of the $33.7 billion spent on public-sector agricultural research worldwide or 3.0 percent of the research spending of the less-developed countries.[65]

Perhaps even more dramatic is the shift in the size of the CGIAR relative to particular rich and middle-income countries. In 1970 public spending on agricultural research in the United States was 30.7 times more than that of the CGIAR ($1,883 million against $60.7 million for the CGIAR in 2005 dollars), while Brazil, India, and China as a group spent only 19.6 times more than the CGIAR. By 2009 the spending relativities had shifted dramatically. US public funding had fallen to just 8.5 times larger than the CGIAR that year compared with 19.8 times larger for the Brazil, India, and China group.[66]

## US government contributes an increasingly smaller share of funds

The majority of CGIAR funding (59.7 percent in 2010) comes from high-income countries, although the relative importance of countries within that group has changed over the years (figure 13). Notably, the US share of CGIAR funding has declined. In the first few years after the CGIAR's formation (1972 to 1975), the United States accounted for 20.8 percent of CGIAR funding. The US share

**Figure 13 – Sources of Consultative Group on International Agricultural Research funding, 1972-2010**




Note: Data in US dollars deflated to 2005 prices with implicit GDP deflator from Bureau of Economic Analysis (2012).

*Source: Developed by authors with data from CGIAR (various years).*

peaked at 29.3 percent in 1983 but stood at only 12.8 percent in 2010. [67]

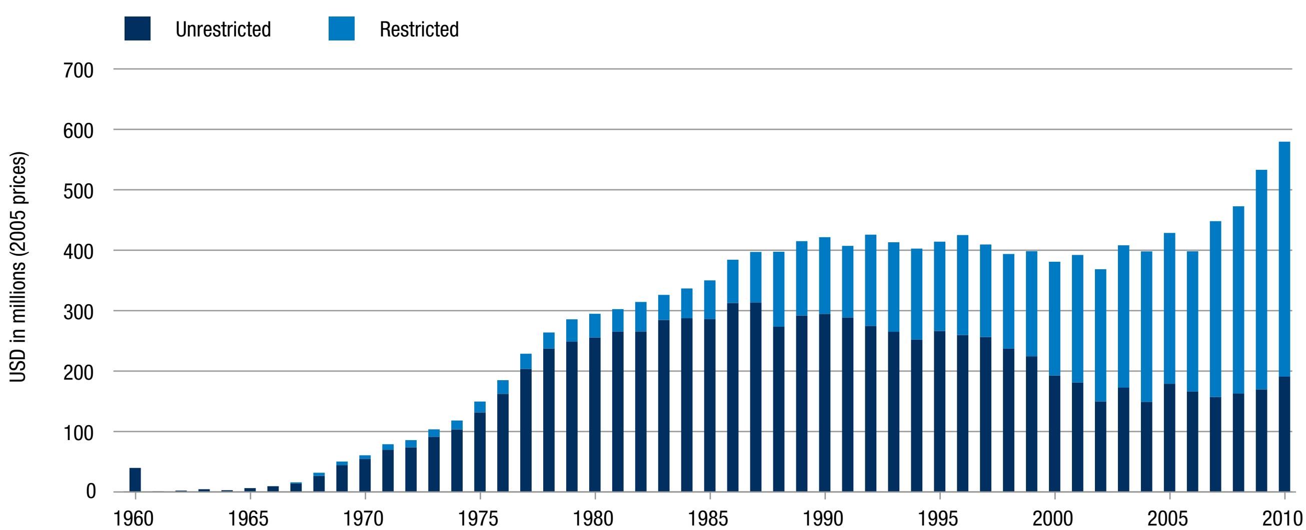
Notwithstanding the fluctuations in US support, the United States is still the largest single (country) donor to the CGIAR.  Other countries have increased their share of CGIAR funding in the past few years, especially the United Kingdom, Australia, and Norway. The other high-income group of countries—i.e., excluding the traditional major donors (consisting of the United States, European Union, United Kingdom, and Japan)—accounted for 30.8 percent of total CGIAR funding in 2010 ($186.9 million in 2005 dollars). The low- and middle-income countries have always accounted for a small share of the total (3.7 percent in 2010). The amount of funding coming from these countries, however, fueled especially by increases from China and India, has increased relatively rapidly of late (albeit from a comparatively small base), growing at an average inflation-adjusted rate of 11.5 percent per year from 2006 to 2010 (from $14.1 million to $22.4 million in 2005 dollars). This compares with growth of 8.4 percent per year for the United States and 9.9 percent per year overall over the same recent period.

Two other notable developments have been the decline in support from Japan (peaking at $48.1 million in 1994 and falling to $14.7 in 2010 in 2005 dollars) and the reemergence of philanthropic support. While the Ford and Rockefeller Foundations were instrumental in the establishment of a collective funding approach to international agricultural research that evolved into the CGIAR, they now provide a relatively small share of the CGIAR's funding (a total of $1.8 million in 2010). Recently there has been a dramatic rise in support from the Bill and Melinda Gates Foundation (BMGF), which has been pivotal to the revival of overall CGIAR funding in the past few years. In 2010 BMGF contributed $71.4 million to the CGIAR coffers, almost as much as the entire US contribution.

## Consultative Group on International Agricultural Research's unrestricted funds have declined

Another dramatic shift in CGIAR finances is the decline in unrestricted funding compared with restricted funds (figure 14). In CGIAR parlance, unrestricted funds are grants made directly available to centers "with no restrictions on their use," whereas restricted grants are made to centers "with terms restricting the use of money for a particular project or use."[68] Thus, unrestricted funds are earmarked for a particular center, with spending within a center being largely at the discretion of that center's management. This was the dominant

**Figure 14 – Restricted versus unrestricted Consultative Group on International Agricultural Research funding, 1972-2010**




Note: Data in US dollars deflated to 2005 prices with implicit GDP deflator from Bureau of Economic Analysis (2012).

*Source: Developed by authors with data from CGIAR (various years).*

method of funding for the CGIAR throughout the 1970s. Typically, newly created centers were fully funded with unrestricted support, and unrestricted funding for existing centers remained a significant share of their revenues through the early 1980s. In 1982 an average of 84.5 percent of total CGIAR funds were unrestricted (82 percent for the four founding centers and 87.5 percent for the newer centers). By 2010 that percentage had dropped to just 32.9 percent.[69] Correspondingly, the share of funds earmarked for specific purposes rose from 10.2 percent in 1970 to 67.1 percent in 2010. This is a massive change in how and who makes decisions about the deployment of CGIAR resources.

Beginning in 2010, a new funding and operational model for the CGIAR was launched in an effort to make a clearer distinction between funders and researchers, and to set up more strategic, multicenter modes of operation and funding.[70] A new Strategy and Results Framework, developed by the Consortium of Agricultural Research Centers and endorsed by a Funders Forum, is being implemented through a number of CGIAR Research Programs (CRPs). The CRPs are intended to become the dominant mechanism for funding and executing R&D throughout the system, reducing the role of bilateral (or direct) funding of individual centers by donors.[71]

This latest attempt to strategically "reform" the funding and operations of the CGIAR centers is still in its early stages. To what extent these new (and still evolving) institutional structures will enhance the operational efficiencies of and social payoffs to funds spent by the CGIAR centers is an open question. Notwithstanding the changes presently under way, some things have not changed. Efforts to fundamentally streamline the system by merging centers or programs within centers have yet to be achieved. And, as Alston, Dehmer, and Pardey observed, a "fundamental design flaw" of the system still exists, with priorities determined (or at least still markedly influenced) by donors who typically do not represent the science agencies of these donors (e.g., in the case of the United States, USAID rather than, say, the National Science Foundation or the USDA's National Institute of Food and Agriculture).[72] This builds in pressures to direct the system to shorter-term, economic development efforts at the expense of doing R&D with longer-term, economic growth objectives in mind. It also tends to disconnect decisions about funding international research from decisions about funding domestic R&D.

The long-run reduction in the share of CGIAR resources being used for research intended to enhance the productivity performance of agriculture is one indication that the traditional comparative advantage of the CGIAR (as a unique, research-based instrument for economic growth and agricultural development focused on staple food crops) has diminished. Putting flesh to the bones of this new CGIAR structure that enables the CGIAR to *meaningfully* prioritize and (re-)engage itself in a global public and private R&D landscape that has and will continue to grow and change markedly will be the ultimate test of success.

## Direct US support for country research programs has trended downward

Beyond support for the CGIAR, the United States (mainly government, but also some philanthropic and private firms) promotes agricultural productivity and economic growth in other parts of the world through direct support of agricultural R&D carried out by other, mainly poor countries. The nature of this funding has changed dramatically as well over the years. Total public funding for this form of foreign aid has followed a familiar pattern, growing rapidly through the 1960s and 1970s, peaking in the 1980s, and falling precipitously during the 1990s until beginning a renewed upward trend after bottoming out in 2008.[73] The fluctuating fortunes of agricultural research funding quite closely mirrored the priorities afforded agriculture in overall development assistance funding (box 6).

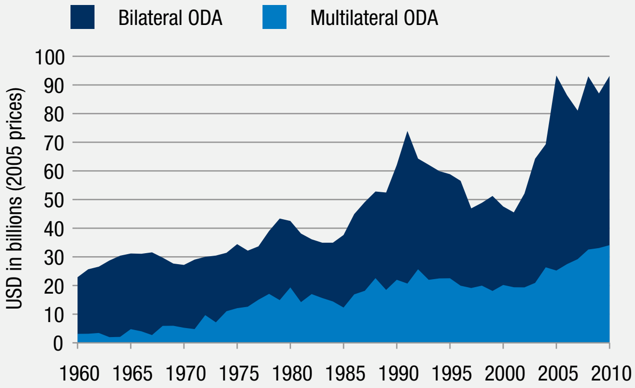
The shifting geography of US aid earmarked for agricultural R&D is also revealed in figure 15. During the 1950s and 1960s, 33 percent of USAID funding going to rest-of-world (ROW, or the world excluding the United States) agricultural R&D went to the Asia & Pacific region. The share of support going to Latin America & Caribbean also began growing in the 1960s, and especially during the 1970s. Thereafter, support to national research activities in Asia & Pacific and Latin America gave way to increased funding for research in Sub-Saharan Africa, which peaked in the 1980s. Africa now accounts for the lion's share of USAID funding

## BOX 6

# Development aid—total and agriculturally oriented, 1960-2010

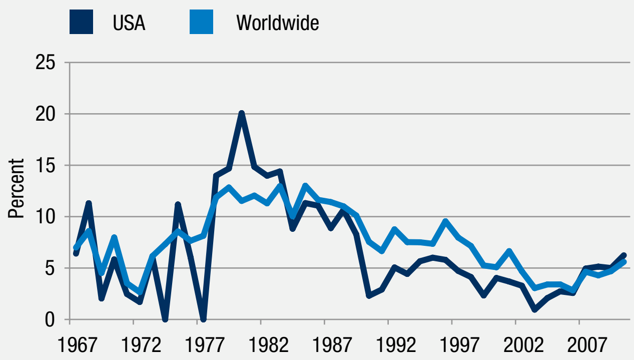
### 6a – ODA worldwide, 1960-2010

Total official development assistance (ODA) worldwide grew from $26 billion in 1960 to $127 billion in 2010. About 73.2 percent of the aid flows bilaterally from country to country; the remainder supports work by a host of multilateral agencies, including the CGIAR. In 2010 the United States accounted for 22.1 percent of total ODA. This was just 0.22 percent of the country's GDP (compared with an average of 0.51 percent of GDP for the other rich countries of the world), or $101 per person (compared with a rest-of-rich-world average of $198 per person).



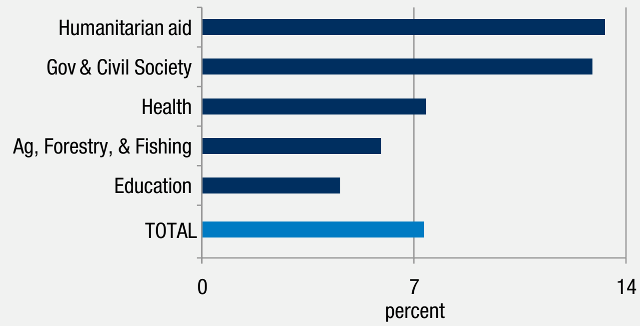

### 6c – Agricultural share of ODA, 1967-2010

As real food prices declined and the perceived threat of a shortfall in global food production receded, the agricultural share of worldwide ODA (light blue line) trended down from a high of 13.0 percent in 1985 (20.1 percent for the United States in 1980, dark blue line) to bottom out at 2.8 percent in 2006 (1.0 percent for the United States in 2003). Since then the agricultural share has risen, but is still below the corresponding 1967 shares.



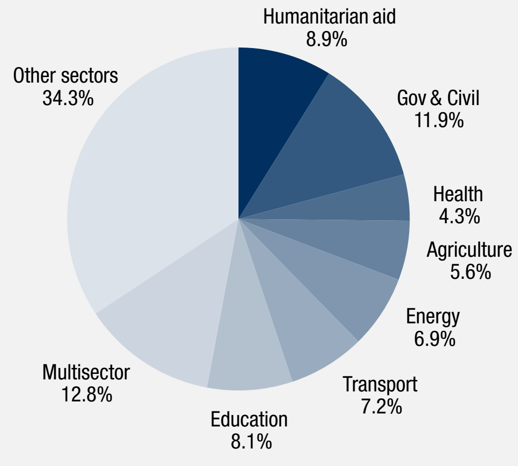

### 6b – Growth of ODA by type, 1971-2010

Since 1971 the fastest-growing component of the world's ODA has been humanitarian aid (13.3 percent per year), directed mainly to the food, shelter, and health consequences of wars, famines, and natural disasters. In contrast, aid to agriculture has grown on average by only 5.9 percent per year, below the average rate of growth of ODA of 7.3 percent per year.




### 6d – Sectoral structure of ODA, 2010

In 2010, 5.6 percent of all ODA was directed to agriculture, less than the funds going to other sectorally oriented aid spent on education, transport, and energy, a smaller share than is used for humanitarian aid and the development of government and civil institutions.

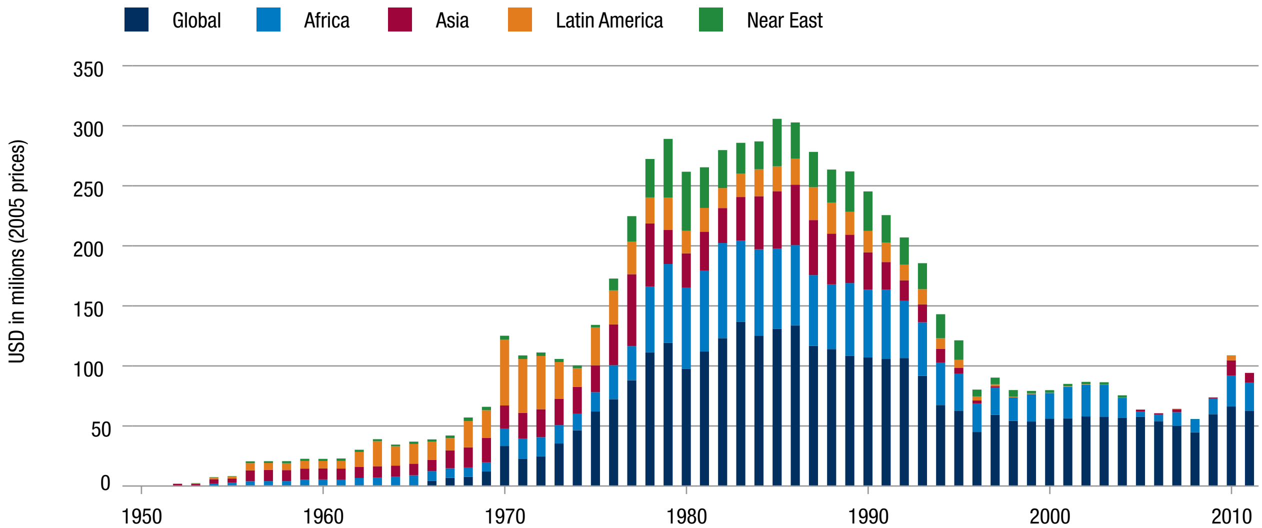



Agriculture includes forestry and fishing. Transport includes storage.

Note: Data pertain only to funding from countries that are members of the Development Assistance Committee (DAC).

*Source: OECD,* Aggregate Official and Private Flows *(2012) and OECD,* Aggregate Sector Level Data *(2012).*

## Figure 15 – US aid directed to agricultural research by region, 1950-2010




Note: Data in US dollars deflated to 2005 prices with implicit GDP deflator from Bureau of Economic Analysis (2012).

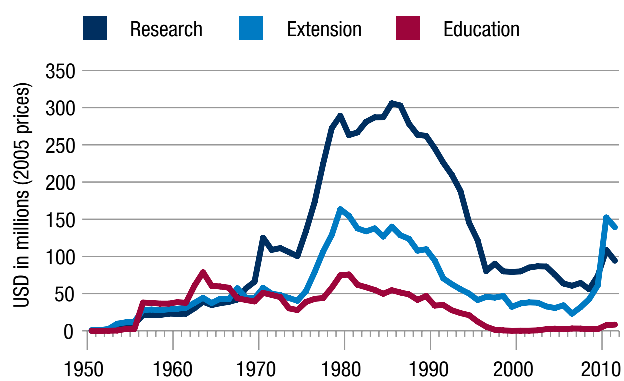
*Source: Developed by authors with data from Alex (2012).*

for ROW national agricultural research (75 percent in 2011).

Over the long run, there has been an inexorable rise in the share of USAID's ROW agricultural research funding going to international—mainly CGIAR—research that has come at the expense of funding for national research programs. In the 1950s and 1960s, before the CGIAR was formed, almost all USAID funding went to support research carried out within national systems, mostly in low- and middle-income countries. As the CGIAR developed, ROW funding directed to the CGIAR and other global efforts grew from 37.4 percent during the first half of the 1970s to an average of 51.3 percent during the 1990s and 75.8 percent by the last half of the 2000s. Thus, while US support to the CGIAR declined after the mid-1980s, this was in the context of an even more dramatic drop in USAID support to research (and agriculture) generally. As a consequence, US support to ROW research shifted heavily in favor of research carried out by the CGIAR rather than research carried out by national programs around the world.[74]

In addition to spending on ROW research, the United States has sought to promote productivity growth in ROW agriculture through investments in agricultural extension and education. Figure 16, shows the shifts in these priorities over time. From the mid-1950s to mid-1960s, funding to agricultural education was the highest priority; now it ranks last on this list. From the mid-1960s to all but the past few years, research funding received the highest priority, with strong growth from 1965 to 1985 followed by a sustained and sharp decline through 2007. Although real funding to agricultural R&D has picked up since then, the recent growth in funding to agricultural extension activities has been more pronounced, comprising 57.6 percent of the total research, education, and extension budget in 2011 ($139 million in 2005 dollars) compared with 39 percent going to R&D ($94 million).

## Figure 16 – US investments in agricultural knowledge, 1950-2010




Note: Data in US dollars deflated to 2005 prices with implicit GDP deflator from Bureau of Economic Analysis (2012).

*Source: Developed by authors with data from Alex (2012).*

# CHAPTER 3
# Rethinking Global Agricultural Research and Development

To safeguard the hard-won productivity gains made in agriculture over the past half century and meet the future challenge of feeding two billion more people by 2050 will require revitalizing the institutions and investments that promote productivity growth in global and poor-country agriculture. Refinancing and refocusing CGIAR efforts to emphasize innovation activities with potentially high social payoffs is one way forward. But the CGIAR constitutes just 1.6 percent of global food and agricultural R&D investments in the public domain and less than 1 percent of total (public and private) food and agricultural R&D worldwide (data from 2009).[75] A more comprehensive perspective on the entire world's innovative capacity in food and agriculture is needed to effectively tap the rest-of-world knowledge stocks for the benefit of poor-country producers and take advantage of some especially promising and economically rewarding opportunities, especially given the fragile and shifting nature of funding for food and agricultural research. In this section, new data on the accumulated knowledge stocks and spillover potentials of countries around the world are presented to help provide this perspective and better inform and guide innovation policies.

While bilateral (country-to-country) spillovers of agricultural innovations have long been, and still are, a significant source of agricultural productivity growth for all countries, the nature of and prospects for spillovers have typically failed to figure highly in the formulation of domestic research policies and institutions designed to spur local agricultural sectors. Repositioning and reconceiving public R&D efforts to make more effective use of spill-in potentials for all (especially poor) countries are likely to have high payoffs, especially given a likely continuation of the global underinvestment in food and agricultural R&D.[76] While the low-income countries as a group had accumulated an agricultural knowledge stock of just $452 million (2005, PPP prices) by 2009, we show that on average they individually have the potential to tap over 1,000 times their own knowledge stock from the stock of global knowledge, even after accounting for differences due to the site specificity of most agricultural innovations.

## Estimating accumulated knowledge stocks and spillover potentials

The size of the accumulated stock of knowledge, not merely the amount of investment in current research and innovative activity, provides a more meaningful measure of a country's technological capacity and the state of innovation. To illustrate the current comparative innovation capacity in agriculture worldwide, encourage long-term thinking about these innovation processes, and properly place that thinking in an international setting, we have developed money measures to quantify these stocks of productive knowledge resulting from agricultural R&D spending. Two types of measures have been developed. One is a measure of the accumulation of productive knowledge from a country's own R&D (dubbed "home-grown" knowledge), and the other is a measure of the potential stock of knowledge spill-ins from R&D done elsewhere in the world.[77]

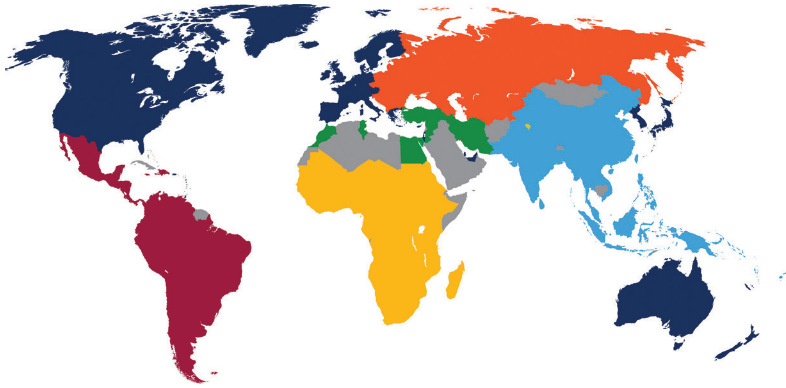
The current stock of productive knowledge and the contribution of past research spending to that stock are affected by the type of research, the institutional structures surrounding the research, and the economic context that affects the use of this stock. For example, while some science makes persistent (and even perpetual) contributions to the accumulated stock of locally produced knowledge, spending in societies ravaged by wars, institutional instability, and outright collapse may have a much more ephemeral effect.

### "Home-grown" knowledge

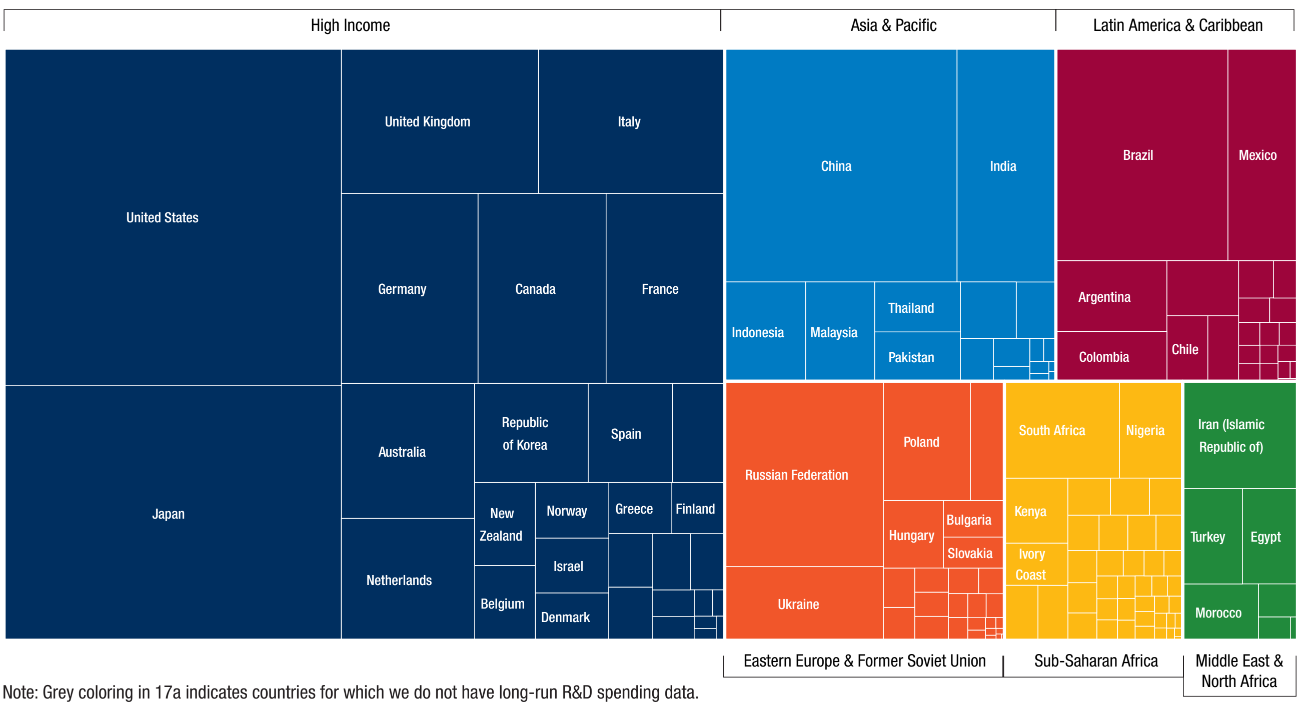
In calculating own-country knowledge stocks, we account for the lag between research spending and the production of useful knowledge since expenditures in a given year not only make immediate or near-term additions to the knowledge stock, but also contribute to a stream of useful knowl-

## Figure 17 – Total world knowledge stock, as divided by region and country
*(greatest knowledge stocks in high-income countries and Brazil, Russia, India, and China)*

### 17a – Country groupings



### 17b – Global agricultural knowledge landscape




Note: Grey coloring in 17a indicates countries for which we do not have long-run R&D spending data.

*Source: Authors' calculations as described in Beddow, Pardey, and Bittinger (in process).*

edge over the next half century (if the lag structure found by Alston et al. 2010 is imposed). Using data on country-by-country public R&D spending from 1960 to 2009, along with this lag structure, we calculate that the global, public pool of productive scientific agricultural knowledge in 2009 was about $18.6 billion (2005 PPP dollars).[78] About one-third of the world's public agricultural knowledge stock was generated by three countries: the United States (14.9 percent), Japan (11.2 percent), and China (7.1 percent). Nearly half of the world's agricultural knowledge stock was generated by seven countries (the three listed previously plus Brazil, Russia, the United Kingdom, and Italy).

To aid in interpretation, we divide the world into six groups (figure 17a).[79] First, we separate out the 33 high-income countries regardless of where they are located. The remaining middle- and low-income countries are grouped by region: Asia & Pacific (19 countries), Eastern Europe & the former Soviet Union (28 countries), Latin America & the Caribbean (24 countries), the Middle East & North Africa (7 countries), and Sub-Saharan Africa (43 countries). The 33 high-income countries account for about 56 percent (an average share of 1.7 percent per country) of world agricultural knowledge stocks, while the Sub-Saharan African countries account for about 6 percent, or an average of 0.14 percent per country. The regional breakdown of world agricultural knowledge stocks is shown in figure 17b, where the size of each rectangle represents a region's share of total agricultural knowledge stocks. Each region is sub-divided into its constituent countries, with each country's rectangle scaled accordingly. Of particular note is that while some regions account for a relatively small share of world agricultural knowledge stocks, there are still countries within the respective regions that play an important role in generating new knowledge. For example, China, Brazil, Russia, South Africa, and Nigeria all accounted for relatively large shares of the global public stock of productive agricultural knowledge.

## "Other people's" knowledge (spillover potential)

In the decades ahead, substantive institutional innovation may be necessary to achieve efficient jurisdictions for agricultural R&D that differ among commodities and according to the lines of work being undertaken, especially in light of the rapidly changing technologies of agriculture, communication, bioinformatics, transportation, and science itself. One way to gain a better sense of the nature and magnitude of cross-country R&D spillovers is to estimate the *potential* for research done in one country to affect agricultural productivity elsewhere in the world. As a first approximation, Beddow, Pardey and Bittinger assume that countries conduct research largely in proportion to the makeup of their agricultural systems.[80] For example, a country's research program is likely to be shaped by the crops produced in the country and the environments in which those crops are produced. Thus, a country that grows little rice will devote few resources to rice research, and a country that does not produce in tropical environments will put little effort to improving agricultural productivity in those environments. The authors developed a metric of similarity to characterize the agricultural systems of a country; not just in terms of what is produced, but also where and under what agroecological conditions.

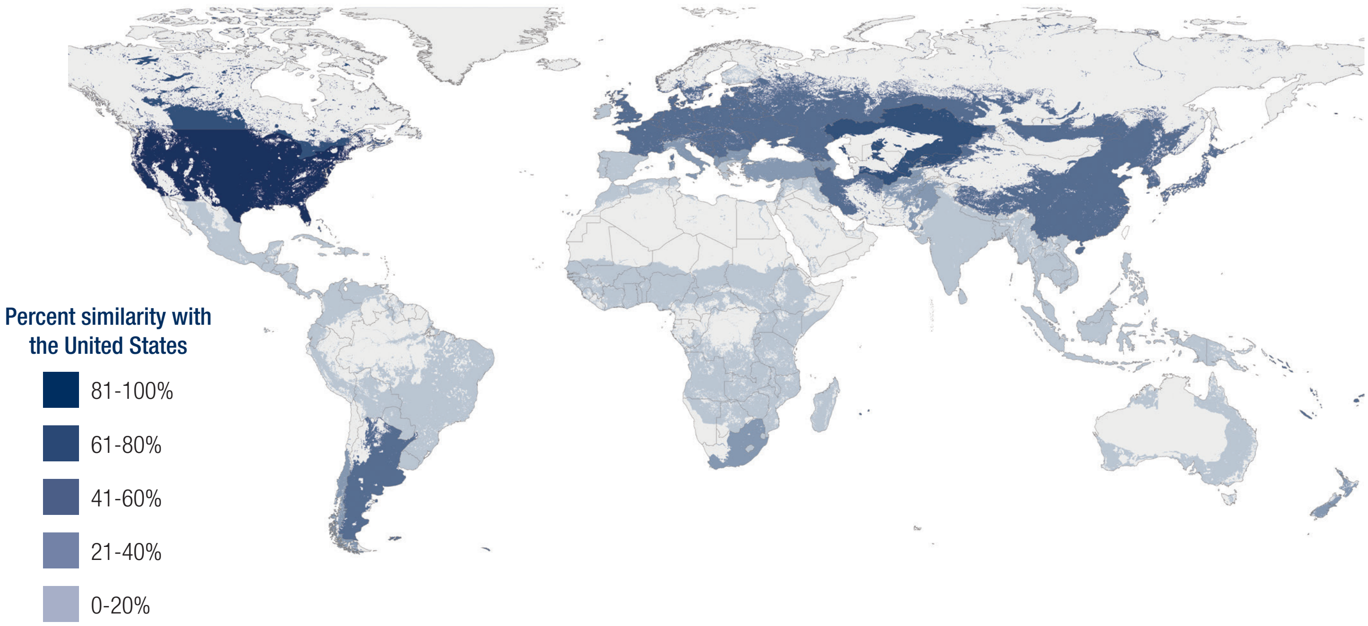
### Agroecology-based spillover potential

The agroecological view of the landscape of production takes various types of ecological zones into account, considering factors such as aridity (moisture), temperature regimes, and thermal zones (e.g., tropical, temperate, and subtropical). From this information, 20 distinct agroecological zones were identified. The share of a country's agriculture that takes place in each of these zones gives a high-level view of the country's production from an agroecological perspective and gives insight into the potential for knowledge spillovers between countries. For example, over 70 percent of Kenya's production area is within arid and semiarid, warm tropical areas, while almost 80 percent of the United Kingdom's agricultural area is in temperate, subhumid areas. We would expect, therefore, that comparatively little of the United Kingdom's research would generate knowledge suitable to be of direct benefit to Kenya (and vice versa). Some technologies may well spill over, but most would require further research to adapt them to local conditions.[81] In locales with similar agroecologies to the United Kingdom, technology transfers would be less problematic and less costly.

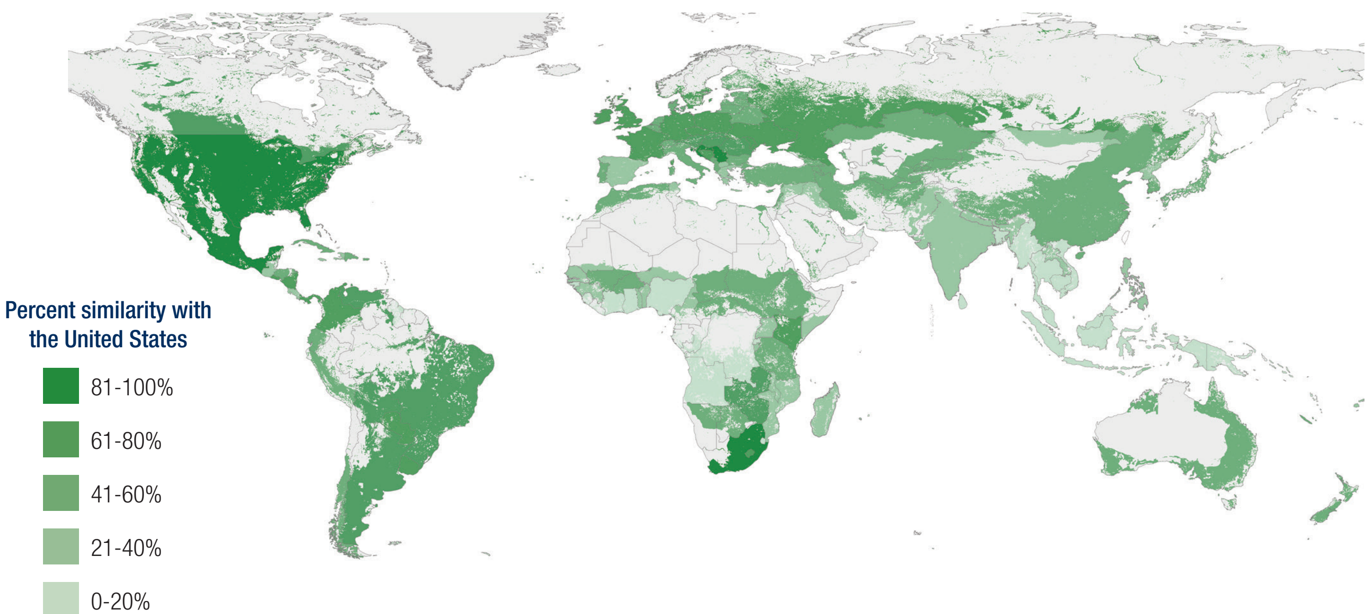
Figure 18a shows the similarity of the agricultural area of countries the world over to that of the United States using a cross-country "technological distance metric." A metric value near one indicates that the agroecology of production is very similar to that of the United States, and a value near zero indicates that the agroecology of production is very different. The map reveals that countries in the middle northern latitudes tend to have agricultural environments that are, on average, more similar to that of the United States than countries located elsewhere. From this agroecological perspective, we therefore expect that more of the agricultural research undertaken in the United States might be transferable to the middle northern latitude countries (and vice versa).

## Figure 18 – Agrotechnological distances

### 18a – Similarities in agroecologies




### 18b – Similarities in agricultural production




*Source: Calculated by the authors as described in Beddow, Pardey, and Bittinger (in process).*

### Production-based spillover potential

Another view is that the overall research effort within a country may be apportioned in ways that are roughly congruent with the value shares of the commodities that are domestically produced. Figure 18b shows the similarity of each country's mix of agricultural outputs relative to the United States. This assessment yields a quite different view of potential knowledge spillovers, with countries such as Mexico and South Africa being able to potentially benefit more from R&D performed in the United States. The production-based comparisons also give a markedly different view of US research spillover potential for eastern and southern Sub-Saharan Africa. These areas are fairly similar to the United States in terms of their overall production mix (figure 18b), but are quite dissimilar in their agroecologies (figure 18a). Thus, while commodity-based research in the United States will likely be useful in eastern and southern Africa (and vice versa), that research would likely need to be adapted to the ecological realities of the recipient countries. This is also true for research results emanating from Brazil, much of Eastern Europe, Australia, and to a lesser extent, Argentina. On the other hand, few countries with similar agroecologies to the United States are also highly dissimilar in terms of what they produce.

### Local versus spill-in knowledge

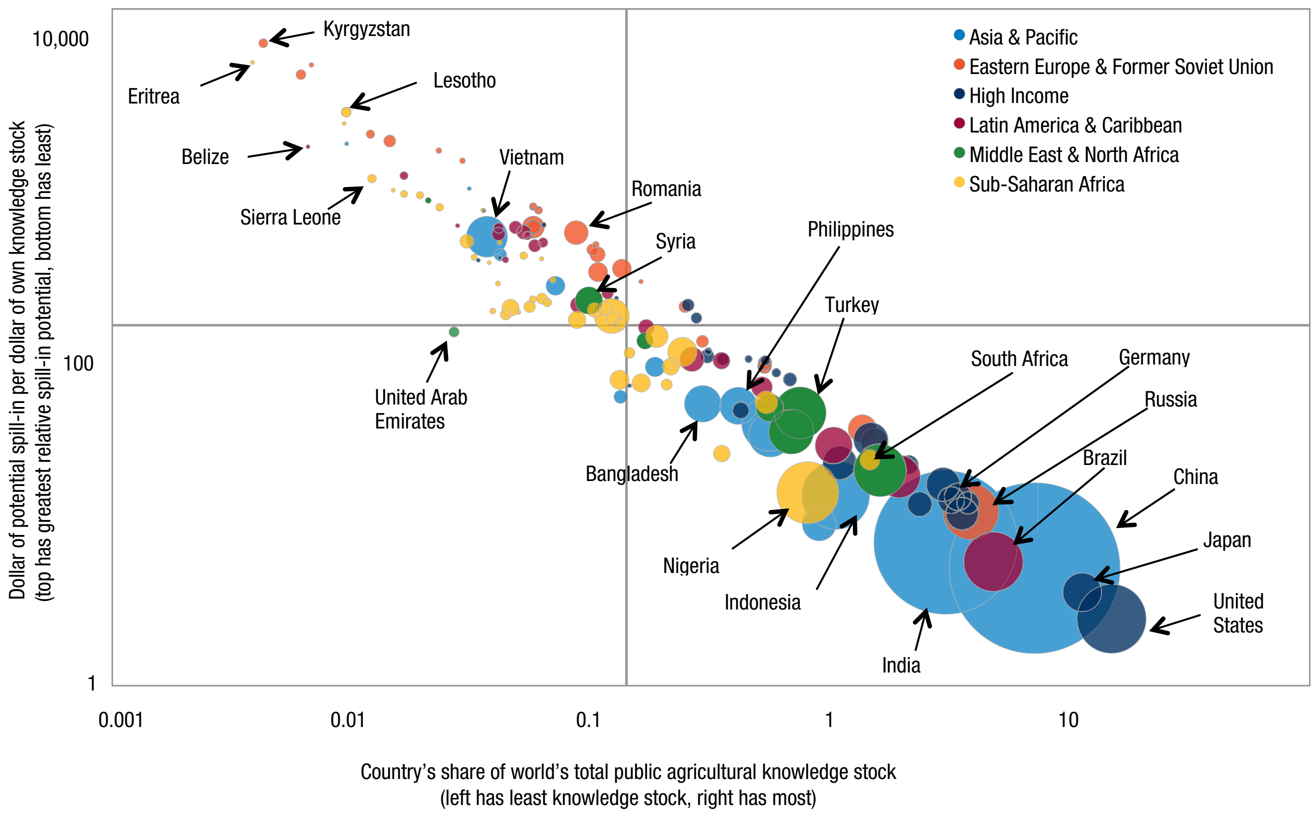
In addition to looking at spillover potentials between the United States and all other countries of the world, Beddow, Pardey, and Bittinger estimate the potential for agricultural knowledge to spill into each country from every other country, averaging the potential based on agroecological and production similarities.[82] For example, by this measure of spillover potential about 49 percent of US agricultural knowledge could be applicable to Danish agriculture, while only about 29 percent of US agricultural knowledge might be applicable to South Africa. For a given country, the total knowledge that could spill in from another country is given by the percentage similarity multiplied by the stock of knowledge in the other country. Summing these values for all countries provides an estimate of the total global stock of knowledge that might be relevant to each country—the amount that could spill in.

Figure 19 brings together a number of different measures to provide a new perspective on global spillover potentials. Each country is represented by a circle, the area of which is proportional to that country's agricultural GDP in 2009.[83] The colors of the circles represent geopolitical groupings of countries (see figure 17a). The horizontal axis of figure 19 shows each country's share of the world's pool of productive, public agricultural knowledge. The United States is positioned on the far right of the horizontal axis, with the largest share (14.9 percent) of the 2009 global public stock of knowledge. Eritrea is on the far left with the smallest share (just 0.007 percent).[84] The vertical axis shows a country's spill-in ratio, or the total amount of knowledge in dollars that could potentially spill in relative to a country's own stock of knowledge. The higher the ratio, the higher the *relative* spill-in potential. For example, a ratio of 1,000 indicates that for each dollar a country invests in agricultural R&D, it could potentially tap $1,000 of spill-in knowledge. All countries have positive spill-in ratios—ranging from about 2.6 for the United States to over 16,700 for Albania (not shown in figure)—and therefore, all countries can potentially benefit from knowledge generated elsewhere.

There are few agricultural technologies that can be transplanted from one country to another without modification. Alston and Pardey broached the idea of diseconomies of economic distance in R&D and its implications for R&D spillovers, and their core idea holds here as well.[85] As a region, by some measure, is more distant (technologically different) from another, the costs of adapting R&D increase. A high spill-in ratio indicates that a large pool of knowledge could potentially be adapted to the local environment relative to the domestic stock of knowledge and that much technology could likely be used with little or no modification. As spill-in ratios decline, this indicates that relative to the domestic stock, there is less foreign knowledge to tap.

The data show that most of the Sub-Saharan African countries have above-average potential spill-in ratios. On average, Sub-Saharan African

**Figure 19 – Spill-in potential and world share of knowledge stock by country, 2009 (area of circle is proportional to a country's agricultural GDP)**




*Source: Authors' calculations as described in Beddow, Pardey, and Bittinger (in process).*

countries can tap around 574 times their locally produced agricultural knowledge by adapting and adopting technologies produced in other countries (ranging from 15 times in Nigeria to over 7,000 in Eritrea). Thus, these areas show great potential for tapping foreign knowledge. Countries with relatively low spill-in ratios such as the United States, Japan, China, and Brazil, could also potentially tap large knowledge stocks, but the relative cost of importing versus producing knowledge locally might be higher on average.[86] Thus, it is not clear that countries with both low potential spill-in ratios and large domestic agricultural R&D enterprises would be as successful in adapting foreign knowledge as would countries with high spill-in ratios and small domestic R&D systems. Nonetheless, all countries have sizable spill-in potentials that should be integral to domestic decisions about the orientation and operational details of their own R&D efforts.

## Leveraging spillover potentials as part of domestic (and global) research decision making

In an economically ideal world, the extent and pattern of potential spillovers would be integral to decisions on how much and what types of research to fund and where in the world is best to conduct the research. Notwithstanding the intrinsic site specificity of many agricultural innovations, substantial shares of commodity research are highly likely to spill across geopolitical boundaries within a country, if not internationally. Thus, an individual state, or even a single country, is unlikely to be an efficient jurisdiction for R&D into certain new crop traits, varieties, or improved crop management practices.

In the United States, an efficient national jurisdiction might include all of the midwestern states where these commodities are important and where local technological innovations are likely to be approximately equally applicable. Even so, certain types of corn research, for example, might be locally applicable within a particular state, while certain types would be applicable beyond the Midwest and beyond the United States. This is because biological technologies are sensitive to variations in agroecological factors such as day length, soil type, and rainfall patterns, plus other production realities, factors that do not usually correspond closely to political boundaries. Nevertheless, for certain types of commodity research, a regional or multicountry approach would be more appropriate than for individual states or countries to conduct uncoordinated, competing programs of research.

The same may be said of certain types of noncommodity research. Natural resource problems in particular tend to be geographically specific by definition. Simple generalizations are impossible since some resource issues cross state and national boundaries (e.g., rivers or off-shore fisheries), while others are confined within a local area.

# Conclusion

As we move into the second decade of the new millennium, the lie of the global innovation landscape for food and agriculture is noticeably different than it was half a century ago. This report reveals seismic and ongoing geoeconomic shifts in the funding and performance of public agricultural R&D worldwide, with the middle-income countries growing in relative importance as producers of agricultural innovations emanating from the public sector. Private sector participation in food and agricultural R&D has grown as well, and now accounts for more than half the total in the rich countries. Nonetheless, estimates indicate that barely one tenth of the global private-sector food and agricultural R&D is carried out in the low- and middle-income countries. This means most of the domestic innovative capacity for these countries still stems from public research, although spillovers of public and privately generated ideas and innovations from the rest of the world is a major, and arguably underutilized, source of technical change for this part of the world.

After several decades of slowing and stagnant spending, funding for the CGIAR of international research centers has picked up over the past decade, but the system represents a small portion (1.6 percent) of public global food and agriculture R&D investments worldwide. As the number of centers has increased and donors have shifted toward providing predominately restricted funds targeted toward special projects, with, it seems, increasing emphasis on economic development activities, priority on research-based productivity enhancements for the main staple crops has declined. Taken together, these changes may have diminished the traditional role of the CGIAR as a unique, research-based instrument for sustained economic growth and agricultural development over the long run. The CGIAR is but one dimension of the complex and changing innovation landscape affecting global agriculture. Failing to take a more comprehensive perspective on the entire world's innovative capacity related to food and agriculture is bound to let some especially promising and economically rewarding opportunities slip by.

More concretely, while bilateral (country-to-country) spillovers of agricultural innovations have long been, and still are, a significant source of agricultural productivity growth for all countries, the nature of and prospects for spillovers have typically failed to figure highly in the formulation of domestic research policies and institutions designed to spur local agricultural sectors. One obvious option is to reposition and reconceive domestic public R&D and innovation efforts to make more effective use of spill-in potentials for all (especially poor) countries. Whether or not investments in domestic programs of agricultural R&D are revitalized, tapping other country's knowledge is likely to reap substantial additional rewards.

Being conscious of the ever-shifting but often complementary public and private roles in generating and marketing food and agricultural innovations is also an important part of the policy rethink required to economically sustain global agriculture productivity growth in the decades ahead. The new measures of knowledge stocks and spillover potentials presented in this report provide a starting point for moving toward a more comprehensive view of agricultural investment that increases research efficiencies and helps meet the challenges facing global agriculture that lie ahead.

## About The Chicago Council on Global Affairs

Founded in 1922 as The Chicago Council on Foreign Relations, The Chicago Council on Global Affairs is one of the oldest and most prominent international affairs organizations in the United States. Independent and nonpartisan, The Chicago Council is committed to influencing the discourse on global issues through contributions to opinion and policy formation, leadership dialogue, and public learning.

The Global Agricultural Development Initiative (GADI), launched in 2008 and expanded in 2010, purposes to build support and provide policy innovation and accountability for a long-term US commitment to agricultural development as a means to alleviate global poverty. It aims to maintain the policy impetus towards a renewed US focus on agricultural development, provide technical assistance to agricultural development policies' formulation and implementation, and offer external evaluation and accountability for US progress on food security. The Initiative is led by Catherine Bertini, former executive director, UN World Food Program, and Dan Glickman, former secretary, US Department of Agriculture, and overseen by an advisory group comprised of leaders from government, business, civic, academic, and NGO sector circles. For further information, please visit thechicagocouncil.org/globalagdevelopment.

# Endnotes

1. The United Nations mid-line projections put the world's population at a projected 9.3 billion by 2050. Also factoring in projected growth in per capita incomes (and the distribution of that income), Kharas put the number of middle-income people worldwide (i.e., individuals with consumption in the range of $10 to $100 per day in 2005 purchasing power parity dollars) at an estimated 4.9 billion people by 2030, three billion more people than in 2009. See Homi Kharas, "The Emerging Middle Class in Developing Countries," (Working Paper No 285, OECD Development Centre, Paris: Organisation for Economic Cooperation and Development, 2010).

2. There are substantial uncertainties associated with the estimates for increased demand. See Philip G.Pardey, Jason M. Beddow, Terrance M. Hurley, Timothy K.M. Beatty, and Vernon R. Eidman, "A Bounds Analysis of the World Food Problem: Global Agriculture in 2050" (International Science and Technology Practice and Policy (InSTePP) Center Report, University of Minnesota, St. Paul, 2013) in process; Nikos Alexandratos and Jelle Bruinsma, "World Agriculture Towards 2030/2050: The 2012 Revision," (Working Paper No. 12-03, Food and Agriculture Organization of the United Nations, 2012), 3.

3. Julian M. Alston, Jason M. Beddow, and Philip G. Pardey, "Agricultural Research, Productivity, and Food Prices in the Long Run," *Science* 325, no. 4 (2009).

4. See USDA, NASS (National Agricultural Statistical Service), *Quick Stats,* agricultural statistics database (Washington, DC: United States Department of Agriculture, 2012), accessed October 2012, http://quickstats.nass.usda.gov; USDA, ERS (Economic Research Service), *Food Dollar Series,* online application (Washington, DC: United States Department of Agriculture, 2012), accessed November 2012, http://www.ers.usda.gov/data-products/food-dollar-series/; and FAO (Food and Agriculture Organization of the United Nations), FAOSTAT database (Rome: Food and Agriculture Organization, 2012), accessed October 2012, http://faostat.fao.org/.

5. Although the long-run trend is a reduction in corn acreage relative to the area of 1900, in fact corn acreage declined from 94.9 million acres in 1900 to 54.6 million in 1969 and since then has increased to 84.0 million acres in 2011.

6. To put this in a long-run international development perspective, present (2010) average corn yields in Sub-Saharan Africa are barely above the corresponding 1900 US average yields.

7. Beddow and Pardey showed that the changes in the location of corn production (enabled by and in conjunction with changes in technology and other factors of production) accounted for 16 to 21 percent of the increase in US corn output from 1909 to 2007. See Jason M. Beddow and Philip G. Pardey, "Moving Matters: The Effect of Location on Crop Production" (International Science and Technology Practice and Policy (InSTePP) Center Report, University of Minnesota, St Paul, 2013), in process.

8. In 2007 when the value of US agricultural output was $281.5 billion, 78 percent of the output in that year (i.e., $219.6 billion) was attributable to productivity growth since 1949. Absent that productivity growth, it would have taken an equivalent 78 percent more inputs to achieve the same output, so productivity growth since 1949 saved $219.6 billion worth of inputs in 2007 alone. In more concrete terms, it would take an additional 729.5 million acres combined with an additional labor force of 1.76 million hours as well as many other inputs to produce the 2007 output using 1949 technology. This computation assumes that factor proportions would remain as they are in 2007. But in 1949 agriculture was more land- and especially labor-intensive than at present. Some of these factor intensity differences reflect the substantial changes in relative prices, especially of labor, but some may reflect the factor bias of technological change, which was to some extent land- and labor-saving, rather than factor neutral.

9. Specifically, in present value terms the benefits are worth 10 to 20 times the costs or more, even though only some of the productivity growth is attributable to the improved production efficiencies and new technologies resulting from organized public research and extension, and even after we account for the fact that it takes a very long time for the consequences of research investments to be reflected in productivity gains in farmers' fields. The total US investment includes R&D in food, but excludes forestry. See Julian M. Alston et al., *Persistence Pays: US Agricultural Productivity Growth and the Benefits from Public R&D Spending* (New York: Springer, 2010) and also Julian M. Alston et al., "The Economic Returns to US Public Agricultural Research," *American Journal of Agricultural Economics* 93, no. 5 (2011): 1257-1277. For a recent review and recalibration of the economic returns to agricultural R&D investments worldwide see Xudong Rao, Terrance M. Hurley, and Philip G. Pardey, "Recalibrating the Reported Rates of Return to Food and Agricultural R&D" (Staff Paper no. P12-8, University of Minnesota, St Paul, Department of Applied Economics, 2012).

10. Philip G. Pardey, Julian M. Alston, and Connie Chan Kang, "Agricultural Production, Productivity and R&D over the Past Half Century: An Emerging New World Order,"

(Staff Paper no. P12-7, Department of Applied Economics, University of Minnesota, 2012).

11. Ravi P. Singh et al., "The Emergence of Ug99 Races of Stem Rust Fungus Is a Threat to World Wheat Production," *Annual Review of Phytopathology* 49 (2011).

12. Ravi P. Singh et al., "Current Status, Likely Migration and Strategies to Mitigate the Threat to Wheat Production from Race Ug99 (TTKS) of Stem Rust Pathogen," *CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources* 1 (2006).

13. Philip G. Pardey, Jason M. Beddow, Darren Kriticos, Terrance M. Hurley, Robert F. Park, Etienne Duveiller, Robert Sutherst, Jeremy J. Burdon, and David Hodson, "Right-Sizing Stem Rust Research," *Science* (2013, in press).

14. Alfred W. Crosby, *The Columbian Voyages, the Columbian Exchange and their Histories* (Washington, DC: American Historical Association, 1987); Jared M. Diamond, *Guns, Germs, and Steel: The Fates of Human Societies* (New York: Norton, 1999).

15. As early as the mid-1850s, the federal government employed "agricultural explorers" to scout the globe for new plant and seed material for shipping back to the United States. US Navy expeditions and consular staff were also regularly used to collect new plant material from countries around the world and ship that material back to the United States. See Knowles A. Ryerson, "History and Significance of the Foreign Plant Introduction Work of the United States Department of Agriculture," *Agricultural History* 7, no. 3 (1933): 110-128; Calestous Juma, *The Gene Hunters: Biotechnology and Scramble for Seeds* (Princeton: Princeton University Press, 1989); Julian M. Alston and Philip G. Pardey, "Agricultural Productivity," in *Historical Statistics of the United States, Earliest Times to the Present,* ed. Susan B. Carter, Scott Sigmund Gartner, Michael R. Haines, Alan L. Olmstead, Richard Sutch, Gavin Wright, Millennial Edition, volume 4, Part D, Economic Sectors (Cambridge: Cambridge University Press, 2006); and Alan L. Olmstead and Paul W. Rhode, "Biological Globalization: The Other Grain Invasion," in *The New Comparative Economic History: Essays in Honor of Jeffrey G. Williamson,* ed. Timothy J. Hatton, Kevin H O'Rourke, and Alan M Taylor (Cambridge, MA: Massachusetts Institute Press, 2007).

16. Jason M. Beddow et al., "The Changing Landscape of Global Agriculture," in *The Shifting Patterns of Agricultural Production and Productivity Worldwide*, ed. Julian M. Alston, Bruce A. Babcock, and Philip G. Pardey, CARD-MATRIC online volume (Ames, IA: Iowa State University, 2010).

17. Warren C. Baum, *Partners Against Hunger: The Consultative Group on International Agricultural Research* (Washington, DC: Published for the CGIAR [by] the World Bank, 1986), 5-6; John C. Culver and John Hyde, *American Dreamer: The Life and Times of Henry A. Wallace* (New York: W. W. Norton and Company, 2000). Perkins also points to the pivotal role played by Wallace in seeding the Green Revolution. See John H. Perkins, *Geopolitics and the Green Revolution: Wheat, Genes, and the Cold War* (Oxford: Oxford University Press, 1997).

18. Brian D. Wright, "Grand Missions of Agricultural Innovation," *Research Policy* 41, no. 10 (2012): 1720.

19. The CGIAR is an informal organization providing oversight to a system of international research centers, a mechanism for collectively funding those centers, and a forum to discuss and affirm overall research policy objectives.

20. As Hazell noted, "[T]he breeding of improved varieties [of rice and wheat] combined with the expanded use of fertilizers, other chemical inputs, and irrigation led to dramatic yield increases for these two crops in Asia and Latin America, beginning in the late 1960s. This development was coined the "Green Revolution" by USAID Administrator W. S. Gaud [in 1968, see Gaud 1968]. . . ." See Peter B.R. Hazell, "The Asian Green Revolution," IFPRI Discussion Paper 00911 (Washington, DC: International Food Policy Research Institute, 2009).

21. CIMMYT (International Maize and Wheat Improvement Center), Website, accessed February 2013, www.cimmyt.org/en/about-us.

22. Mahabub Hossain et al., "International Research and Genetic Improvement in Rice: Evidence from Asia and Latin America," in *Crop Variety Improvement and its Effect on Productivity: The Impact of International Agricultural Research,* ed. Robert E. Evenson and Douglas Gollin (Wallingford: CAB International, 2003).

23. Julian M. Alston, "The 'Domain' for Levy-Funded Research and Extension: General Notions with Particular Applications to the Australian Dairy Industry," *Connections: Farm Food and Resource Issues* 3 (2002), http://www.agrifood.info/connections/winter_2002/Alston.html; Philip G. Pardey, Julian M. Alston, and Connie Chan-Kang, *Public Food and Agricultural Research in the United States: The Rise and Decline of Public Investments, and Policies for Renewal,* AGree Backgrounder (Washington, DC: AGree, 2013).

24. Philip Pardey et al., "The Evolving Landscape of Plant Varietal Rights in the United States, 1930-2008," *Nature Biotechnology* 31, no. 1 (2013).

25. CIMMYT (which is the Spanish acronym for the International Maize and Wheat Improvement Center) is an international research center based in El Batan, Mexico. Norman Borlaug, a University of Minnesota graduate who won the Nobel Peace Prize in 1970, led CIMMYT's wheat breeding program from 1963 to 1979 and spearheaded efforts to develop high-yielding, semidwarf wheat varieties that spread the world over. See Philip Pardey et al., *Hidden Harvest: U.S. Benefits from International Research*

*Aid* (Washington, DC: International Food Policy Research Institute, 1996), http://www.ifpri.org/sites/default/files/publications/pr6.pdf.

26. Moreover, the benefits from research are sizable. Alston et al. report that a dollar invested in research carried out by a state agricultural experiment station (SAES) in the United States returned benefits of $21.0 on average to each state, and $32.1 to the nation as a whole if spillover benefits to other states were added to the own-state benefits. See Julian M. Alston et al.,"The Economic Returns to US Public Agricultural Research," *American Journal of Agricultural Economics*, 1257-1277; Julian M. Alston et al., *Persistence Pays: US Agricultural Productivity Growth and the Benefits from Public R&D Spending* (New York: Springer, 2010).

27. Stanley Wood and Philip G. Pardey, "Agroecological Aspects of Evaluating Agricultural R&D," *Agricultural Systems* 57, no. 1 (1998): 13-41.

28. Philip Pardey et al., "The Evolving Landscape of Plant Varietal Rights in the United States, 1930-2008," *Nature Biotechnology.*

29. Ibid.

30. Between 1940 and 2011, food consumed away from home rose from 19.7 percent to 48.7 percent of total US food expenditures. See USDA, NASS (National Agricultural Statistical Service), *Quick Stats,* 2012.

31. OECD (Organisation for Economic Co-Operation and Development), *Frascati Manual: Proposed Standard Practice for Surveys on Research and Experimental Development* (Paris: Organisation for Economic Co-Operation and Development, 2002).

32. This characterization is by no means meant to imply a simple sequential pattern to all public and private research. For example, the technology timelines included in box 2 are indicative of a complex, sometime rivalrous, sometimes complementary, and somewhat unpredictable pattern of interaction between public and private science. The point here is that public research plays a different and often complementary role to private research such that it is highly unlikely that an optimal economic mix will entail only public or only privately performed research. This is especially pertinent if the perspective is to sustain technological changes and associated economic growth over the longer run. Private firms, motivated by profit incentives, have a presumptive comparative advantage in developing innovations with (often nearer-term) commercial potential. Public agencies, motivated by scientific reward systems, tend to be relatively good at producing scientific public goods that are the building blocks for complementary, often private, investments in innovative activities. See Richard R. Nelson, "Government Support of Technical Progress: Lessons from History," *Journal of Policy Analysis and Management* 2, no.4 (1983): 499-514; Nathan Rosenberg and Richard R. Nelson, "American Universities and Technical Advance in Industry," *Research Policy* 23 (1994): 323-348.

33. These shares apply to *all* private research conducted in the United States and are taken to be indicative of the corresponding shares for private research directed to food and agriculture (for which comprehensive data of this type are unavailable). See NSF (National Science Foundation), *Science and Engineering Indicators 2012* (Arlington VA: National Science Foundation (NSB 12-01), 2012), 4-4.

34. USDA, ERS (Economic Research Service), *Food Dollar Series,* online application, (Washington, DC: United States Department of Agriculture, 2012), accessed November 2012, http://www.ers.usda.gov/data-products/food-dollar-series/.

35. For example, Kalaitzandonakes, Alston and Bradford estimated that compliance with regulatory requirements added between $6 million and $16 million to the cost of developing a single new biotech crop product. Just, Alston and Zilberman provide a comprehensive economic assessment of regulations that affect agricultural biotechnologies. See Nicholas Kalaitzandonakes, Julian M. Alston, and Kent J. Bradford, "Compliance Costs for Regulatory Approval of New Biotech Crops," *Nature Biotechnology* 25 (2007): 509-511; and Richard E. Just, Julian M. Alston, and Daniel Zilberman, *Regulating Agricultural Biotechnology: Economics and Policy* (New York: Springer-Verlag, 2006).

36. Julian M. Alston, Philip G. Pardey and Vernon W. Ruttan, "Research Lags Revisited: Concepts and Evidence from US Agriculture," (Staff Paper no. P09-14, Department of Applied Economics, University of Minnesota, 2008).

37. Archeologists deem agriculture to be the domestication of plants and animals. See Bruce D. Smith, *The Emergence of Agriculture* (New York: Scientific American Library, 1995). Evidence presented by Fuller et al. indicates that the process of domestication of rice occurred in the Lower Yangtze region of China between 6,600 and 6,900 years ago. Tanno and Willcox place the domestication of wheat at some 9,500 to 10,500 years ago in the region of southeastern Turkey and northern Syria. See Fuller et al., "The Domestication Process and Domestication Rate in Rice: Spikelet Bases from the Lower Yangtze," *Science* 323 (2009): 1607-1609; and Ken-Ichi Tanno and George Wilcox, "How Fast was Wild Wheat Domesticated," *Science* 311 (2006): 1186.

38. Donald N. Duvick, "Biotechnology in the 1930s: The Development of Hybrid Maize," *Nature Reviews-Genetics* 2 (2001): 69-74; Wayne C. Smith, Javier Betrán, and E. C. A. Runge, *Corn: Origin, History, Technology and Production* (Hoboken, NJ: John Wiley and Sons, 2004).

39. The first hybrid corn seed sales were in Connecticut in 1920 and in Iowa four years later, though it took until the early 1930s for commercially sufficient quantities of successful seeds to become more widely available.

40. Peggy G. Lemaux, "Genetically Engineered Plants and Foods: A Scientist's Analysis of the Issues (Part I)," *Annual Review of Plant Biology* 59 (2008): 771-812.

41. Alston, Pardey, and Ruttan, "Research Lags Revisited: Concepts and Evidence from US Agriculture," staff paper. McDougall reports that averaging across the crops and biotechnology traits he examined spanning the six largest biotech crop developers in the world, the time from initiation of a "discovery project" to commercial launch was just over 13 years, but with a wide range around that average (from 7 to 24 years). Moreover, the regulatory science, registration, and regulatory affairs processes involved accounted for almost 37 percent of the lag to launch. See Phillips McDougall, *The Cost and Time Involved in the Discovery, Development, and Authorisation of a New Plant Biotechnology Derived Trait,* a consultancy study for CropLife International (Midlothian, U.K.: CropLife International, 2011).

42. See Zvi Griliches, "Hybrid Corn: An Exploration in the Economics of Technological Change," *Econometrica* 25 (1957): 501-522; Gerald O'Mara "A Decision-Theoretic View of the Microeconomics of Technique Diffusion in a Developing Country" (PhD thesis, Stanford: Stanford University, 1971); and Robert K. Linder, Alistair Fisher, and Philip G. Pardey, "The Time to Early Adoption," *Economics Letters* 2 (1979): 187-190.

43. Bruce L. Gardner, *American Agriculture in the Twentieth Century: How it Flourished and What it Cost* (Cambridge: Harvard University Press, 2002).

44. Steven Dehmer and Philip.G. Pardey, "Global Science Spending, 1980-2009" (International Science and Technology Practice and Policy (InSTePP) Center Report, University of Minnesota, St Paul), in process. For consistency with the reported global food and agricultural R&D totals to follow, we exclude spending by the eastern European and former Soviet Union countries from this "world" total. In 2009 R&D spending by these countries was estimated to be around $44 billion (2005 PPP prices).

45. International comparisons of R&D expenditures in this section are based on spending amounts measured in international purchasing power parity (PPP) dollars (2005 prices). See Dehmer and Pardey, "Global Science Spending, 1980-2009," in process.

46. Low-, middle-, and high-income designations are based on World Bank. See World Bank, *World Development Report 2011: Conflict, Security, and Development* (Washington, DC: World Bank, 2011).

47. This section draws heavily on Philip G. Pardey, Julian M. Alston, and Connie Chan Kang, "Agricultural Production, Productivity and R&D over the Past Half Century: An Emerging New World Order" (2012).

48. World Bank, *World Development Report 2011: Conflict, Security, and Development,* 2011).

49. The share of total R&D done by China, and thus the BIC (Brazil, India, and China) aggregate, shrank substantially throughout the 1960s, a response to the turmoil of the Great Leap Forward and the subsequent Cultural Revolution. This caused the initial drop in the middle-income totals plotted in figure 8a. As Fan and Pardey described, during 1960–61, one-third of the CAAS (Chinese Academy of Agricultural Sciences) institutes were moved to rural areas or disbanded and the academy's total number of staff declined by 70 percent from 7,500 to 620 personnel. China's share of the total then grew steadily from a low of 3 percent in 1968 to 10.7 percent in 2001 and then rapidly to 19.4 percent by 2009. The BIC trend followed a similar path, with these three countries alone accounting for 31.1 percent of the world total by 2009 and 63.1 percent of the low- and middle-income total. See Shenggen Fan and Philip G. Pardey, *Agricultural Research in China: Its Institutional Development and Impact* (The Hague: International Service for National Agricultural Research, 1992).

50. As a group the BIC countries spent $10.5 billion (2005 PPP) on public agricultural R&D in 2009, 2.3 times the amount spent by the United States that year.

51. Many African agricultural public research systems have been (and some still are) heavily reliant on external sources of support. A large part of the decline in R&D spending stems from the substantial reduction in support by international donor agencies for African agricultural research, particularly during the last half of the 1990s, with no offsetting increase in support from national governments. See Nienke M. Beintema and Gert-Jan Stads, *Agricultural R&D in Sub-Saharan Africa: An Era of Stagnation,* ASTI Background Report (Washington, DC: International Food Policy Research Institute, 2006), 16.

52. Pardey and Beintema estimated that the private share of global agricultural R&D was almost 35 percent in circa 1995, and about 94 percent of that research occurred in developed countries. Beintema and Stads put the private share of the total at 41 percent in 2000, of which 94.4 percent took place in high-income countries. Fuglie et al. estimated the private share of total to be 39 percent for 2000, with the high-income country share of total private food and agricultural R&D being 89 percent. See Philip G. Pardey and Nienke M. Beintema, *Slow Magic: Agricultural R&D a Century After Mendel,* IFPRI Food Policy Report (Washington, DC: International Food Policy Research Institute, 2001); Nienke M. Beintema and Gert-Jan Stads, *Measuring Agricultural Research Investments: A Revised Global Picture,* ASTI Background Note (Washington, DC: International Food Policy Research Institute, 2008); and Fuglie et al., *Research Investments and Market Structure in the Food Processing, Agricultural Input, and Biofuel Industries Worldwide,* ERS Report no. 130 (Washington, DC: USDA Economic Research Service, 2011). Finally, see Philip G. Pardey and Connie Chan-Kang, *Public and*

*Private R&D for Food and Agriculture in Rich Countries, 1960-2009* (International Science and Technology Practice and Policy (InSTePP) Center Report, University of Minnesota, St Paul), in process.

53. Philip G. Pardey, M. Sandra Kang, and Howard Elliott, "The Structure of Public Support for National Agricultural Research Systems: A Political Economy Perspective," *Agricultural Economics* 3, no. 4 (1989).

54. Philip G. Pardey, Julian M. Alston, and Connie Chan Kang, "Public Agricultural R&D over the Past Half Century: An Emerging New World Order," *Agricultural Economics* (2013, in press).

55. Philip G. Pardey, Connie Chan-Kang, and Steven Dehmer, *Global Food and Agricultural R&D Spending, 1960-2000,* (International Science and Technology Practice and Policy (InSTePP) Center Report, University of Minnesota, St Paul), in process.

56. Pardey, Alston, and Chan-Kang, *Public Food and Agricultural Research in the United States: The Rise and Decline of Public Investments, and Policies for Renewal.* Using an implicit GDP deflator to adjust for inflation (as we do for almost all of the R&D data reported in this paper) indicates that real spending on publicly performed agricultural R&D in the United States flat-lined since 2004. Using a purpose built US agricultural R&D deflator (which grew at an annual average rate of 3.83 percent per year from 2004 to 2009, compared with 2.61 percent per year growth for the implicit GDP deflator) indicates a cutback in real spending since 2004.

57. In the one year in which it grew (2008), spending increased by a mere 0.42 percent relative to the amount spent in the previous year.

58. For a range of earlier estimates see M.N. Heim and L.L. Blakeselee, "Biological Adaptation and Research Impacts on Wheat Yields in Washington," American Agricultural Economics Association, Reno, 1986; Swallow et al., *Agricultural Depreciation and the Importance of Maintenance Research* (Department of Agricultural Economics Research Report no. 56, Virginia Polytechnic Institute and State University, Blacksburg, 1985); Edward O. Adusei and George W. Norton, "The Magnitude of Agricultural Maintenance Research in the USA," *Journal of Production Agriculture* 3 (1990): 1-6. Sparger reports results from a 2008 survey of US agricultural scientists that suggests the share of commodity research directed to maintenance has risen to around 41 percent relative to the 35 percent estimate for the mid-1980s reported by Adusei and Norton. See John A. Sparger, "Is the Share of Agricultural Maintenance Research Rising? Implications for Future Productivity Growth in US Agriculture," unpublished MSc thesis, Department of Agricultural and Applied Economics (Blacksburg: Virginia Polytechnic Institute and State University, 2009).

59. For prior compilations and interpretations of US agricultural R&D spending data, see Wallace E. Huffman and Robert E. Evenson, *Science for Agriculture: A Long-Term Perspective,* 2nd ed. (Ames: Iowa State University Press, 2006, first published 1993); Julian M. Alston and Philip G. Pardey, *Making Science Pay: The Economics of Agricultural R&D Policy* (Washington DC: American Enterprise Institute Press, 1996); Alston and Pardey, "Agricultural Productivity" (2006); Fuglie et al., *Agricultural Research and Development: Public and Private Investments Under Alternative Markets and Institutions,* Agricultural Economic Report No. 735 (Washington, DC: Economic Research Service, United States Department of Agriculture, 1996); David Schimmelpfennig and Paul Heisey, *US Public Agricultural Research: Changes in Funding Sources and Shifts in Emphasis, 1980-2005,* Economic Information Bulletin Nos. 45 (Washington, DC: Economic Research Service, United States Department of Agriculture, 2009); and Alston et al., *Persistence Pays: US Agricultural Productivity Growth and the Benefits from Public R&D Spending* (2010).

60. Steven Dehmer and Philip G. Pardey, "Private Food and Agricultural R&D in the United States, 1953-2009" (International Science and Technology Practice and Policy (InSTePP) Center Report, University of Minnesota, St Paul), in process. The Dehmer and Pardey series is an entirely new compilation of US private food and agricultural R&D spending and supersedes the series reported in Alston et al. See Fuglie et al. for an alternative set of private-sector R&D estimates and the references in Dehmer and Pardey for other, earlier compilations. See Alston et al., *Persistence Pays: US Agricultural Productivity Growth and the Benefits from Public R&D Spending* (2010); Fuglie et al., *Research Investments and Market Structure in the Food Processing, Agricultural Input, and Biofuel Industries* (2011).

61. A relatively rapid real rate of growth of 4.8 percent per year was realized in the period 1953 to 1980, a period of correspondingly rapid growth in public investment in agricultural R&D. Real growth slowed during the 1980s and early 1990s (2.03 percent per year from 1986 to 1992), but picked up pace during the latter part of the 1990s (6.7 percent per year during the period 1993 to 1998), as large agricultural chemical, machinery, and food companies ramped up their investments in agricultural research in the United States, along with a substantial number of smaller, new entrants. Private food and agricultural R&D spending declined immediately thereafter—from $4.7 billion (nominal dollars) in 1998 to $4.0 billion in 2000. It then recovered (even after adjusting for inflation) for a few years beginning in 2001, only to falter again in 2009. See John King, *Concentration and Technology in Agricultural Input Industries,* USDA Agricultural Information Bulletin no. 763 (Washington, DC: USDA, Economic Research Service, 2001).

62. Philip G. Pardey and Connie Chan-Kang, *Public and Private R&D for Food and Agriculture in Rich Countries, 1960-2009* (International Science and Technology Practice and Policy (InSTePP) Center Report, University of Minnesota, St Paul), in process.

63. Through 1971 all funding went to the four founding CGIAR centers. During the 1970s, real funding for the four founding centers grew by 9.9 percent per year. During the 1980s, however, the rate of growth of real funding slowed to an average of 2.5 percent per year and then declined for the following 15 years before beginning to grow again in 2005 at an average annual rate of 6.5 per year from 2005 to 2010.

64. Unfortunately, the CGIAR has not maintained a set of science indicator statistics that enable funding trends to be meaningfully parsed into commodity-specific or other research program areas. Here the shift in center-specific funding is being used to illustrate the shift away from "research" on staple food crops. The extent to which CGIAR funds are used for research versus other purposes (e.g., outreach or extension type activities, training, agricultural development efforts, or even administrative overhead) is also difficult to determine, impossibly so, it seems, for meaningfully examining long-term trends in these attributes.

65. In 1990 the CGIAR constituted 5.3 percent of public agricultural R&D spending in the less-developed countries.

66. If private-sector research is also factored in, the United States was 55.3 times larger than the CGIAR in 1960 and 20.2 times larger in 2009.

67. In inflation-adjusted terms, US funding to the CGIAR continued to grow to a peak of $97.7 million (2005 prices) in 1985 (figure 13). Thereafter, United States support for the CGIAR waned, dropping to a low of $45.4 million in 1999. It rebounded thereafter, especially in the past several years, although US funding in 2010 totaled just $77.8 million, about the same amount of US funding made available to the CGIAR in the early 1980s.

68. CGIAR (Consultative Group on International Agricultural Research), *Financial Report: 2011* (Washington, DC and Montpellier: CGIAR Fund Office and CGIAR Consortium Office, 2012).

69. This decline had three distinct phases. From 1983 to 1991 the unrestricted share fell, but total funding for the CGIAR (in real, inflation-adjusted terms) continued to rise. For the period 1992 to 2002, both real funding and the unrestricted share declined, partly reflecting the fact that most of the new centers admitted to the CGIAR in the 1990s joined with comparatively small amounts of unrestricted support (unlike those that joined during the 1970s). Since 2003 the share of unrestricted funding has continued to decline, but growth in real funding has rebounded, increasing by an average of 5.3 percent per year from 2003 to 2010.

70. Selcuk Ozgediz, *The CGIAR at 40: Institutional Evolution of the World's Premier Agricultural Research Network* (Washington, DC: CGIAR Fund Office, 2012).

71. Funding made available to individual centers by way of the Fund Council (overseen by the Funders Forum) is classified as restricted funding, meaning that the nature and terms of the "restrictions" are entering yet a new phase. At this point, bilateral funding (i.e., direct donor to center funding arrangements) is still possible, but this mode of funding the CGIAR will soon be subject to review. In 2011, funding via this means (so-called window 3 funding) was $61.7 million, 8.9 percent of the $695.8 total CGIAR funding that year.

72. Julian M. Alston, Steven Dehmer, and Philip G. Pardey, "International Initiatives in Agricultural R&D: The Changing Fortunes of the CGIAR," in *Agricultural R&D in the Developing World: Too Little, Too Late?* ed. Philip G. Pardey, Julian M. Alston, and Roley R. Piggott (Washington, DC: International Food Policy Research Institute, 2006), 348.

73. Funding reached a low of $80.2 million (in 2005 dollars) in 1996, where it stalled for several years, then declined further during the mid-2000s to reach a new low of $55.8 million in 2008.

74. Another focus of USAID support for international R&D is the Collaborative Research Support Program (CRSP), launched with funds made available by way of Title XII of the Foreign Assistance Act of 1961 (as amended). The CRSPs are "a partnership between US universities, developing country institutions, and USAID designed to apply science and technology and build HICD [human and institutional capacity development] to address issues of hunger and poverty." See Robert J. Jones, Karen Brown, Derek Byerlee, Carol Kramer-LeBlanc, David Sammons, and Barbara Stoecker, *BIFAD Review of the Collaborative Research Support Program (CRSP) Model* (Washington,DC: Board for International Food and Agricultural Development, 2012), http://www.agrilinks.org/sites/default/files/resource/files/BIFAD%20REVIEW%20FINAL_0_0.pdf. Core USAID support to the CRSPs has been little changed since 1987, averaging $24.3 million per year for the period 1987 to 2011 (although a little above average in recent years, averaging $28.1 million per year for the period 2008 to 2011) (USAID). See Jones et al., *BIFAD Review of the Collaborative Research Support Program (CRSP) Model,* (Washington, DC: Board for International Food and Agricultural Development, 2012); and USAID, "Unpublished data file 'USAID-EGAT Core Support to CRSPs'" (Washington, DC: United States Agency for International Development, 2012).

75. Share estimate is based on the assumption that private food and agricultural R&D performed in low- and middle-income counties is 10 percent of the total amount of corresponding private R&D performed worldwide in 2009.

76. In the US context, for example, this might involve restructuring the relationship between the domestic funding for research conducted by US state and federal agencies (e.g., by way of the Research Title of the US Farm Bill) and the funding made available for internationally conceived R&D (e.g., by way of USAID).

77. The remainder of this section draws heavily on Jason M. Beddow, Philip G. Pardey, and Alison Bittinger, "Agricultural R&D Spillovers and Global Stocks of Scientific Knowledge," (International Science and Technology Practice and Policy (InSTePP) Center Report, University of Minnesota, St Paul, 2013), in process.

78. This metric only includes formal scientific knowledge; much tacit knowledge of farmers and others is not counted. Importantly (because of data availability), the metric only accumulates R&D done by the public sector. The considerable amount of innovation associated with private R&D is not counted. For the present purpose, we take R&D spending as a metric of knowledge generation, recognizing that there is a more complex relationship between current and past R&D spending and knowledge stocks. See Pardey, Alston, and Chan Kang, "Public Agricultural R&D over the Past Half Century: An Emerging New World Order," *Agricultural Economics*.

79. Only the countries for which we have long-run R&D data are included.

80. Beddow, Pardey, and Bittinger, "Agricultural R&D Spillovers and Global Stocks of Scientific Knowledge," (2013, in process)

81. This is by no means a new idea, although we now have new ways of conceiving, measuring, and managing prospective international technology transfers. For a brief description of the various pan-territorial research agencies formed during the colonial era throughout Sub-Saharan Africa, see, for example, Philip G. Pardey, Johannes Roseboom, and Jock R. Anderson, "Regional Perspectives on National Agricultural Research," in *Agricultural Research Policy: International Quantitative Perspectives*, ed. Philip G Pardey, Johannes Roseboom, and J.R. Anderson (Cambridge: Cambridge University Press, 1991): 217-221. As but one example, the East African Agricultural and Forestry Research Organization (EAFRO), a regional (cross-country) research agency formed and largely funded by the British government, accounted for about one-fifth of the total number of agricultural researchers working in Kenya, Tanzania, and Uganda around the time these countries gained political independence.

82. This calculation entailed the estimation of 23,562 bilateral, country-to-country measures of agrotechnological distances. See Beddow, Pardey, and Bittinger, "Agricultural R&D Spillovers and Global Stocks of Scientific Knowledge" (2013), in process, for details.

83. Just five countries (China, India, the United States, Indonesia, and Nigeria) accounted for about one-half of the entire world's agricultural output.

84. Countries with very small agricultural knowledge stocks or with insufficient data to estimate knowledge stocks are not shown in figure 19.

85. Julian M. Alston and Philip G. Pardey, "The Economics of Agricultural R&D Policy," in *Paying for Agricultural Productivity*, ed. Julian M. Alston, Philip G. Pardey, and Vincent H. Smith (Baltimore: The Johns Hopkins University Press, 1999).

86. Beddow, Pardey and Bittinger, "Agricultural R&D Spillovers and Global Stocks of Scientific Knowledge."

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