THE PAYOFF TO INVESTING IN CGIAR RESEARCH

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SoAR FOUNDATION

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Authorship is alphabetical. Julian Alston is a distinguished professor in the Department of Agricultural and Resource Economics, University of California, Davis, and a member of the Giannini Foundation of Agricultural Economics; Philip Pardey is a professor in the Department of Applied Economics and director of the International Science and Technology Practice and Policy (InSTePP) center, both at the University of Minnesota. Xudong Rao is an assistant professor in the Department of Agribusiness and Applied Economics at North Dakota State University. Alston and Rao are research fellows at InSTePP.

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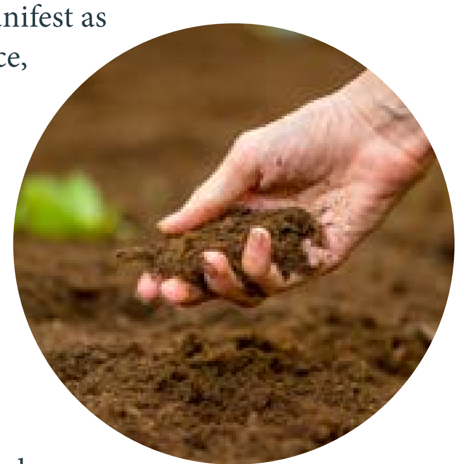
KEY FINDINGS

In round figures, over the past five decades the CGIAR has spent about **$60 billion** in present value terms. This investment—mainly through its contributions to enhancing yields of staple food crops—has returned tenfold benefits (i.e., a benefit-cost ratio of 10:1), manifest as less-easily measured payoffs for poor people from greater food abundance, cheaper food, reduced rates of hunger and poverty, and a smaller geographical footprint of agriculture. This does not count substantial benefits accruing in high-income countries.



What Motivated Us

The CGIAR and its precursor centers were conceived to play a critical role, working in concert with the national agricultural research systems (NARSs) in low- and middle-income countries, to develop farm technologies that would help stave off a global food crisis. They succeeded. But the issues persist, and new challenges have emerged. Many commentators express concerns about the ability of the NARSs in low-income countries, especially in Africa, to meet food security targets while also addressing the global environmental agenda confronting agriculture. The CGIAR could potentially play a pivotal role in supporting that effort. Against this background, we sought to provide a hard-nosed assessment of the past payoffs to CGIAR research investments to help guide decisions regarding future funding.

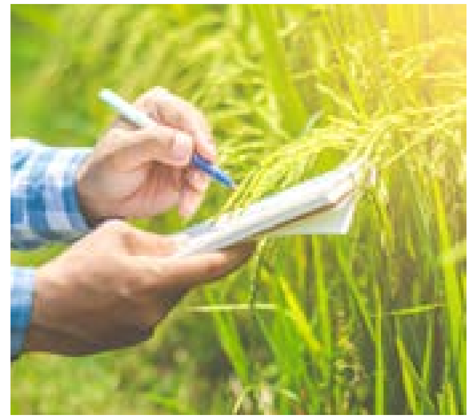
What We Did

- To begin, we provided a detailed quantitative context for a review of the payoffs to investments in the CGIAR over the past five decades. We juxtaposed the CGIAR's institutional and investment history against the rapidly evolving investment realities in agricultural R&D and the shifting structure of agricultural production, worldwide. We showed:
    - The increase from four to fifteen (and with recent mergers, now effectively thirteen) centers contributed to a commensurate expansion in the scope of science and subject matter covered.
    - In the 1970s and 1980s, funding for agricultural R&D by high-income countries grew rapidly, and these countries provided the bulk of funding for the CGIAR.
    - In recent decades, high-income countries have scaled back their support for both national public agricultural R&D and international agricultural research.
        - In the context of rising global investments in agricultural R&D, total funding for the CGIAR peaked at over $1 billion (2016 dollar values) in 2014 after a surge in response to the global food crisis.

- Since 2014, total inflation-adjusted funding for the CGIAR fell rapidly to around $800 million in 2018.

- The share of unencumbered funding shrank from around 80% in 1971 to 50% in 2000, and since 2010 has plummeted to very low levels.

- Concerns have begun to emerge about the capacity of the world to sustainably reduce global hunger and poverty over the coming decades, and about the ability of the NARSs in developing countries, working in concert with the CGIAR, to provide the requisite technologies.



- To assess the payoffs to CGIAR spending we used money-metric measures: in particular, the benefit-cost ratio (BCR) and dollar-denominated measures of total benefits.
  - These money-metric measures are explicitly conceived as indications of the economic welfare consequences of R&D and are widely used for that purpose.
  - The BCR is an indicator of value for money, which is important both to investors and to those who manage research.
- We did not document evidence of other consequences of CGIAR research spending, such as effects on poverty rates.
  - Money-metric measures of total benefits could in principle be applied to specific groups (such as the poor), but distributional impacts were not the focus of this review and typically are not the focus of research evaluation reports.
  - Since the main beneficiaries from improvements in technology for staple crops are the producers and consumers of those crops, the lion's share of the total benefits from CGIAR crop-improvement research has gone to the poor.
  - Reports of other income and economic development consequences of agricultural R&D are less abundant, have been less scrutinized, and are open to greater skepticism and stronger concerns over attribution—perhaps especially for the part of that R&D conducted by the CGIAR.

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- We employed three complementary approaches to assess the research payoffs:
    - We compiled the largest set to date of studies with comparable estimates of returns to CGIAR research and to public research undertaken by low- and middle-income countries.
    - We derived standardized measures of BCRs from most of those studies.
    - We analyzed results from studies that reported total payoffs to probe whether a subset of research activities with documented high payoffs could justify investments in the CGIAR as a whole, including spending on some research and other CGIAR activities for which benefits are not documented.
    - We estimated the aggregate value of total factor productivity growth—a widely accepted first-order approximation to money-metric measures of social benefits—for 1961–2020.
        - We attributed various portions of the incremental value to research by public agencies in developing countries and CGIAR.
        - We compared the measure of benefits with the cumulative aggregate costs of research over the period.

What We Found

- CGIAR research has been intensively evaluated, compared with its share of R&D spending:
    - 440 estimates of BCRs or IRRs (internal rates of return) per billion dollars of CGIAR spending in 2015 (2016 dollar values).
    - 47 estimates of BCRs or IRRs per billion dollars of public agricultural R&D spending in developing countries in 2015 (2016 dollar values).
    - 63 estimates of BCRs or IRRs per billion dollars of public agricultural R&D spending worldwide in 2015 (2016 dollar values).
- Our meta-analysis yields a median estimated BCR of approximately 10:1 for both CGIAR and developing-country NARS research; that is, on average, a dollar invested today brings a future return equivalent in (present) value to ten dollars today. This is a high BCR: any ratio over the threshold of 1:1 justifies investment.

- We projected estimates of benefits from nine research evaluation projects (all related to high-payoff crop varietal changes) to 2020, summed them and compared the total against costs of CGIAR research carried out in concert with NARSs.
  - In 2016 present value terms, the estimated benefits across these nine projects (1966–2020) sum to $1,783 billion (2016 dollar values), all accruing in developing countries, home to the preponderance of the world's food poor.
  - In 2016 present value terms, the costs of the entire CGIAR portfolio over the period 1960–2010 was $59.7 billion (2016 dollar values).
  - If we attribute just one-quarter of the benefits reported in the nine high-payoff projects to the CGIAR (with the remainder to national partners and others), the BCR is 7.5:1; if we count only the costs of the CGIAR centers that conducted the relevant R&D, the BCR is 10:1.
- If one-half the value of all the reported agricultural TFP growth from 1960–2016 in developing countries is taken as a measure of the benefit from research investments by both CGIAR and public agencies in developing countries, a BCR on the order of 10:1 is implied for research by the CGIAR and national partners combined.

Credit: S. Modela (USDA)

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Implications of our Findings

- Agricultural research is slow magic. Returns accrue over long periods—decades—and realizing the full potential from agricultural R&D requires far-sighted investments. It is also a cumulative endeavor, best done with steady and sustained investments.

- The evidence we assembled and examined shows that in agricultural R&D persistence and patience are well rewarded. Past investments in agricultural research, both by the CGIAR and by public agencies in low-and middle-income countries, have yielded very high returns.

- This does not count the spillover benefits to high-income countries, including donor countries "doing well by doing good" (Tribe 1991). Pardey et al. (1996) estimated substantial benefits attributable to CGIAR breeders from adoption of improved wheat and rice varieties in the United States, based on releases from CGIAR centers, sufficient to cover all costs of the entire CGIAR system. Likewise, Brennan (1989) and Brennan and Fox (1995) found large impacts in Australia from adoption of CGIAR-based wheat varieties.

- These findings mean that national governments and development partners have persistently underinvested in the enterprise at home and abroad.

    - A BCR significantly greater than 1:1 indicates that governments would have profited society by doing more agricultural R&D, compared with investment opportunities normally available to them.

    - A BCR of 10:1 indicates that agricultural R&D was clearly more profitable than almost any other government investment.

    - Opportunities for investment in other national and global public goods (like education and infrastructure) might also have yielded very high returns, but comparable (and comparably strong and abundant) evidence is not available to support a claim that those other opportunities yielded BCRs in the range of 10:1.

- That the BCRs for CGIAR and non-CGIAR research are of similar magnitudes, and not statistically distinguishable, does not imply that funding for internationally conceived R&D could be reduced or replaced by investment in the NARSs.

    - The unique position of the CGIAR allows it to leverage R&D capacity in middle- and high-income countries for the benefit of low-income countries.

        - Internationally conceived R&D outputs and services complement those produced in NARSs.

- CGIAR centers have comparative advantage in developing broadly applicable agricultural technologies.

- The measures of payoffs to CGIAR R&D typically reflect the consequences of R&D conducted jointly with NARS partners.

- Internationally conceived R&D explicitly addresses high-potential gaps in NARS research—often multinational or global public goods.

- The totality of the evidence in this report and elsewhere (see, e.g., Pardey and Alston 2011; Fuglie and Heisey 2007) supports at least doubling the total public investment in agricultural R&D performed by both national and international agencies.

  - The past benefits have been many times larger than the investments that generated them.

  - Allowing suitable time to economically expand capacity, we see ample scope for reinvesting a modest fraction of the surplus generated by past R&D to generate comparably large future net benefits.

  - We see no evidence of diminishing returns and a strong case for investing in the global public good of preparedness to meet expanding demands for new technologies to serve the world's food poor and to mitigate the ongoing (and arguably increasing) challenges to global food supplies and farmer livelihoods posed by weather, pests, political strife, policy risk and market risk.

- Recent trends and geopolitical patterns in research investment are troubling:

  - High-income countries have scaled back their investments in agricultural R&D, both at home and through the CGIAR.

  - Although middle-income countries have developed national capacity in agricultural research, the same is not true for many low-income countries still heavily dependent on agriculture for livelihoods and food security.

  - In particular, research investment in sub-Saharan Africa lags significantly, and the gap has grown over time.

- Some African governments are losing ground in their efforts to apply science and technology to current and future agricultural challenges, including climate change:

  - One-third of the NARSs spent less in 2015 than in 2000, after adjustment for inflation.

- The focus of CGIAR research has appropriately shifted toward low capacity, low-income countries, and partnerships there are still much needed.

- The CGIAR funding model still depends crucially on allocations from a small group of national governments and private foundations mostly in high-income countries.

- Many agriculturally large middle-income countries have yet to contribute significantly to funding the CGIAR.

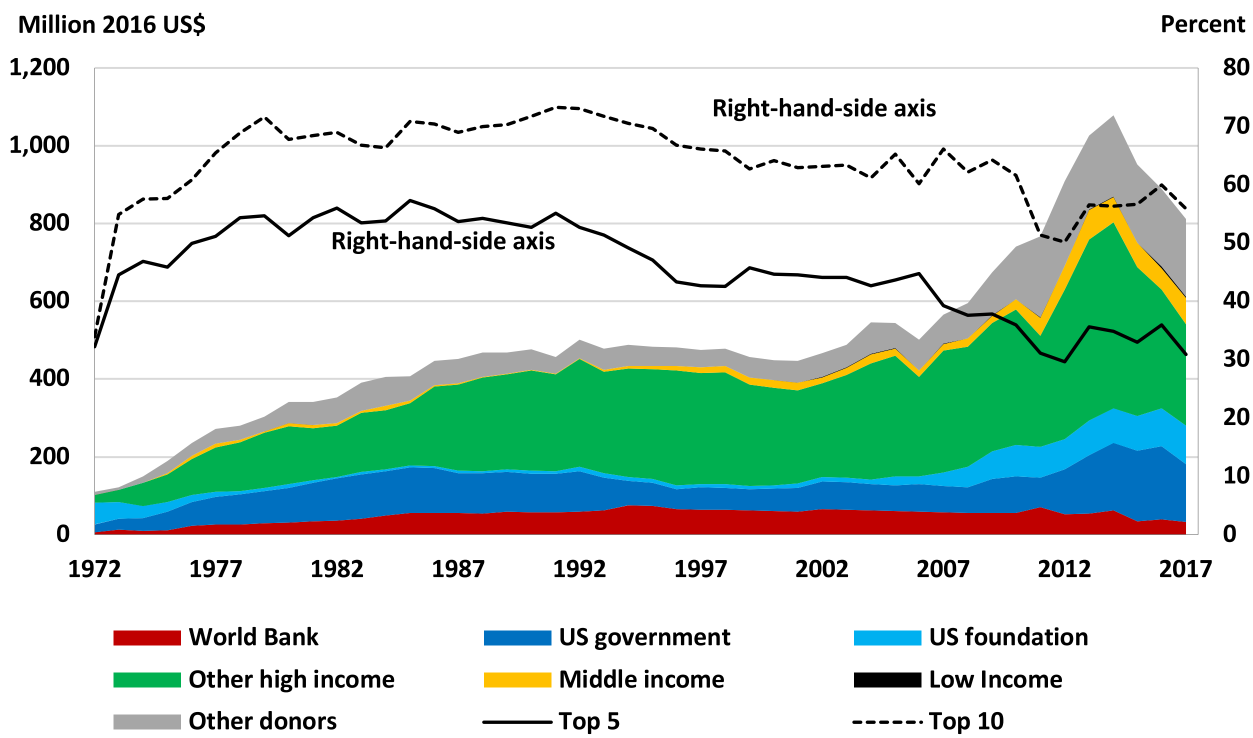
EXECUTIVE SUMMARY

The roots of what became the CGIAR extend back 80 years. In the 1940s, a few far-sighted public and private agencies began making modest investments to improve the yields of staple food crops in selected developing countries. By the 1960s, those investments had produced four fledgling international research centers. The CGIAR was established in 1971 on the foundation laid by those centers. The system underwent two waves of expansion: in the 1970s, it added seven centers focused on crop and livestock productivity, and in the 1980s and 1990s, it added another six centers focused on environmental issues and other outputs such as forest products and fish.

Today's middle-income countries as a group now outspend the rich countries on public agricultural and food R&D and out-produce them.

Most CGIAR funding comes from a comparatively small (but changing) group of public and private agencies. In 2017, just five funders accounted for 45% of the $812.1 million (2016 prices) funding total; ten funders provided 60%. All but two (i.e., Mexico and India) of these principal funders are based in rich countries. The middle- and low-income countries as a group, which are the target beneficiaries of CGIAR research, still provide comparatively little of the funding (8.5 percent in 2017) even though the global landscape for agriculture and agricultural R&D has changed markedly since the CGIAR's inception. In particular, today's middle-income

High-income countries continue to provide the bulk of CGIAR funds



Sources and Notes: See Figure 7, main text.

Credit: Georgina Smith (CIAT)

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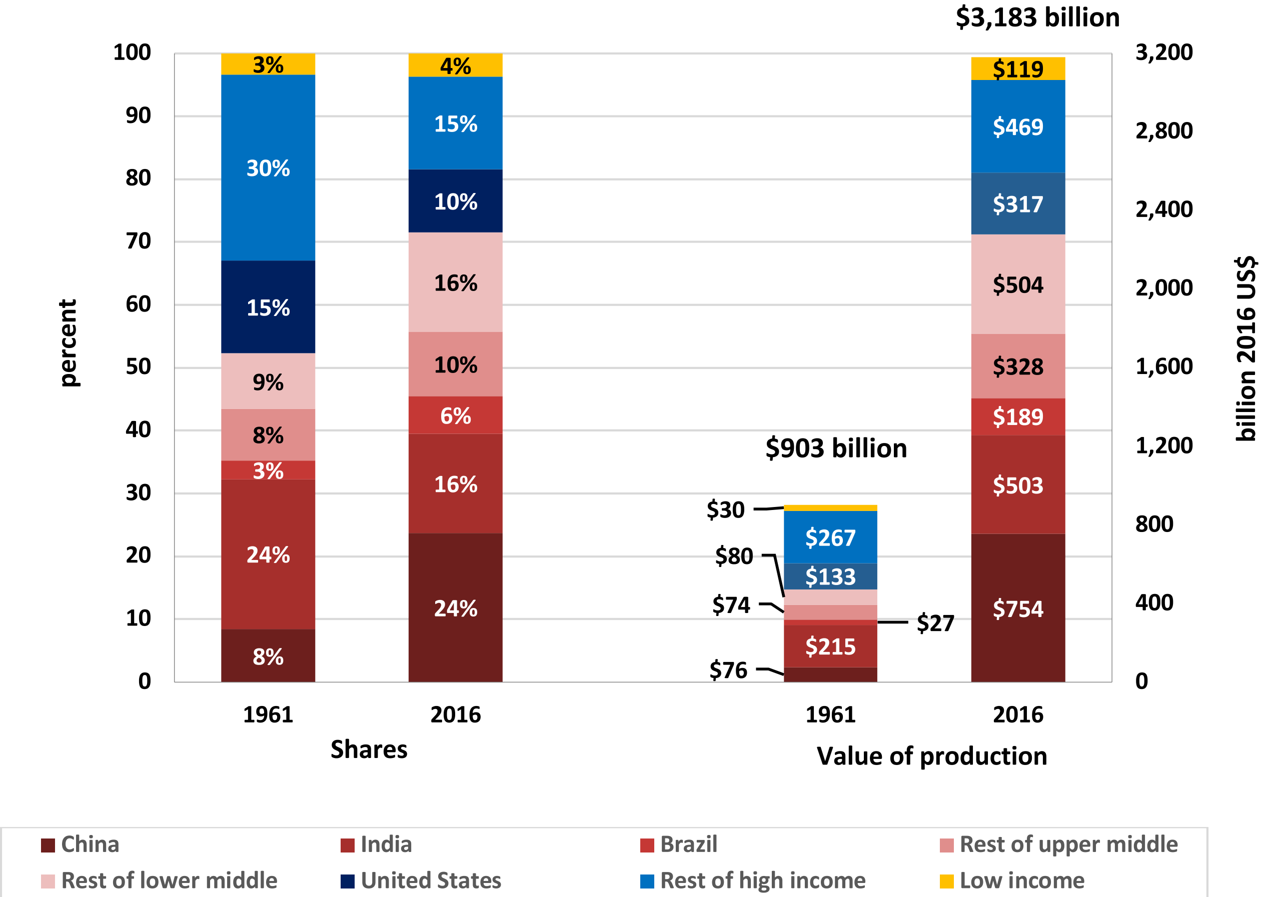
From 1961 to 2016, global agricultural production has shifted significantly from high-income to middle-income countries, especially China, India, and Brazil.



Source and Notes: See Figure 1, main text.   All figures expressed in 2016 PPP dollars.

countries as a group now outspend the rich countries on public agricultural and food R&D (53.4% of the total in 2015) and out-produce them (accounting for 72.0% by value of global agricultural output in 2015, versus 24.4% for the high-income countries). Moreover, privately performed research is now a feature of agricultural and food R&D in both the rich and agriculturally large middle-income countries. Critically, the agricultural innovation capacity of low-income countries (especially those in Africa) continues to lag well behind.

Meanwhile, in the high-income countries serving as the mainstay of support for CGIAR research, public and private spending on agricultural R&D has lost ground. Real spending growth has faltered—indeed, in many countries real spending has fallen—and a shrinking share of the total focuses on traditional farm productivity. Mirroring these trends in the high-income country NARSs, and probably for the same types of reasons, somewhat similar shifts can be seen in the total amount and emphasis of (increasingly earmarked) donor funding for CGIAR research: a shrinking total with a smaller proportion devoted to enhancing farm productivity. These trends may have dire long-term consequences.

Agricultural R&D is slow magic (Pardey and Beintema 2001). R&D investments are like some tree crops: they take many years to begin to produce useful outputs and the dividends—from the eventual adoption of the resulting innovations—can also continue to flow for many decades. R&D is also an uncertain business. To make for a profitable portfolio the projects that produce significant innovations, widely adopted by farmers, will have to pay for the less successful efforts.

Decision-makers must assess past payoffs and evidence provided to shore up existing funds, or justify increasing them. Even more difficult, they must prioritize the use of the increasingly scarce agricultural R&D resources available in the high-income countries or being made available to the CGIAR. Much depends on these decisions. They will limit or expand future possibilities. Understanding the immediate and long-term implications of today's R&D choices demands a thorough understanding of how past choices have shaped the present.

The purpose of this project was to make economic sense of the existing evidence on the benefits and costs of research undertaken by the CGIAR, with a view to informing future funding decisions. We first present newly developed detailed data on the evolving institutional structure of the CGIAR and its shifting portfolio of research investments and funding sources, in the context of the broader changes in agriculture and agricultural R&D worldwide. This background information helps us all to better understand and interpret the evidence on the payoffs and to evaluate future prospects.

Credit: Georgina Smith (CIAT)

The main part of the report documents and analyzes past payoffs, based on a comprehensive review of published rate-of-return studies. We present two main types of evidence, drawing on these studies. First, and foremost, our meta-analysis reports on and assesses the most comprehensive compilation of evidence on the economic returns to CGIAR research created to date. Drawing on this evidence, we model and measure relevant attributes of the distribution (mean, median, standard deviation) of the rate-of return (ROR) measures and draw inferences for the total payoff to the portfolio. Second, we update and extend an analysis by Raitzer (2003) and Raitzer and Kelley (2008, Tables 3 and 4) that details the total benefits reported in just six studies of CGIAR R&D—selected based on the total size of their measured payoffs and some screening criteria. Third, we compute the value of total agricultural productivity growth in developing countries, some part of which is attributable to R&D investments by the CGIAR and other agencies.

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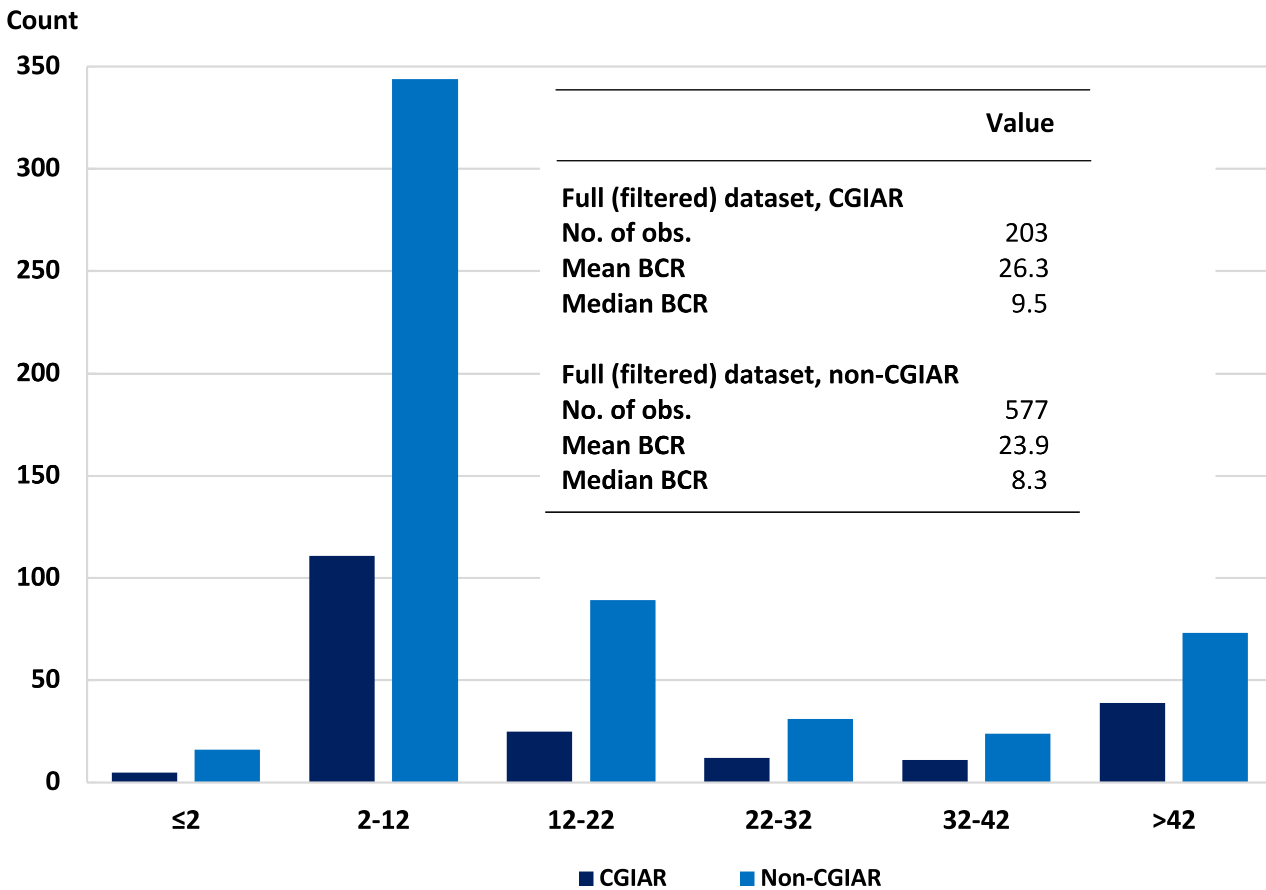
In meta-reviews of any type, one key challenge is to decide which studies (and results) to include—and conversely which to exclude—and, relatedly, the weight to give a particular study or group of studies in drawing inferences about the population of interest. As discussed by Alston et al. (2000a, 2000b), evaluating the returns to agricultural R&D is inherently challenging, requiring a great many assumptions (some made tacitly or implicitly), often driven by data and other limitations. Given these considerations—compounded by the prevalence of incomplete documentation (of the type that makes published quantitative economic analysis generally difficult to replicate)—it is hard to make confident judgements about the quality of any one study or estimate, even after a detailed and time-consuming assessment. Thus, we opted for an open-minded and inclusive (but nonetheless hard-nosed, cautious, and critical) approach to the problem, using as much of the published work as would be amenable to our analytical approach. We took the view that the best way to handle any general skepticism about the CGIAR-related evidence as a whole is by considering the broadest-possible sample, rather than by arbitrarily excluding studies.

The overwhelming conclusion is that the predicted BCRs for these and other sub-categories are all substantially greater than one—generally on the order of 10:1—without any significant differences among them, statistically or economically.

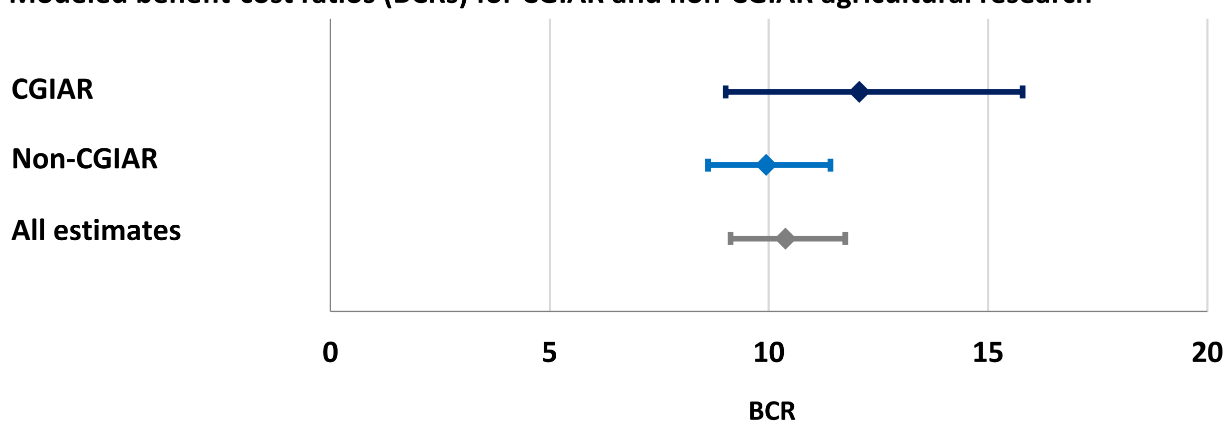
The total pool of evidence is large. We identified and scored 115 studies that report 363 RORs—either as benefit-cost ratios (BCRs) or internal rates of return (IRRs) for CGIAR-related research. For comparative purposes we also identified and scored a further 403 studies reporting 2,600 RORs for non-CGIAR agricultural research conducted by public agencies in national agricultural research systems (NARSs) in low- and middle-income countries. The majority of those studies report IRRs, but we prefer BCRs and were able to recalibrate many of the estimates into an equivalent, standardized BCR measure. The resulting recalibrated database comprises 203 standardized, imputed BCRs from 78 studies for CGIAR research, and 2,007 standardized imputed BCRs from 341 studies for non-CGIAR developing-country public research. Almost all of these BCRs are for crops research.

Across the available evaluation evidence, and the portfolio of R&D it represents, the reported BCRs are widely dispersed. We examined the differences in BCR estimates across various sample subsets, and also employed a meta-regression analysis more formally to explore the extent of systematic differences in BCRs between CGIAR and non-CGIAR R&D investments and among CGIAR centers. Our approach enabled us not only to account for the influence of covariates in disentangling the differences among particular groupings of BCR estimates, but also to derive a predicted BCR for CGIAR R&D, conditioned on the covariates, to make statements about the past payoffs. The main alternative would be to rely directly on the distribution of the reported BCRs, and then compare results from these two approaches. The preferred regression model yields generally large predicted BCRs: 10.4 across all observations, with a relatively narrow 95% confidence interval, between 9.1 and 11.7. The results are similar for both the non-CGIAR subsample, which accounted for a significant majority of the data, and the CGIAR subsample.

Distribution of imputed benefit-cost ratios (BCRs) for CGIAR and non-CGIAR research



Modeled benefit-cost ratios (BCRs) for CGIAR and non-CGIAR agricultural research



Sources: See Figures 9 and 10, main text.

Notes: BCR groupings (first panel) such as "2-12" indicate greater than 2 and less than or equal to 12, and so on. Whiskers (second panel) denote 95% confidence interval for predicted BCRs.

*estimated payoffs range widely around that average

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The overwhelming conclusion is that the predicted BCRs for these and other sub-categories are all substantially greater than one—generally on the order of 10:1—without any significant differences among them, statistically or economically. The evidence supports a view that the overall BCR for CGIAR (and non-CGIAR) research is on the order of 10:1 (and generally in the range of 5:1 to 15:1), but that we cannot make more precise statements about the differences among centers, nor according to research focus or other differences among studies.

BCRs are scale-free numbers. To add more meaning to those numbers, we inferred measures of the present value of benefits by applying BCRs to various particular streams of research expenditures. For example, if we compound forward at a rate of 5% per year over the period 1971–2018, the stream of R&D spending by the founding four CGIAR centers had an equivalent present value in 2018 of $31 billion (2016 dollars). Applying a BCR of 10:1 to that same stream of spending and compounding the implied benefits (in annual present value terms) forward over the period 1971–2018 (or equivalently, applying 10:1 to the compounded present value of that stream of benefits) yields an equivalent present value in 2018 of $314 billion. Applying a BCR multiplier of 10 to the total present value in 2018 of CGIAR spending over the period 1971–2018 ($64.8 billion) implies a present value in 2018 of benefits from CGIAR spending equal to $648 billion.

Billion-dollar studies of returns to CGIAR research show benefit-cost ratios (BCRs) of 10 or higher even if only the benefits measured in these studies are compared to all CGIAR costs.

	Present value of costs 1960-2010	***Present value of benefits 1966-2020***	
		100 % attribution	**50% attribution**
		1,782.5	***891.3***
		BCRs	
Centers in evaluations	***44.5***	40.1	20.0
Total CGIAR centers	***59.7***	29.9	14.9
NARS and CGIAR	***2,628.3***	0.68	0.34

Sources: See Table 10, main text.

Notes: Present value in 2016 of benefits and costs, all expressed in billions of 2016 dollars using a 5% real discount rate.

Credit: Leo Sebastian (IRRI-CCAFS)

We also compiled detailed data from a subset of impact-assessment studies that report measures of total benefits or net present values (NPVs) as well as (or instead of) IRRs or BCRs. In doing so, we sought to identify "billion-dollar" studies—those for which the total respective reported benefits exceed $1 billion in 2016 values. To do this, we began with a set of studies reported in the meta-review by Raitzer (2003) and Raitzer and Kelley (2008) and augmented them with studies reported by Renkow and Byerlee (2010) and subsequent studies. After some sorting, we settled on a subset of nine large-scale studies that reported measures of total benefits from CGIAR R&D. In 2016 dollar terms, after projecting gains to 2020, the present value of benefits across these nine billion-dollar studies total $1,783 billion, of which perhaps one quarter may be attributable to the CGIAR alone: a total benefit of $422 billion. On that basis, the BCR would be 7.5 if we count all CGIAR expenditure, rising to 10.0 if we count just the expenditure by the centers included in our nine billion-dollar evaluation studies.

The technologies arising from investments in agricultural R&D are the primary drivers of the sector's increased productivity. As a further frame of reference and check on plausibility, we first computed estimates of the total economic value arising from agricultural productivity growth in developing countries as a group, expressed as present values in 2016. We then contrasted this measure of benefits with the present value of total expenditure by the CGIAR and R&D agencies in developing countries, also expressed as present values in 2016. Again, the evidence reinforces the findings from the meta-analysis: our most-plausible combinations of assumptions and attribution rules yield approximate BCRs very close to 10:1.

Estimates of the value of agricultural productivity growth corroborate the BCR evidence

	Present value of costs 1960–2006	***Present value of benefits 1961-2026***	
		100 % attribution	**50% attribution**
		47,974	*23,987*
BCRs	*2,508*	**19.1**	**9.6**

Sources: See Table 12, main report.

Notes: Present value in 2016 of benefits and costs, all expressed in billions of 2016 dollars using a 5% real discount rate.

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THE PAYOFF TO INVESTING IN CGIAR RESEARCH

Credit: Anne Wangalachi (CIMMYT)

1. Introduction

The group of international agricultural research centers (IARCs), now collectively known as the CGIAR, have been conducting applied research and development (R&D) to serve the world's food poor for more than half a century. These centers, financed primarily by a small group of rich-country governments and a few private foundations, played a pivotal role in the Green Revolution and in the broader transformation of global agriculture in more recent decades. In the second half of the 20th century, in particular, global food supply grew faster than demand, and real food prices fell significantly, alleviating hunger and poverty for hundreds of millions around the world. Will that pattern be repeated in the first half of the 21st century? The answer to this question matters, and it will depend on investments in agricultural R&D, including investments made through the CGIAR.

Investments in CGIAR research have been closely scrutinized and subject to considerable cost-benefit analysis over the decades. The findings have been consistently favorable. The current consensus is that from a comparatively modest investment, the CGIAR has generated great benefits, primarily by way of crop varietal improvements and related innovations that increase agricultural productivity and lower farmers' costs of production, ultimately benefiting non-farm consumers and the economy more broadly, as well as farm families. Even so, some commentators have questioned the past payoffs, and further questions have been reasonably raised, looking forward, about the prospective payoffs and priorities. Today, as at times in the past, funding streams for CGIAR research are in decline and under threat (Box 1). This mirrors a pattern of declining support for agricultural R&D at home in the countries that have served as the mainstay of support for the CGIAR (Pardey et al. 2016a).

This pattern of declining support for CGIAR research is of particular concern in light of the challenges facing global agriculture and the world's poor, whose livelihoods depend on it, directly or indirectly. Global demand for food is projected to grow by 70% from 2010 to 2050 (Pardey et al. 2014). Simply to meet that demand will call for transformative innovations in agriculture to adapt to a changing climate, to combat co-evolving pests and diseases, and to increase productivity of a fairly fixed land base and a shrinking supply of agricultural water. To make food abundant and affordable for the increasingly urban poorest of the poor demands doing much more—and much better—than simply keeping up.

This study was commissioned to assess the extant economic evidence on the payoffs to past investments in CGIAR research, with a view to providing information that will help encourage donors to reinvigorate the enterprise to the extent and in the ways that the evidence warrants. Research is a potentially highly rewarding business, but risky at the project level: some science leads to economically successful outcomes, but much does not. In a profitable portfolio of any kind, the winners have to earn enough to cover the costs of the losers as well as their own costs, and in agricultural R&D, as in wildcat oil prospecting, just a few gushers may have to pay for a great many

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Box 1: Finding the Funds—Warren Baum (1986)

By 1967, the four institutes [i.e. IRRI, CIMMYT, CIAT, and IITA] were in various stages of construction or operation, and costs were beginning to mount rapidly. In their budget requests for 1968 to their boards of trustees, officials of the two foundations [Rockefeller and Ford] committed themselves to a maximum contribution of $750,000 each to each center, at least for the time being. The total of $3 million to be contributed by each foundation was recognized to be arbitrary and probably inadequate for the centers to reach their full potentials. But some ceiling was considered necessary in order to secure financial support from other sources, to induce cost-effectiveness in the management of the centers, and to encourage the center directors to take the initiative in seeking outside financial help. Moreover, the early successes of IRRI and CIMMYT had given rise to various proposals for additional institutes to work on other crops or regions of the world, which gave further impetus to the search for funds. It had been anticipated from the outset that financial support from additional sources might be desirable, if not essential, and provision had been made in the charter of each institute to enable it to receive gifts and grants from any appropriate source for purposes consistent with the institute's mission and responsibilities. The expected life of the institutes had not been explicitly addressed, but some of the founding fathers thought that the institutes might work themselves out of their jobs in twenty or twenty-five years… .

The time had come, in Hill's words, to "go public" [Forrest (Frosty) Hill was at the time vice president for overseas operations of the Ford Foundation]. The first source to which the foundations turned was the U.S. Agency for International Development (USAID). In 1965, USAID had made a one-time grant of $350,000 to IRRI for a special project (outside the regular or "core" budget) for the development of agricultural machinery. The five-year project was highly successful, but did not immediately lead to other contributions from USAID. During the first half of the 1960s, USAID was hamstrung by congressional attitudes opposing foreign assistance for the development of crops that might compete with U.S. farm production. These attitudes changed in the mid-1960s at the time of the disastrous harvests in India and Pakistan. USAID made a grant of $400,000 to IRRI in June 1968. Eighty percent of the money was tied to the purchase of goods or services from the United States… .

[USAID] was gearing up to accept the foundations' invitation to become a "full and official" partner in supporting the centers on a long-term basis. It declined the foundations' offer to have an agency-appointed representative serve on the boards of trustees of the centers, but it did send observers to board meetings and participate in the centers' program reviews.

Overtures to the Canadian International Development Agency (CIDA) and its president, Maurice Strong, also fell on receptive ears. CIDA proposed to the Canadian government that it provide core budgetary support to IRRI in 1969, but the government turned down its request: Canadian wheat was piling up in storehouses as a result of bumper harvests, and the government did not find the time opportune to seek funds from Parliament to support food crop research in developing countries. CIDA, nevertheless, proceeded with plans, to be implemented when the moment was ripe, to join as a full and equal partner with the foundations by pledging $750,000 to one of the centers.

The Kellogg Foundation, as noted previously, had been an early supporter of CIAT. In 1968 it indicated its willingness to continue its support of CIAT'S outreach and communications programs with grants of up to $250,000 annually. Discussions were also initiated with other potential sources. There were a number of contacts during 1967 and 1968 with the United Nations Development Programme (UNDP), and formal requests for support were submitted, but no assistance was in sight… .

This was the state of play in the early months of 1969. Numerous contacts had been made, and there were encouraging signs of interest. But the process was slow and time-consuming, and, as Hill observed, the centers needed something more concrete than encouragement with which to pay their bills. As costs continued to rise, the need for more outside support became urgent. The establishment of some kind of consortium of international aid agencies and donor countries had been mooted by Hill and others in 1968, but they were skeptical of the possibility of organizing it.

Clearly some kind of more comprehensive approach to raising funds was badly needed. The conference that was held in Bellagio, Italy in April 1969 provided just the opportunity.

Source: This text is extracted from Baum (1986, pp. 24-26) and illustrates the fragile and fraught nature of CGIAR funding from the very outset. Warren C. Baum from the World Bank was he second chair of the CGIAR and held the position for ten critical and formative years, ending his term in 1983.

dry holes. Consequently, a selective and partial view of investments could be highly misleading, one way or another.

We sought to develop meaningful measures of (and broader quantitative insights into) the evolving structure of and returns to the diverse portfolio of R&D undertaken by the CGIAR centers over their varied history during the past six decades—not just the big winners. We thus compiled all of the available published studies that reported usable cost-benefit or rate-of-return evidence on investments in agricultural R&D undertaken by the CGIAR. Our main analysis centers on the estimates from these studies.[1] Next, to enable aggregation and analysis, we transformed the estimates from these studies into equivalent standardized benefit-cost ratios (BCRs). As a basis for comparison and a benchmark, we also present comparable evidence on the returns to investments in agricultural R&D undertaken by national research agencies in low- and middle-income countries.

The data set used in the main analysis includes 235 standardized BCRs imputed from 90 CGIAR studies and 2,007 BCRs imputed from 341 non-CGIAR studies. Across those 235 estimates for CGIAR research, the median BCR was 10.6 (the mean was 25.5, and the standard deviation was 37.5), and across the 2,007 estimates for non-CGIAR investments, the median BCR was 7.9 (the

1 This is a subset of the total “impact assessment” evidence compiled on the much-studied CGIAR system. Some of that assessment is largely qualitative; some of it involves quantitative assessment of performance indicators that do not translate well into economic indicators, let alone money-metric indicators of impact. See, for example, the recent performance reviews of the system (CGIAR 2017 and 2018). We opted, at the outset, to limit our attention to studies that provided conformable and comparable money-metric measures of impact, as BCRs or IRRs, and sought to include all available such studies.

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mean was 28.2, and the standard deviation was 114.5).[2] A BCR of 10.6 would indicate that a dollar invested in agricultural R&D today would yield a stream of benefits—typically over many future years—equivalent in present value to an immediate payoff of $10.60. Such a high BCR indicates an exceptionally profitable investment—a BCR of 1.0 or more is sufficient to justify an investment. Taken at face value, these estimates would indicate that both national and international agricultural research have paid handsome dividends and that the world has seriously underinvested in these national and global public goods. The same is true of various subsets of the BCR data that may be more relevant for particular purposes.

Details were also compiled on relevant attributes of the assessments underpinning the BCRs and the investments to which they referred—in terms of the commodity focus, the country of reference, the CGIAR center(s) involved, the role of co-funding by national agencies, and so on. Using these attributes and other resources, beyond simply compiling and reporting the estimates themselves, we undertook some critical assessment, interpretation, and filtering. We used regression analysis to formally compare the ex post BCRs for CGIAR research vis-à-vis non-CGIAR research conducted in developing countries and for various aggregations of CGIAR research. In this analysis we sought to account for other attributes of the studies (such as commodity focus and technical details of the estimation methodology) that can influence the reported returns to research (see, e.g., Alston et al. 2000a and 2000b and Rao et al. 2019). And, as a further check for external validity, we compared our own findings with the results from previously published, less-comprehensive reviews and meta-analyses of returns to agricultural R&D.

BCRs—and other summary statistics such as the internal rate of return (IRR)—are often misunderstood, even by the economists who measure them. In any event, they are scale-free measures that do not convey the full import of the findings. To go beyond the BCRs, we inferred implications of the evidence for the total payoff to the investment. To do this, we present complementary data on the total investment in agricultural R&D undertaken by the CGIAR and by the national agricultural research systems (NARSs) in the developing countries to which the BCRs could be applicable.

Given these measures of research investment (corresponding to the denominator of the BCR) and the size of the BCR associated with the investment, we developed procedures for recovering the corresponding implicit measures of total benefits (in the numerator of the BCR)—an indication of the total opportunity cost if the investment had not been undertaken. In 2018 the CGIAR invested $824.3 million in agricultural R&D. A BCR of 10:1 indicates this investment will yield a stream of benefits over the coming decades worth $8.2 billion in present value terms. We applied this approach, retrospectively, to derive estimates of the total payoff to the investment in agricultural R&D over the life of the CGIAR as a whole or for various subsets of the CGIAR. For perspective, we also juxtaposed these measures with comparable estimates of the total value of agricultural production and the payoffs to non-CGIAR investments in agricultural R&D over the same period.

2 In our detailed analysis we use a subset of these data, with small and negligible differences in the measures of central tendency.

Empirical concerns with this approach relate to representativeness of the average measures of BCRs in view of potential sample-selection (cherry-picking) biases in impact assessment and other possible sources of bias, relevance in terms of applicability beyond the R&D to which they applied, and scaling. In the meta-analysis, all observations of BCRs are treated equally, regardless of both the scale of the investment from which they were derived and the scale of the total benefits that they reflect; it is a *simple average*. However, referring to the portfolio as a whole, the relevant overall BCR would be given by a *weighted average* in which each BCR is weighted by a share of the total research budget it represents. Hence, scaling research investments using the simple average of the BCRs may result in a misleading indicator of total benefits to the portfolio unless the distribution of the BCRs is similar across all scales of investment such that the simple (unweighted) and weighted averages are similar.

In the last part of the report, we introduce additional evidence as a check on the external validity of our inferences. First, we present the findings from a selected (non-random) subset of specific studies of CGIAR R&D that have presented measures of total benefits and show large payoffs. These studies were identified drawing on the review by Raitzer (2003) (see also Raitzer and Kelley 2008) encompassing studies published before 2002, the subsequent review by Renkow and Byerlee (2010) encompassing studies since 2000, and some selected others suggested by members of the review team and from our own literature searches. Expressing the total payoffs from this subset relative to the total CGIAR investment provides a lower-bound estimate of the overall BCR. We also juxtapose our measures of the total payoffs to CGIAR research against the part of the value of agricultural productivity growth that may be attributable to CGIAR R&D. All these alternative angles support using a BCR of 10:1 as a general indicator of the payoff to CGIAR R&D.

1.1 Report Roadmap

This report is divided into three main parts. The first is "Introduction and Overview," which ends here. Next is "Context for the Assessment," which details the evolving structure of the CGIAR investments and institutional arrangements and the global agricultural and innovation realities within which the CGIAR operates. As well as relevant facts and figures, this part discusses the broader role of the CGIAR working in concert with the NARSs to enhance farm productivity growth and thereby alleviate hunger and poverty in developing countries. Part three, "The Returns to CGIAR Research," presents the substantive core of our work to develop new insights into the extant evidence on returns to investment in the CGIAR, supported with extensive data and methodological details documented in Annexes. This part ends with a brief "Bottom Line." Some readers might choose to skip the "Context" and go straight to the analysis of "Returns," which is written as a stand-alone section. However, understanding the "Context" is essential to making sense of some parts of the evidence.

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CONTEXT FOR THE ASSESSMENT

Credit: Stephanie Malyon (CIAT)

2. Evolving Structure of Global Agriculture, Agricultural R&D, and the CGIAR

A lot has changed since the institutional innovation known as the CGIAR came into being. Before assessing the returns to CGIAR research, we provide some background on the evolving institutional and financial structure of the CGIAR and its portfolio of research, and on where that sits within the evolving structure of global public agricultural R&D and the changing global landscape of agriculture itself. As well as providing context for the analysis, this information includes data used in scaling up the BCRs to estimate the dollar value of the global payoff to CGIAR research.[3]

2.1 Global Perspectives on Food, Agriculture, and R&D[4]

Since about the middle of the 19th century, the application of science to agriculture—increasingly by way of targeted investments in R&D—has released much labor and other (especially land) resources from the production of food and other agricultural outputs (Ruttan 1982). In 1800, before this R&D-induced process of agricultural transformation got underway, the planet's population was around 980 million people, most of whom worked in agriculture (an estimated 75–80% of the working population earned its livelihood in agriculture, see Bairoch 1988). By 2020, the world's population had increased almost eightfold. Although a significant number of people still live a hand-to-mouth existence, growing much or all of the food they consume, more than half the world's population now lives in urban areas while less than 40% of the working population earn their livelihoods from agriculture.[5] Land used in agriculture worldwide increased by much less than global population: in 2017 agriculture had to feed 1.56 persons per hectare compared with just under one person in 1800.

The Malthusian nightmare envisioned by many in the 1960s and 1970s was largely averted by remarkable gains in agricultural productivity achieved through R&D-enabled technological and structural change in agriculture. Over the past 50 years, the world's population more than doubled and per capita incomes grew, compounding the growth in demand, but the global food supply grew even faster. Hence, prices of staple grains fell significantly in real terms, global famines were averted, and many millions (or billions) were saved from much misery, contrary to the dark and dire prophecies of the late 1960s and early 1970s—e.g., see Paul Ehrlich's *Population Bomb* (1968) and the Club of Rome's commissioned report on the *Limits to Growth* (1972).[56] Indeed, between 1961 and 2016, real output from agriculture grew by 2.3% per year (equivalent to a 252% increase in real output) and, in spite of the ever-tighter land constraint, agricultural output per person grew by 46%—from $292 per person in 1961 (2016 prices) to $426 per person in 2016. These increases in land and labor productivity were accomplished by intensifying the use of "modern" inputs—in particular machinery, fertilizers and irrigation—combined with improved genetic material and

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methods of production increasingly derived from organized scientific research[6]. Investments in agricultural R&D in general, and the CGIAR in particular, played a central role in developing the Green Revolution technologies that were important in this process.

Economists widely take the view that agricultural R&D, including (perhaps especially) that undertaken by the CGIAR, has played a crucial role in priming the pump of economic development and lifting the shackles of poverty—most directly by promoting agricultural productivity growth or preventing a slowdown in growth caused by (co-)evolving pests and diseases or other environmental or economic challenges. The link between agricultural R&D and farm productivity is well established and documented (see, e.g., Griliches 1963, Alston et al. 2010, Fuglie et al. 2020), but we continue to lack comparably strong, direct evidence on the downstream linkages between agricultural R&D, economic growth, and other economic development indicators. As Gollin (2010, p. 3825) wrote: "Thus, even after 50 years of research on agricultural development, there is abundant evidence for correlations between agricultural productivity increases and economic growth but little direct evidence for a causal connection." Recent research (see., e.g., Gollin et al. 2019) is shedding new empirical light on these causal links, which economists who work on these issues tend to take for granted.

The uptake of new farm technologies, especially at the early stages of economic development, helps economies to diversify and transform in ways that substantially improve standards of living, life expectancy, and other measures of well-being (e.g., see Alston and Pardey 2014, 2015, and Box 2). Global patterns of these and other measures of poverty and well-being have changed considerably in the six decades since the CGIAR was founded and began contributing to these changes. At the same time, changes also occurred in the global structure of agriculture within the broader economy, and in the economic geography of agricultural R&D performance. These changes in the broader economic and social context in which the CGIAR sits are relevant for contemplating both its past and potential future contributions.

2.2 The Global Incidence of Hunger and Poverty

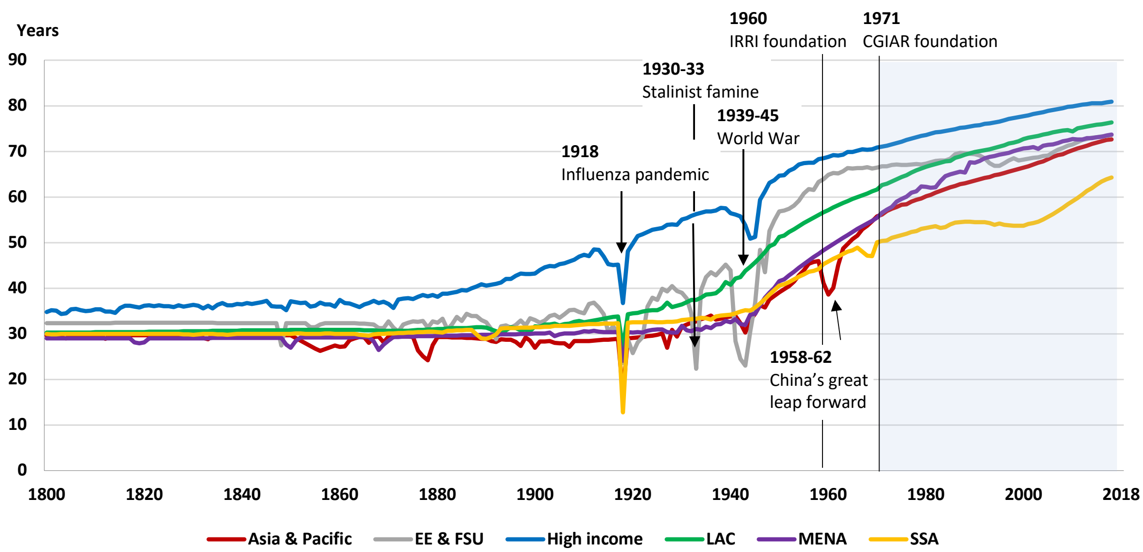
While we have abundant money-metric measures of the returns to agricultural research (such as the BCRs and IRRs described and assessed in this report), we have much less concrete or comparable evidence on the consequences of agricultural R&D for food security of the poor or more generally on how the benefits from agricultural R&D are distributed among consumers, producers, agribusiness interests, and so on.[7] We also lack a useful set of indicators of the extent to

7 Along with conventional rate-of-return measures, Alene and Coulibaly (2009) estimate poverty-reducing consequences of agricultural R&D done by NARSs and the CGIAR in sub-Saharan Africa, and Fan et al. (2005) discuss the consequences of national and international rice research for rural poverty in India and China. But these are rare exceptions among the careful empirical studies; few go beyond rates of return.

Box 2: Life Expectancy and Infant Mortality Trends

What do we know about the associations between R&D-enabled agricultural production and productivity growth—and the commodity composition of that growth—and the human nutrition and health outcomes associated with food consumption? Some aspects of these issues are understood. Cutler et al. (2006) critically assessed the reasonably extensive literature regarding the determinants of mortality, including its historical decline and the prevalence of premature death in today's poor countries. They singled out improvements in nutrition and public health along with urbanization, the avoidance of disease, and modern medical, especially therapeutic, treatments as putative factors accounting for the decline in mortality over time (Box Figure 1).

Box Figure 1: Life expectancy at birth, 1860-2018 by region of the world



Source: Rosling (2017a).

Note: Shaded area indicates period during which the CGIAR has been operating.

Changes in the association between life expectancy at birth and per capita income are revealed in Box Figure 2. Comparing Panel a with Panel b, three developments are evident. First, the spread in life expectancies among countries is now less pronounced than it was almost six decades ago. Second, at any particular level of income, people lived substantially longer in 2018 than they did in 1961. In fact, life expectancy at birth for African countries in 1961 averaged just 46.4 years, but by 2018 had increased to 64.3 years (roughly equivalent to the rich-country average in 1950). Third, life expectancy at birth appears to be positively, but not exclusively, related to per capita income. Box Figure 2, Panels c and d plot country-level data on child mortality rates against per capita income that are largely the mirror image of the corresponding plots of life expectancy at birth against per capita income. Increasing income is associated with declining child mortality rates, and Box Figure 2 shows a dramatic and pervasive decline in the rate of child deaths over the past six decades.

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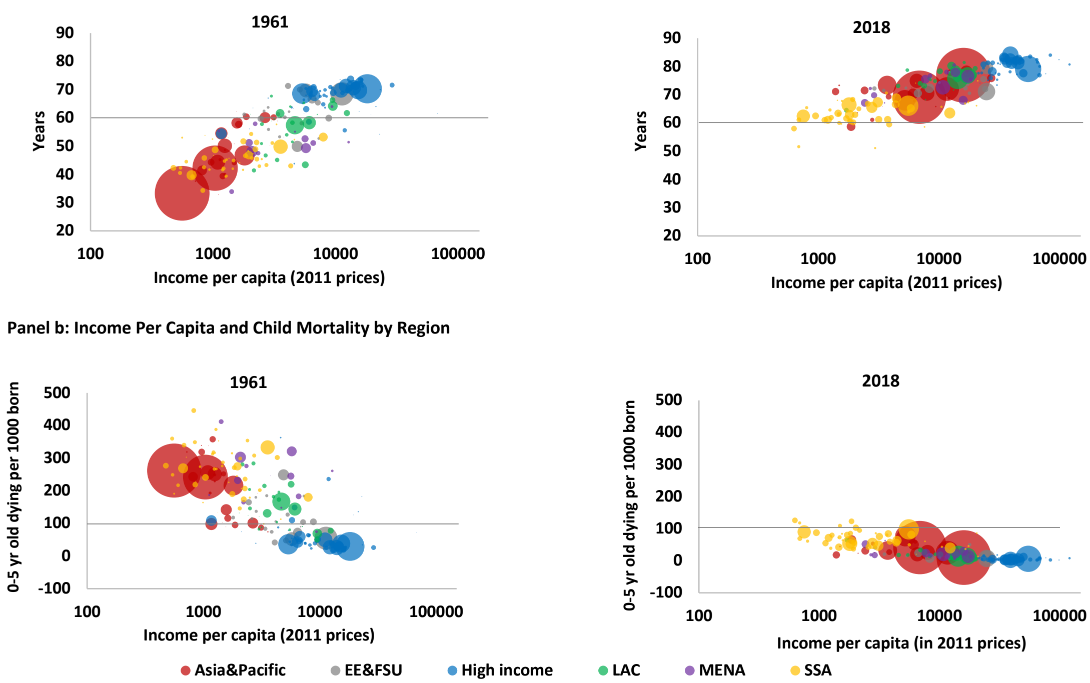
Box Figure 2: Life expectancy at birth and child mortality rates, by country, 1860-2018 by region

Panel a: Income Per Capita and Life Expectancy by Region

Box Figure 2: Life expectancy at birth and child mortality rates, by country, 1960 and 2018

Panel a: Income Per Capita and Life Expectancy by Region



Source: Authors' construction based on Rosling (2017a, 2017b, 2018a, and 2018b).

Notes: Bubbles represent countries, sized by population shares.

which agricultural R&D has affected nutrition and health outcomes, such as infant mortality rates and life expectancy at birth.[8] Improvements in these anthropometric indicators of well-being are also associated with declines in the rate of poverty (Table 1, Box 2).

Across all the measures in Table 1, based on a poverty line at $3.20/day, worldwide poverty rates dropped considerably in both relative and absolute terms: the headcount measure fell from 57.4% to 26.6%, the total number of the world's poor fell from 2.5 billion to 1.9 billion, and the depth of poverty was reduced (using the poverty gap and squared poverty gap measures). But this good news was not shared equally everywhere. The Asia & Pacific region stands out with its huge gains by all measures. Conversely, sub-Saharan Africa fared poorly by all measures: the poverty rates did not fall much, and the absolute numbers of poor more than doubled. In 2015, more than one-

8 Indicators of this nature might be more effective than BCRs and IRRs for persuading policymakers to keep investing in agricultural R&D. Certainly, a claim that Norman Borlaug has saved a billion lives captures the imagination more effectively than any claims about the dollar value of his accomplishments. The Wikipedia entry on Norman Borlaug (https://en.wikipedia.org /wiki/Norman_Borlaug) refers to several sources of the claim that Borlaug saved a billion lives. Many others can be found with a Google search. One of the earlier commentaries along the same lines, by Easterbrook (1997), more modestly referred to hundreds of millions of lives saved.

third of the world's poor were in sub-Saharan Africa, where the poverty rate had barely fallen over

Table 1: The global and regional incidence of poverty, 1981 and 2015, various measures

	Headcount		Population in poverty		Poverty gap		Squared poverty gap	
Region	1981	2015	1981	2015	1981	2015	1981	2015
	Percent		*Millions*		*Percent*			
Asia & Pacific	90.3	29.1	2060.4	1088.4	51.5	8.0	33.3	3.1
EE & FSU	11.1	6.3	39.5	25.8	3.3	1.8	1.5	0.8
High income	1.5	1.0	13.9	10.5	0.7	0.6	0.4	0.5
LAC	27.6	10.9	93.8	64.2	11.8	3.7	6.9	1.9
MENA	34.6	15.6	58.6	55.7	10.4	4.4	4.3	1.8
SSA	70.8	67.0	274.5	660.3	37.4	31.9	23.8	19.0
World	**57.4**	**26.6**	**2541.0**	**1908.3**	**31.5**	**9.3**	**20.2**	**4.6**
Low income	79.1	72.9	178.3	427.8	45.1	34.8	30.0	20.7
Lower middle-income	77.5	44.1	1172.4	1267.1	38.1	14.0	22.4	6.2
Upper middle-income	65.5	7.4	1175.6	192.7	39.6	1.9	26.9	0.8
High income	1.5	1.0	13.9	10.5	0.7	0.6	0.4	0.5

Sources: Authors' calculations based on United Nations (2020b) for population data and World Bank (2020) for poverty data.

Notes: Headcount is the percentage of population living in households with consumption or income per person below the poverty line of $3.20/day in 2011 PPP. Poverty Gap is the mean shortfall of income from the poverty line, and the shortfall is expressed as a proportion of the poverty line. Squared Poverty Gap is the mean-squared shortfall of income from the poverty line.

a quarter century—from 71% in 1981 to 67% in 2015. Most of the rest were in Asia, where poverty rates have dropped dramatically, yet still 29% of people live on $3.20/day or less. These patterns point to both an encouraging record of accomplishment in reducing poverty and a continuing demand for research and other economic development policies focused on the poor in sub-Saharan Africa and those parts of Asia where poverty persists most stubbornly.

Of course, research is only one among several critical factors contributing to agricultural change and broader economic development—including political stability, investments in education, infrastructure, and public health. The question of "attribution" and related problems (Alston and Pardey 2001) arises throughout this report in various ways, including here. In principle, at least, it is feasible to measure crop varietal changes and the productivity gains they bring about and to associate those changes with the responsible research (see, e.g., Pardey et al. 1996, 2006). However, we do not have equally clear and compelling quantitative evidence of the extent to which the CGIAR (and other providers of agricultural R&D) contributed to these general reductions in global poverty by enhancing farm incomes and reducing food prices.[9] Nonetheless, international

9 Agricultural R&D undoubtedly played a role, but precise attribution is difficult, even if we know its effect on farm productivity or farm incomes.

agricultural R&D—of the type performed by the CGIAR—will be a critical ingredient in the mix of measures used to accelerate the agricultural transition and reinforce past progress in eliminating food poverty.

2.3 The (Economic) Geography of Agriculture and Food Production

The economic geography of agriculture changed markedly over the past six decades (Figure 1). In 1961, high-income countries produced 45% of the world's agricultural output by value, with the United States alone accounting for 15% of the global total. By 2016, the high-income-country share had shrunk to just 25% and the U.S. share to 10%. While the measure of rich-country agricultural output (in constant 2016 dollar values) roughly doubled over this period (growing at an annual average rate of 1.2% per year), elsewhere agricultural output grew much faster (averaging 2.8% per year). The group of middle-income countries—which includes the now large agricultural economies of China, India, and Brazil—accounted for 72% of global agricultural output in 2016, well up on their 52% share in 1961.[10] The low-income-country share barely budged, from 3% in 1961 to 4% in 2016.

Secular shifts in the location of agricultural production are driven by both supply and demand factors. Unlike manufacturing and other *industrial* production processes, agriculture is a *biological* production process distinguished by its intensive use of land and other natural resources as inputs (such as rainfall, sunshine, and heat). The relevant properties vary markedly over space and time. Some differences in agricultural supply among places reflect differences in soils, climate, or infrastructure—all of which influence agricultural possibilities. Others reflect differences in the relative prices of inputs and outputs, and various other factors that determine comparative advantage, as well as government policies that dampen its relevance.[11]

Demand matters too. As explained by Alston and Pardey (2019), food commodities are predominantly produced close to where they will be consumed.[12] Since per capita food

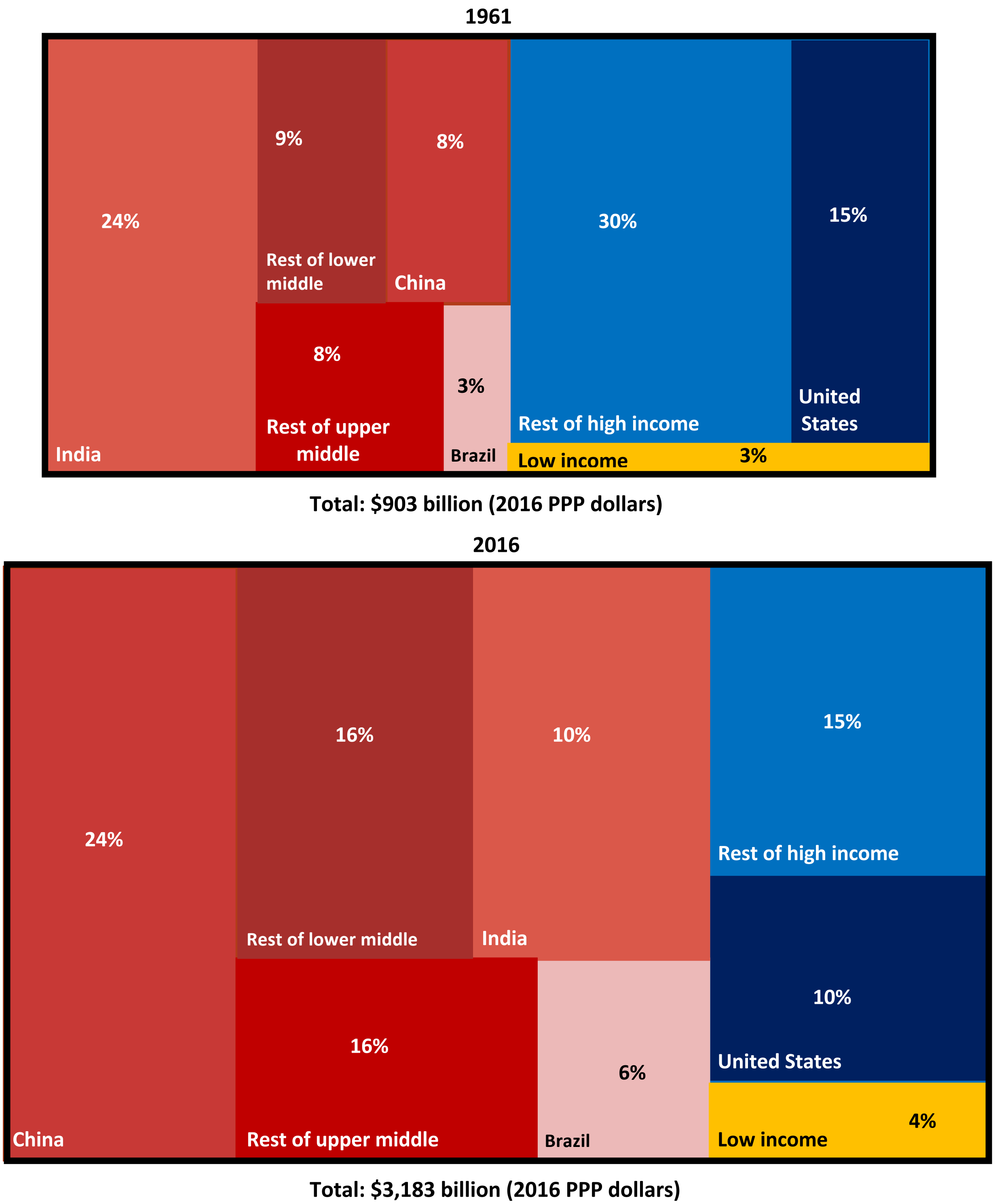
Increasingly, the indirect benefits from farming innovations—through more abundant and cheaper food and factor market adjustments—are outweighing the direct effects on alleviating poverty (Byerlee 2000; de Janvry and Sadoulet 2002, 2010). Studies that seek to measure broader economic impacts of agricultural R&D (or CGIAR R&D)—e.g., on human health, poverty, income per capita, and so on—often involve challenging econometric or other issues, and almost always their results are heavily conditioned by assumptions imposed as maintained hypotheses (see, for example, Alene and Coulibaly 2009, Gollin et al. 2019, Laborde et al. 2020, Pingali and Kelley 2007).

10 Here, and elsewhere in this report, "low-" and "middle-income" countries are identified in accordance with the World Bank's (2020b) 2018 classification and taken together are synonymous with "developing countries." "High-income" countries are also labeled "developed" or "rich" countries.

11 Some places can grow bananas and pineapples, others can grow lettuce and strawberries, and some can at best graze cattle at less than one beast per square mile. As well as affecting what can be grown, and what it is economic to grow, location affects yield and quality of production, as well as susceptibility to biotic stresses (pests and diseases) and abiotic (climate and soils) constraints (see, e.g., Beddow et al. 2014)

12 The logic is simple. Farm outputs tend to be economically heavy, fragile, or perishable. Thus, notwithstanding the growth in agricultural trade, significant quantities of agricultural output are consumed within the (subsistence) households that produced them, or nearby. Some clear exceptions must be made for specific farm products that are (in some cases, at least, of necessity) shipped from other areas. For example, soybeans and bananas are commodities for which international trade is comparatively important and, conversely, rice is a commodity for which international trade is comparatively thin. Like other staple food crops, much of the world's rice is produced and consumed within the same household, and some more is consumed closely nearby.

Figure 1: The shifting global geography of agricultural production, 1961 versus 2016



Source: Authors' calculations based on FAO (2020). Countries classified into 2018 income classes using World Bank (2019).

Notes: Percentages indicate respective shares of the global value of agricultural production in each panel. Relative sizes of panels are indicative. See supplemental notes to tables for additional details.

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consumption patterns are driven to a great extent by income effects (Engel relationships) combined with the total size of the population, income distribution matters much for a country's national bundle of food *production*. Hence, as incomes have grown, the country-by-country mixture of agricultural production has shifted over time in the direction of commodities that have larger income elasticities of demand—away from staple food grains to feed grains (i.e., towards livestock) and horticulture, and within those categories toward individual commodities that have larger income elasticities of demand.[13] And the global balance of food consumption and production has shifted toward those countries that have grown in terms of their shares of global population and global economic activity (Table 2).

By 2016, China had become the world's top-ranked producer of wheat and rice, the second-ranked producer of maize, and the fourth- and fifth-ranked producer of pulses and soybeans, respectively. Other middle-income countries also ranked highly among the crop producers, including Nigeria (first for cassava), India (first for pulses, second for wheat and rice, and fourth for soybeans), and Indonesia (third for rice and fourth for cassava). The United States ranked first for maize and soybeans, and was among the top two dairy, beef, pork, and poultry producers. Notable is the stark spatial concentration of agricultural production, with the top 10 countries accounting for two-thirds (by value) of the world's crops, livestock, and total agricultural output. In contrast, sub-Saharan Africa was home to 13.7% of the world's population in 2016, but accounted for only 6.7% of global agricultural value of production, with just six countries (in rank order, Nigeria, South Africa, Ethiopia, Tanzania, Ghana, and Kenya) producing more than one-half of the region's agricultural output.

2.4 The (Economic) Geography of Agriculture and Food R&D Spending

The CGIAR conducts research in a complex and rapidly changing global innovation environment. When the CGIAR was formed in 1971, the global agricultural R&D landscape was much different than it is now. At that time, today's middle- and low-income countries were home to most of the world's poor people, many of whom farmed for a living, and these countries conducted 41.5% of the world's public agricultural and food R&D. In 1971, China and India—with 37.5% of the world's population (United Nations 2019) and more than half the world's economically active population in agriculture—accounted for only 3.7% of the world's public agricultural R&D; the rich-country share was 58.5%.[14]

13 Indeed, globally, the mix of production has shifted significantly in the direction of commodities used as inputs to produce food eaten by people with higher incomes, especially in the places where incomes are generally higher, implying shifts in the importance of staple food grains in total agricultural production and in the importance of staple grains and animal protein as sources of food calories produced. Alston and Pardey (2019) used country-level data to illustrate these Engel effects on production by showing that calories produced from staple crops as a share of calories from all crops has a visibly negative relationship with average per capita income (on a logarithmic scale)—an Engel effect on the national agricultural output mix. Moreover, the farm share of the food dollar typically declines as incomes increase and consumers increase their demand for processed food and food-away-from-home. This also has substantive implications for the innovation landscape of agriculture, as Alston and Pardey (2020) describe and discuss.

14 InSTePP holds previously downloaded, but now discontinued and unavailable, FAOSTAT data indicating that in 1980 (the earliest reported year), India and China combined accounted for 57.4% of the world's economically active population in agriculture.

Table 2: Top-ranked producing countries of selected agricultural commodities, 2016

	1		2		3		4		5		10	20
	Country	%	Country	%	Country	%	Country	%	Country	%	%	%
Crop												
Maize	USA	36.3	China	58.1	Brazil	64.2	Argentina	68.0	Mexico	70.6	80.3	88.4
Wheat	China	17.6	India	30.0	Russian Fed.	39.8	USA	48.2	Canada	52.3	69.4	85.8
Rice	China	28.3	India	49.7	Indonesia	60.1	Bangladesh	67.2	Viet Nam	73.1	85.2	93.6
Cassava	Nigeria	20.6	Thailand	31.9	Brazil	39.5	Indonesia	47.0	Ghana	53.4	73.2	89.3
Pulses	India	24.2	Myanmar	34.7	Canada	41.3	China	45.8	Brazil	50.1	64.2	78.7
Soybeans	USA	35.0	Brazil	63.8	Argentina	81.3	India	85.5	China	89.1	96.7	99.0
All crop	*China*	*24.9*	*India*	*36.3*	*USA*	*45.2*	*Brazil*	*50.6*	*Indonesia*	*54.2*	*63.8*	*76.6*
Livestock												
Dairy	India	21.8	USA	33.3	Pakistan	39.0	China	44.1	Brazil	48.2	63.6	76.8
Beef	USA	17.5	Brazil	33.1	China	43.2	Argentina	47.7	Australia	51.6	63.9	75.8
Pork	China	47.1	USA	55.8	Germany	59.8	Spain	63.0	Brazil	65.9	77.3	88.9
Poultry	China	27.4	USA	41.6	Brazil	50.3	India	53.3	Russian Fed.	56.3	66.0	78.4
All livestock	*China*	*21.4*	*USA*	*33.4*	*India*	*41.6*	*Brazil*	*48.6*	*Russian Fed.*	*51.6*	*62.6*	*75.0*
Total Ag VOP	**China**	**23.7**	**India**	**34.0**	**USA**	**44.0**	**Brazil**	**49.9**	**Indonesia**	**52.6**	**61.8**	**74.7**
Total Pop	**China**	**18.9**	**India**	**36.7**	**USA**	**41.0**	**Indonesia**	**44.5**	**Brazil**	**47.3**	**58.3**	**70.4**
Total Ag Land	**China**	**11.0**	**USA**	**19.5**	**Australia**	**26.6**	**Brazil**	**31.5**	**Kazakhstan**	**36.1**	**53.4**	**67.2**

Sources: Authors' calculation based on FAO (2020).

Notes: Percentages represent cumulative shares of the respective variable. For example, USA accounts for 36.3% of global value of maize production in 2016, whereas USA and the next largest producer (i.e., China) combined account for 58.1%, and so on, reading from left to right in the table. See notes to tables for additional details.

By 2015 (the latest year for which global research spending estimates are available) the R&D ground had shifted dramatically (Pardey and Chan-Kang 2020). The rich-country share had shrunk to just 45.9%, with the United States now accounting for 9.2% of the total—well down from its share of 12.9% in 1971. Agricultural R&D spending by today's middle-income countries rose to 52.2% of total global public-sector agricultural R&D spending in 2015. Adjusted for differences among countries in the purchasing power of local currencies, public agricultural R&D spending by China surpassed that of the United States in 2010 (Chai et al. 2019), and by 2015 the three largest middle-income countries—China, India, and Brazil—together accounted for 29.9% of global public agricultural R&D.

Since the CGIAR was formed, the global public agricultural R&D landscape has seen a significant geopolitical concentration of agricultural science spending, a growing global R&D divide, and a rising private-sector presence—all a continuation of the trends noted by Pardey et al. (2006). In 2015, the top five spending countries—in descending order, China, the United States, India, Japan, and Brazil—accounted for 46.0% of the world's public agricultural R&D spending, with the top two (China and the United States) accounting for 24.1% of the total. The group of the top 10 countries—which also includes France, Germany, South Korea, Australia, and Canada—accounted for 57.4% of the world total. Meanwhile, the bottom 100 countries—accounting for 13% of the world's population in 2017 but only 6% of global GDP—slipped from conducting 12% of the global public agricultural R&D total in 1971 to 4.3% in 2015. This evidence reveals a large and growing gap between a comparatively small (albeit changing) group of agricultural R&D *haves* and a substantial group of R&D *have-nots*.

Sub-Saharan Africa, where the CGIAR focuses half its research, still relies heavily on agriculture. The sector accounted for 17.5% of GDP in 2016, and 55.6% of the region's economically active population earned their living in agriculture (UN 2019; FAO 2012). However, much of the region's agricultural R&D capacity is still frail and, in some countries, faltering: almost one-third of the 44 countries for which we have R&D estimates spent less (in inflation-adjusted terms) on public agricultural R&D in 2015 than they did in 2000. Moreover, the region as a whole constituted just 6.4% of the total worldwide spending on publicly performed agricultural R&D in 2015 and just 3.5% of the corresponding spending on all (i.e., public and private) agricultural R&D.

Rising private-sector presence

Since the CGIAR was formed the private-sector has markedly increased its presence in the global agricultural and food R&D landscape, responding to changes in the policy and practice of intellectual property or market structures throughout the food value chain as well as changes in aspects of the innovations that make research benefits more appropriable by private investors. In 1980, the private-sector share of total (i.e., public and private) agricultural R&D spending was 32.0%, increasing to an estimated 50.4% by 2015.

Much of the private spending occurs in the high-income countries (52.5% in 2015), although agricultural R&D conducted in the middle-income countries (especially China, India, and Brazil) is increasingly pivoting toward the private sector; in those countries private agricultural R&D grew from 29.5% of total agricultural R&D spending in 1980 to 60.1% in 2015. The private-sector presence is much less pronounced in low-income countries—places where farms tend to be significantly smaller-sized, purchased farm inputs are used less intensively, and post-farm food logistics, food processing, and demands for food-away-from-home are more limited—all aspects of agricultural value chains where private-sector innovation investments often focus.. Preliminary estimates by Pardey and Chan-Kang (2020) put the 2015 private-sector share for low-income countries at around 12.3% (compared with 8.5% in 1980).

Agricultural R&D versus total R&D

Just as the innovations arising from R&D investments made in one country can spill over and benefit other counties, so too have genetic innovations conceived in the health sector benefited agriculture (and vice versa). As discussed by Alston and Pardey (2020), similar inter-sectoral spillovers are occurring with regard to the digital, sensing, and material sciences, as well as other technologies. For these reasons, assessing the returns to, priorities for, and institutional arrangements relating to CGIAR research requires a broad scientific purview that includes research done outside the typical scope of agricultural and food R&D.

Unpublished InSTePP updates of the global GERD (i.e., gross domestic expenditures on R&D that measure public and private spending on *all types* of R&D) estimates reported in Dehmer et al. (2019) show that the agricultural and food (agGERD) share of GERD declined from 8% in 1981 to around 5% in 2015. Of special concern for CGIAR research, which is heavily focused on African agriculture, the African share of global GERD is especially small and shrinking—1.1% in 1981 down to just 0.7% in 2015.

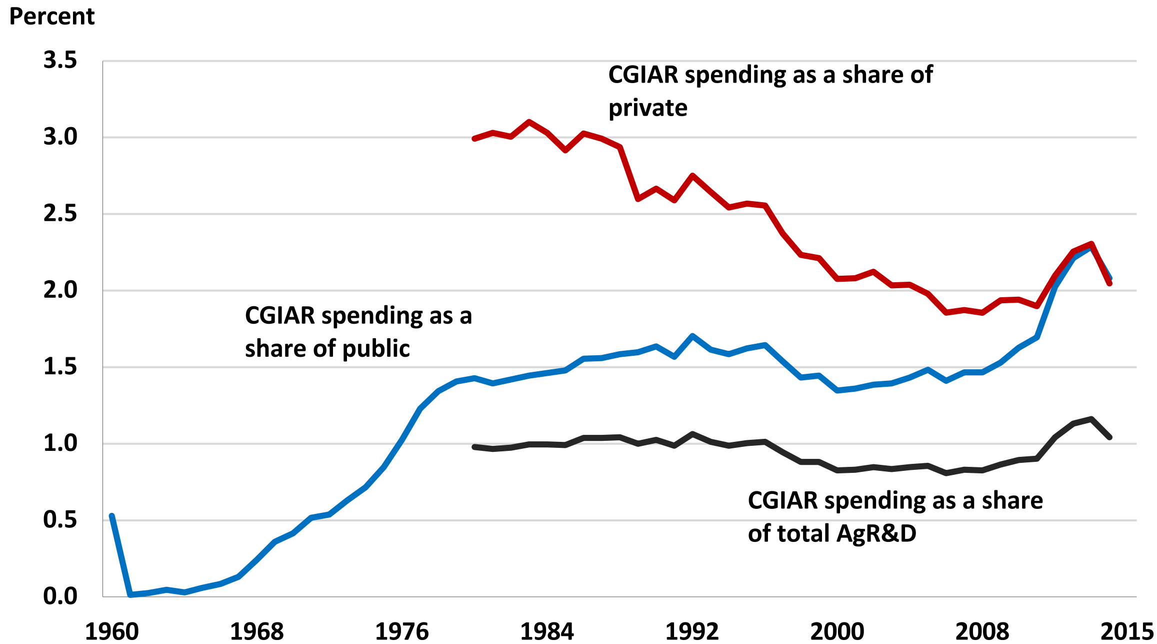
CGIAR spending

Spending by the CGIAR has trended up over time, albeit erratically and with periods of significant surges, stagnation, and declines—including the past few years when total CGIAR spending (in constant 2016 dollar values) peaked at $1,089 million in 2014 and declined to $824 million in 2018. CGIAR research spending constitutes a small share of global spending on agricultural R&D. At its inception in 1971, the CGIAR constituted just 0.52% of the world's public-sector spending in agricultural R&D, trending up to 2.1% by 2015—the latest year for which comparative non-CGIAR research spending data are available (Figure 2, Panel a). The CGIAR accounts for a larger and similarly increasing share of publicly performed agricultural R&D in developing countries (1.2% in 1971 to 4.2% in 2015) (Figure 2, Panel b).

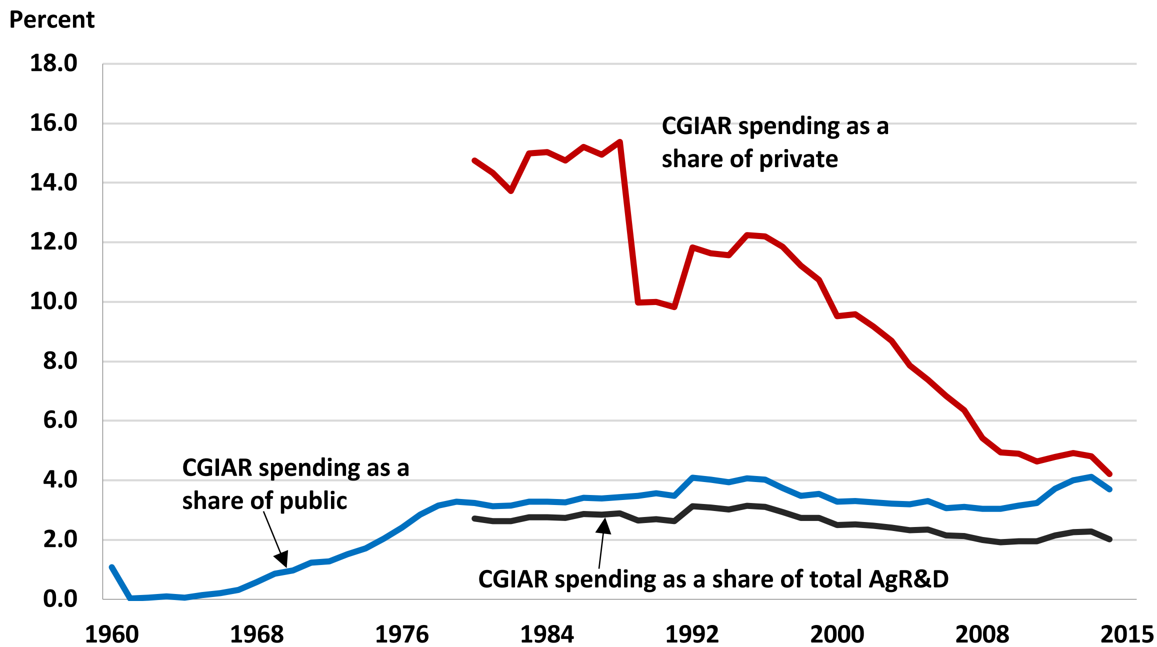
Expressed as a ratio relative to global private-sector spending on agricultural R&D, the CGIAR share shrank from 3.0% in 1980 to 2.0% in 2015, reflecting the relative rapid rise in privately performed research focused on food and agriculture worldwide. Thus, relative to total (public and private) R&D spending on agriculture, CGIAR spending has constituted a reasonably stable share: 0.98% in 1980 and 1.04% in 2015, although a declining share of spending by developing countries (2.72% in 1980 and 2.01% in 2015).

Figure 2: CGIAR vs global public, private, and total agricultural R&D spending, 1960-2015

Panel a: CGIAR Relative to Global



Panel b: CGIAR Relative to Developing



Sources: Non-CGIAR public, private, and total agricultural R&D data are from Pardey and Chan-Kang (2020). CGIAR expenditures are authors' compilation based on data from CG Secretariat (1983), MacNeil (1998), and *CGIAR Financial Reports* (various years).

Notes: See notes to figures for additional details.

3. CGIAR Research Institutions and Investments

The CGIAR and its precursor agencies were instrumental in bringing about the Green Revolution during the 1960s and 1970s. Since then, the CGIAR has continued to play a key role in developing new agricultural technologies that have kept crop yields and overall food production trending up faster than global food consumption. However, the institutional structure, financial foundations, and research emphasis of the CGIAR have evolved considerably. In this section, we document the main threads of that evolution to provide important context for understanding the evidence on returns to the investments, and we present an overview of previous omnibus assessments.

3.1 A Potted (Economic and Institutional) History of the CGIAR

The CGIAR system began modestly but grew dramatically.[15] When the CGIAR was formed in 1971, 16 donors committed $20.2 million (about $100 million in 2016 values) annually to found and foster research in four centers. In 2017, the CGIAR spent about $866 million ($855 million in 2016 terms) obtained from 81 members (and various other sources) to support the work of 16 international agricultural research centers (Figure 3). Funding for the CGIAR has always been fragile and uncertain from year to year (see Box 1), and the growth in the numbers of donors and centers, and the total budget, was not always smooth. The period of initial growth (1971–1984) was followed by periods of stagnation (1984–2000), reinvigorated growth (2000–2014), and now significant decline (2014–2017) in total funding, all accompanied by a decrease in the share of unrestricted funding since 1980.

Funding history

Between 1960 and 1964, of the institutes that would become the CGIAR, only IRRI was operating as such. By 1970, the four founding centers—IRRI, CIMMYT, CIAT, and IITA—were allocated a total of $14.8 million annually. During the next decade, even as the number of centers increased, the funding per center increased progressively and nominal spending rose tenfold, to $141 million in 1980. During the 1980s, spending more than doubled in nominal terms to reach $305 million in 1990 (growing in real terms by 3.6% per annum). The rate of real growth had slowed but was still impressive. In the 1990s, however, although the number of centers grew, real spending for the group declined by 1.01% per year. Since 2000, total funding has generally grown in real terms, but with a continuing trend toward support earmarked for specific projects and for research programs involving multiple centers and research providers outside the CG, and some fluctuations. Reflecting policy responses to the world food crisis, total funding surged (in real 2016 dollar values) from $566 million in 2007 to a peak of $1,079 million in 2014, but then it declined by 22% over three years, to $838 million in 2017.

15 Baum (1986) and Alston et al. (2006) provide details of the early history of the CGIAR. More recently, Byerlee and Lynam (2020) put those details into a broader historical context, while Byerlee (2016) provides details on the history of CIMMYT and Lynam and Byerlee (2017) on the history of CIAT, two of the founding four CGIAR centers.

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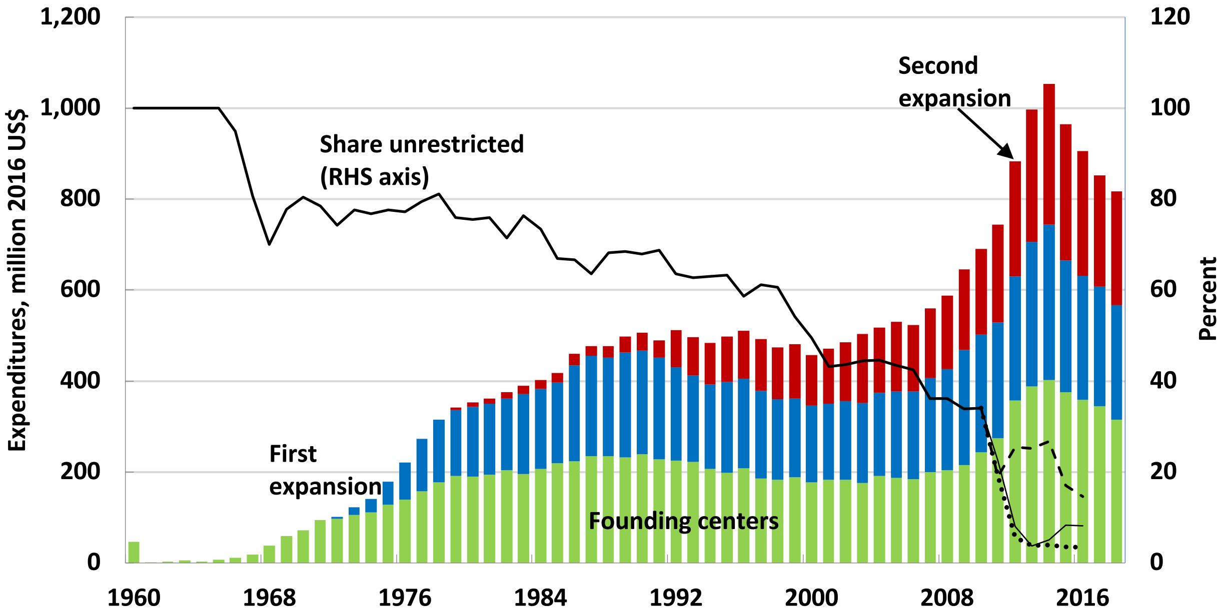
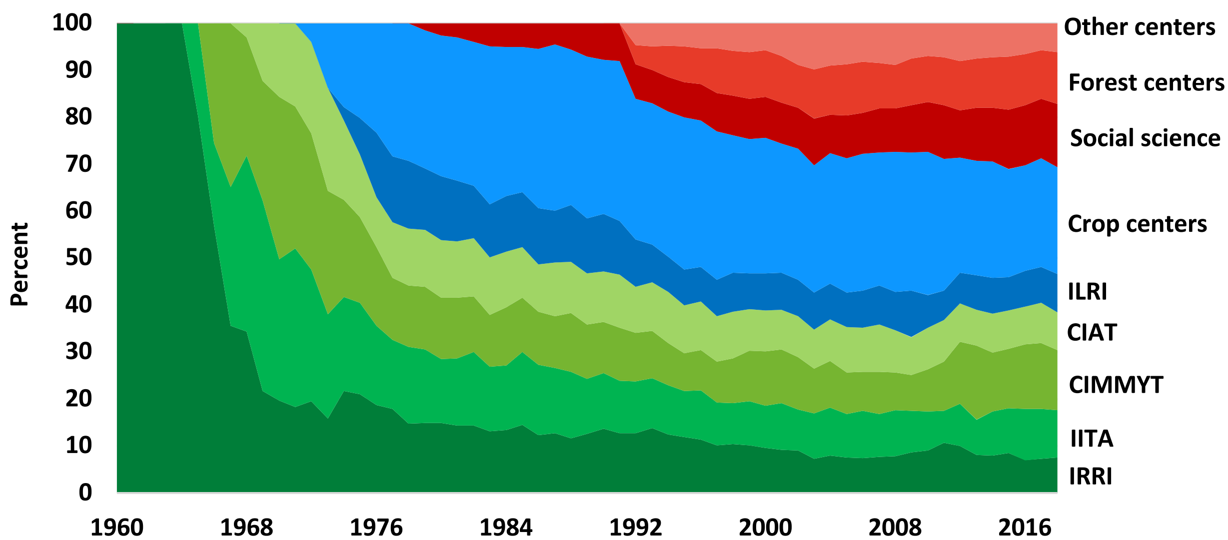
Figure 3: Spending by CGIAR centers, 1960-2018

Panel a: Founding, first and second expansion centers



Panel b: Center shares of total CGIAR spending



Sources: Authors' compilation based on data from CGIAR (1983), MacNeil (1998), and *CGIAR Financial Reports* (various years). Data in nominal U.S. dollars were deflated to 2016 prices using the U.S. GDP deflator from Williamson (2019).

Notes: See text and supplemental notes to figures for grouping of centers into founding, first expansion, and second expansion crop centers, and so on. Share of total expenditures coming from unrestricted funding estimated by authors, as described in notes to figures. Given changes in the reported financial data, v1, v2, and v3 represent alternative versions of the unrestricted funding share for years after 2011. See text and supplemental notes to figures for additional details.

The form and focus of CGIAR funding has changed markedly too. A large and still rising share of the available funds is now earmarked by donors for specific projects. Initially, 100% of the funding was unrestricted, but by the late 1960s this share had dropped to around 75%, where it held steady through the early 1980s. Since then it declined at an accelerating rate to around one-third of total funding in 2010; and since 2014 the unrestricted share fell even faster in conjunction with a 22% fall in total funding.[16] Along with these changes, the CGIAR broadened its research horizons, away from its traditional focus on basic food crops, to include environmental issues and other commodities such as forest products and fish. This broadening agenda was not matched by commensurate increases in funding, causing a scaling back of the CGIAR breeding and crop improvement work.

Figure 3 shows trends in the distribution of total CGIAR system funding through 2018 among three groups of centers, namely:

- The founding four centers (IRRI, CIMMYT, CIAT, and IITA) in 1971.
- The seven centers added during the first wave of expansion in the 1970s, all of which also focused on crop and livestock productivity (ICRISAT, CIP, ILRAD, ILCA—which were merged to form ILRI in 1995—, Bioversity International/IPGRI, AfricaRice/WARDA, and ICARDA).
- The six centers added during the second wave of expansion in the 1980s (IFPRI and ISNAR) and 1990s (World Agroforestry/ICRAF, IWMI, WorldFish/ICLARM, and CIFOR), all focused on issues other than crop and livestock productivity.

Recent years have witnessed a renewed effort to merge or consolidate operations among some centers (CGIAR 2020, p.7). In November 2018, the Boards of Trustees of Bioversity International and CIAT held their first joint Board meeting in Washington, D.C., at which they signed a memorandum of understanding to create an Alliance. The Alliance constitutes an effective merger of the two centers, which as of January 2020 has been operating under the leadership of one Director General (Bioversity International and CIAT 2018, 2019). On January 1, 2019, CIFOR and World Agroforestry/ICRAF also put in place an effective merger with a common governance board of trustees (World Agroforestry 2019).[17] This reduced the number of centers from 15 to 13. These bilateral mergers among centers are taking place against an on-going, system-wide process to create a "One CGIAR" with one of its key objectives being to establish a One CGIAR Common Board and a One CGIAR Executive Management Team (CGIAR 2020, p. 4).

In the early years of plenty, all the centers grew together; but they did not grow at the same rate. Funding allocated to the four founding centers declined significantly as a share of the total, albeit with a partial recovery recently. In 1971, these four centers accounted for 100% of the allocation, but their share had slipped to 54% by 1980 and to less than 35% by 2010; however, since then this

16 Indeed, since 2000 all of the *net* growth in funding has been earmarked, while unrestricted funding in inflation-adjusted terms peaked in 1990 and has trended downward since.

17 In 2018 IRRI and AfricaRice announced a partnership to enhance research and development capacities for rice production in Africa, but still maintain separate center operations (CGIAR 2018).

share recovered somewhat, back to 41% in 2017. These broad trends indicate that, through both the addition of new centers and the allocation of funds among centers, the agenda of the CGIAR shifted dramatically away from its original focus, especially in the 1990s.

CGIAR spending breakdowns

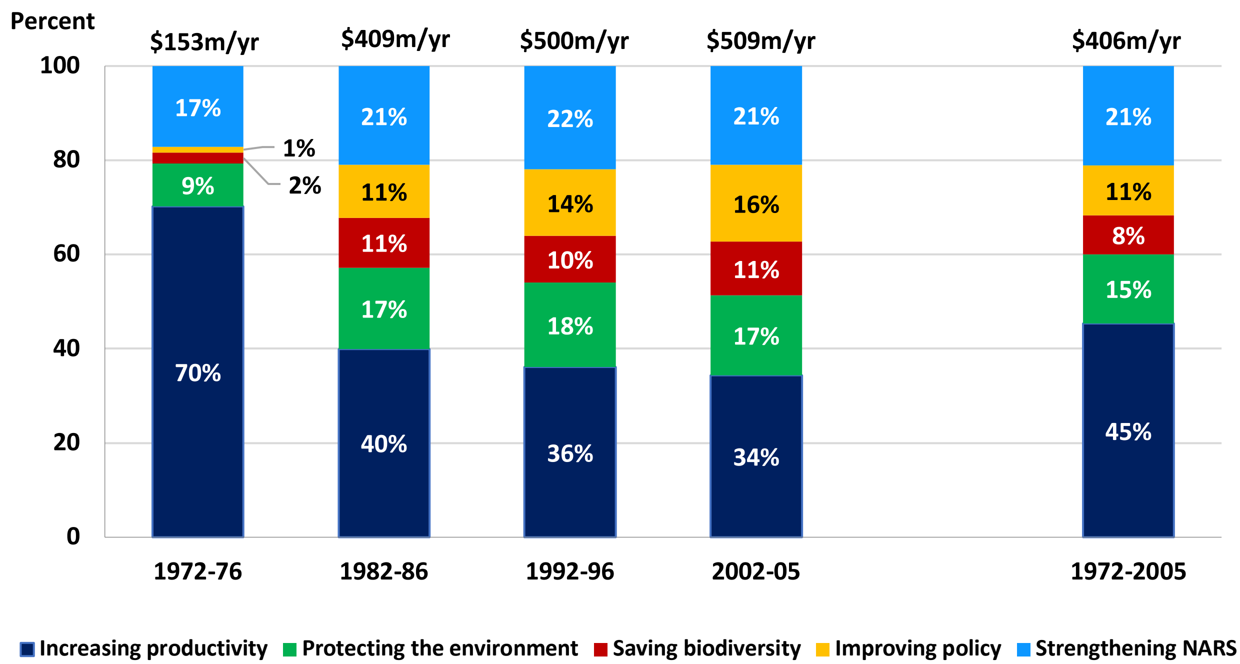
Changes over the years in the institutional structure and the accounting and financial reporting norms used by the CGIAR make it difficult to develop a complete and consistent compilation of research spending that gives a more granular sense of the orientation of CGIAR activities. Nonetheless, drawing on data reported in the annual financial reports of the CGIAR, Pardey and Chan-Kang (2020) compiled evidence on the programmatic orientation of research, from which we draw for this study. Averaging across the full period 1972–2005, for which reasonably comparable data were reported, around 45% of CGIAR funding was directed to "productivity"-oriented activities, 21% to "strengthening NARS (or national agricultural research systems)," 8% to "biodiversity conservation," 15% to "environmental" activities, and 11% to "policy"-related activities (Figure 4 right-hand column).

However, the orientation of CGIAR activities profoundly changed over time. At the outset, in the early 1970s, almost three-quarters of CGIAR spending focused on (crop) productivity improvement, but by the early 2000s the productivity share of CGIAR spending had slipped to less than one-third of the total (Figure 4). Over the decades, CGIAR activities have increasingly emphasized biodiversity conservation (2.4% in the early 1970s, 11.4% by the early 2000s), environmental activities (9.1% in the early 1970s, 17% by the early 2000s), and policy-related efforts (1.1% in the early 1970s, 16.3% by the early 2000s). NARS-strengthening efforts have sustained a reasonably steady share (17.2% in the early 1970s, 21% in the early 2000s).

In terms of the commodity orientation of CGIAR activities, the longer-run trend has been to significantly scale back spending on cereals as a share of total spending (56% in the early 1970s to 33% by the early 2000s) and to reduce legume-related spending (Figure 5). Spending on livestock was around 20% of the total during the 1980s, but this share has been scaled back since then, while spending on trees, bananas/plantains, and water have gained ground as new centers with mandates in these areas joined the system during the second expansion of centers, which began in the 1990s. Because substantive institutional and financial reporting changes were instigated in 2011, the more recently reported commodity shares are not directly comparable with those for earlier years. However, for completeness, the available commodity splits are shown in the right-hand column of Figure 5.

Elven and Krishnan (2019) summarize data obtained from the annual CGIAR financial reports concerning the geographic orientation of CGIAR spending. From our own assessment of the underlying financial reports, we could not see how the geographic focus of the spending was determined nor if the accounting-cum-reporting standards varied over time or across centers. If

Figure 4: Programmatic orientation of CGIAR spending, 1972-2005



Sources: Authors' compilation. Data for 1972-76, 1982-86, and 1992-96 taken from the *CGIAR Financial Report 1997* (1998), and for 2002-05 from the *CGIAR Financial Report 2005* (2006). For expenditure totals, see Figure 1. Data in nominal U.S. dollars were deflated to 2016 prices using the U.S. GDP deflator from Williamson (2019).

Notes: Programmatic shares expressed relative to total expenditures over the designated period. Spending per year estimates are averages of the respective periods. See notes to figures for additional details.

we assume that the CGIAR spending data are reported on a "by-performer" basis, it is still not clear from the reports how the data were allocated to geographic regions.[18] Deducing the jurisdictional extent of research (and other activities) undertaken by a given CGIAR center is analogous to determining the jurisdictional extent of research undertaken by multi-national firms operating in multiple countries, as discussed by Pardey et al. (2016b); similar practical and conceptual measurement problems are involved.

Figure 6 provides earlier versus more recent snapshots of the geographical orientation of the spending as reported by the CGIAR. We take these data at face value as representing where in the world the spending occurred—versus the intended country targets for the outputs of the CG spending or wherethe center conducting the spending was headquartered.[19] These data reveal an

18 For example, the OECD's *Frascati Manual* (OECD 2015) lays down guidelines for collecting and reporting R&D-related data that, among other things, distinguish between R&D spending data on a "by-performer" versus "by-funder" basis.

19 For example, CGIAR (2017) states "Figure 1 provides geographic information on where expenditures were incurred in 2016 and 2015" whereas CGIAR (1994, p. 14) states: "This apparent dramatic decline [in regional expenditures in sub-Saharan Africa] should be interpreted with caution, since centers have re-cast the regional distribution of expenditure in the framework of the Medium-Term Plans (MTP), and a lingering ambiguity persists in the criteria used to allocate expenditures regionally, i.e. location of expenditure, region targeted by the activity, or spillover effects to other regions."

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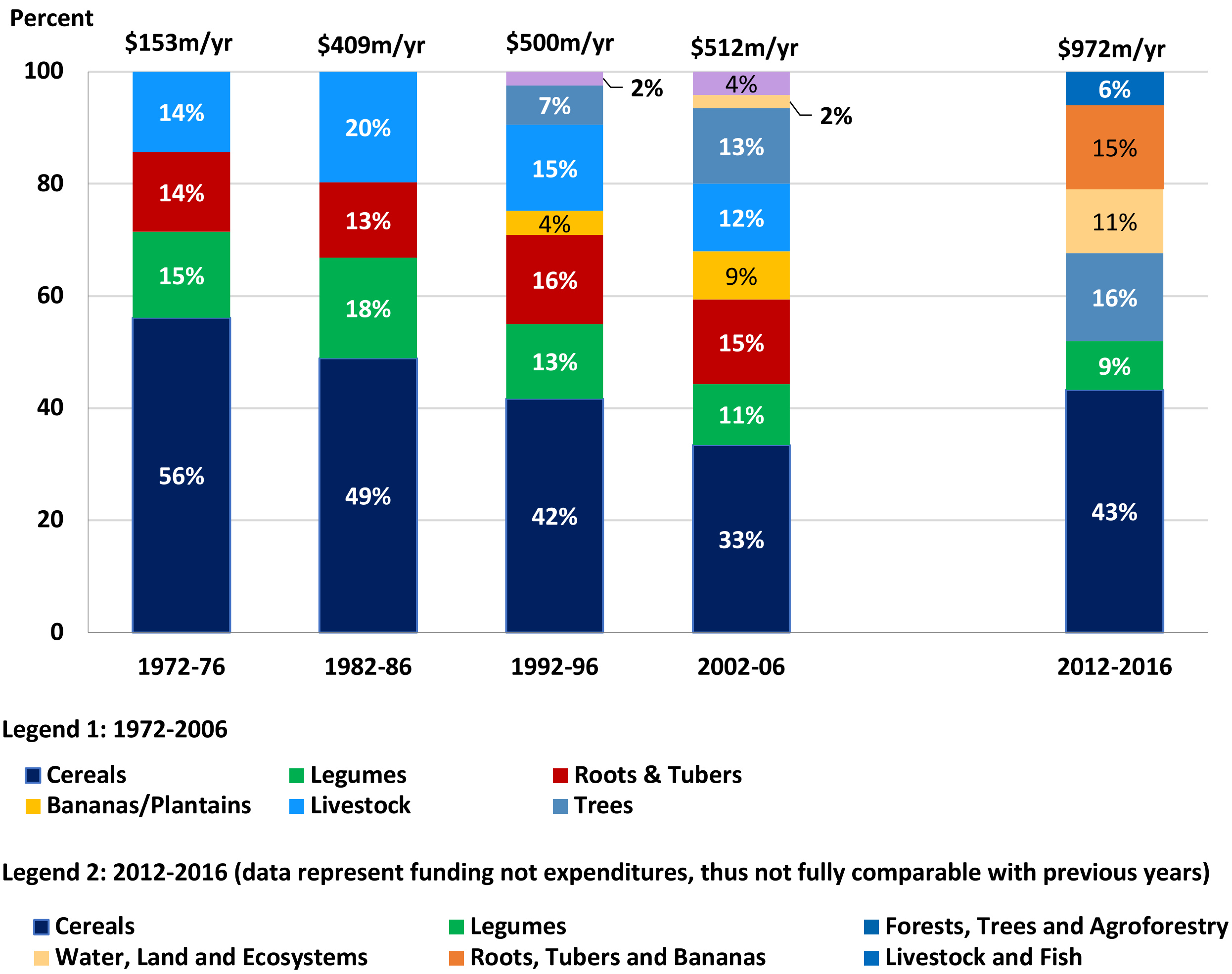
Figure 5: Commodity orientation of CGIAR spending, 1972-2016



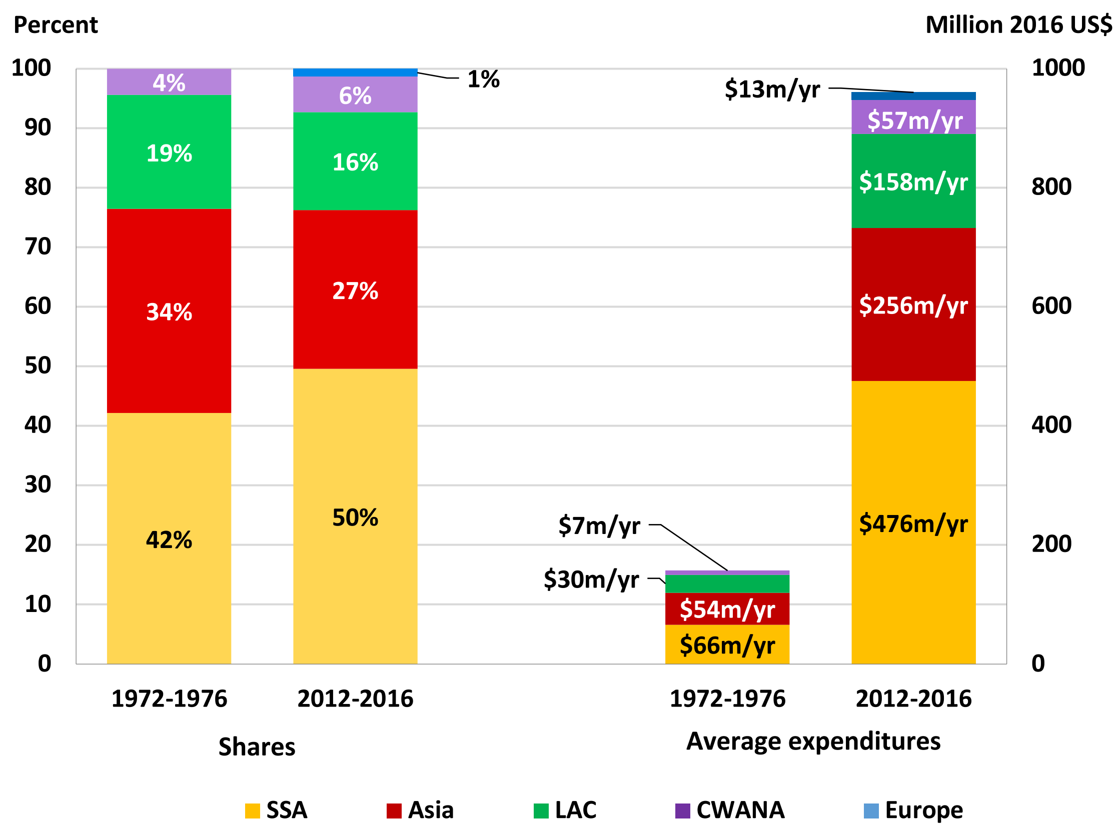
Sources: Authors' compilation. Data for periods 1972-76, 1982-86, and 1992-96 taken from *CGIAR Financial Report 1997* (1998), for period 2002-2005 from *CGIAR Financial Report 2005* (2006) from *CGIAR Financial Report 2006* (2007), and for period 2012-2016 from annual *CGIAR Financial Reports* for years 2012-16. Data in nominal U.S. dollars were deflated to 2016 prices using the U.S. GDP deflator from Williamson (2019).

Notes: See notes to figures for more details. First legend refers to 1972-76 through 2002-06 and the second to 2012-16.

increase in the sub-Saharan African share (from 42% in the early 1970s to 50% in more recent years) of a greatly increased total pot, with modest reductions in the share of spending related to Latin America and Asia.[20]

20 The significant African spending share in the 1970s reflects capital investments in the establishment of ILCA (Ethiopia, established as a CGIAR center in 1974), ILRAD (Kenya, 1973), and WARDA, now AfricaRice (originally Liberia, 1975) in conjunction with the continued expansion of IITA's operations (Nigeria, 1971) (CGIAR *Integrative Paper* 1975, p. 2). Throughout the 1970s, CGIAR centers headquartered elsewhere also expanded their operations in Africa, including staffing and operating satellite facilities, and locating staff in-region to work alongside researchers in selected national systems (Byerlee 2016: Lynam and Byerlee 2017; CGIAR *Integrative Paper* 1975, p. 8; CGIAR *Integrative Report* 1978, p. 20). CGIAR *Integrative Report* (1978, pp. 25–26) indicated that the CGIAR had 516 senior staff in 1979; half the new senior staff positions created during 1977–1979 were for staff posted away from headquarters, and of the 203 outreach staff for 1979, 57% were located in sub-Saharan Africa.

Figure 6: Geography of CGIAR spending, 1972-2016



Source: For 1972-1976 from *CGIAR Financial Report 1997* (1998). For 2012-2016 from *CGIAR Financial Reports* for years 2012-16. Data in nominal U.S. dollars were deflated to 2016 prices using the U.S. GDP deflator from Williamson (2019).

Notes: SSA denotes Sub-Saharan Africa; LAC, Latin America and the Caribbean; CWANA, Central and West Asia and North Africa. Shares and amounts represent reported total CGIAR expenditures by region for the respective periods.

3.2 Sources of Support for CGIAR Research

As the CGIAR system has evolved—with growth in total funding, the numbers of centers, and the reach of its mandate—other changes have taken place as well, in some cases as part of the growth and maturing of the system. The relative importance of particular donors has changed as a part of this evolution. U.S.-based private foundations established the precursor centers and provided the lion's share of the funding at the outset—the Ford Foundation, Rockefeller Foundation (plus a one-off $3.3 million contribution from the Michigan-based Kresge Foundation) together contributed 49% of the total funding of $110.8 million (2016 dollar values) in 1972. The U.S. government contributed a further 18.7%, and the top 10 donors together contributed 91.4%. All of these and the other donors were from high-income countries.

By 1980, the private foundations had faded in the rankings, and for the next 30 years the top 10 donors list was led by the U.S. government and the World Bank, followed by the national governments of a small number of high-income countries, with the ranking among them varying over time. Recent years have seen a resurgence of private foundation support for the CGIAR. In 2011, the Bill & Melinda Gates Foundation (BMGF) was the highest-ranked donor, contributing $77.5 million (in 2016 dollar values). In 2017, the U.S. government regained the donor leadership position it had held for 35 of the CGIAR's previous 46 years, providing $149.9 million, followed by BMGF, which provided $97.6 million (2016 dollar values).

Along with the trend in total funding, and the reshuffling of the list of donors, the concentration of support has drifted down. Compared with 91% in 1972, in 2017 the top 10 donors accounted for just 60% of the total funding, which, in inflation-adjusted terms, had increased more than seven-fold over 45 years to $812 million. U.S.-based foundations (now the BMGF) and the U.S. government still outranked all other donors, together accounting for 30% of the total, compared with 68% in 1972. Although they have risen to dominance in measures of total food production and total public and private agricultural R&D, supplanting today's high-income countries in that role, today's middle-income countries (in particular, China and Brazil) to date have contributed little funding to the CGIAR.

As described above, an important change has been the shift from mostly unrestricted funding (given a simple and well-understood purpose) to a preponderance of earmarked funds allocated on a project basis to a myriad of specific investments.[21] This shift has occurred in tandem with changes in the sources of funding among donors who may differ significantly in their preferences over the projects (or centers) to which they might direct their contributions. Tribe (1991), Pardey et al. (1996) and Alston et al. (2006) emphasized that donor countries are aware of the possibility of "doing well by doing good," and their respective national agencies direct their support for CGIAR research accordingly.

As we discuss below, the greater part of the evaluation evidence pertains to research directed at improving crop and livestock productivity—especially staple food grains (e.g., wheat, rice, maize) and crops (e.g., cassava, edible beans, and pulses). This was the narrow focus of the founding four centers and, albeit to a lesser extent, the early expansion centers added in the 1970s. Much less of the evidence pertains directly to the broader agenda of the centers added since 1980, which accounted for more than 40% of the total CGIAR budget in the mid-1980s and still accounted for almost 30% of the budget in 2017.[22] The lack of evidence on the economic returns to research

21 Vernon Ruttan (2001, 2004) was the first economist to work for a CGIAR center. He quoted David Chandler, the founding director general of IRRI, at a Saturday morning staff seminar during IRRI's early days as saying emphatically, "The purpose of this institute is not to do good science! . . . The purpose of this institute is to raise rice yields in Asia! . . . And raising rice yields in Asia may require that you do good science!" (2001, p. 26). W. David Hopper, chairman of the CGIAR from 1987 to 1990, shifted the emphasis from production to consumption and saw the CG's mission as increasing "…the pile of rice on the plates of food-short consumers" (World Bank 2003a, p. 1).

22 Over time, the goals of the CGIAR system have become more numerous and complex, and it has become much more difficult to achieve a rational process of evaluation and priority setting. The costs of decision-making have risen. In conjunction with these changes, there has been an explosion in the number, size, and costs of management, consultation, and governance structures and processes. The transaction costs of the system are much greater than they were when the original, much smaller and simpler, system was established.

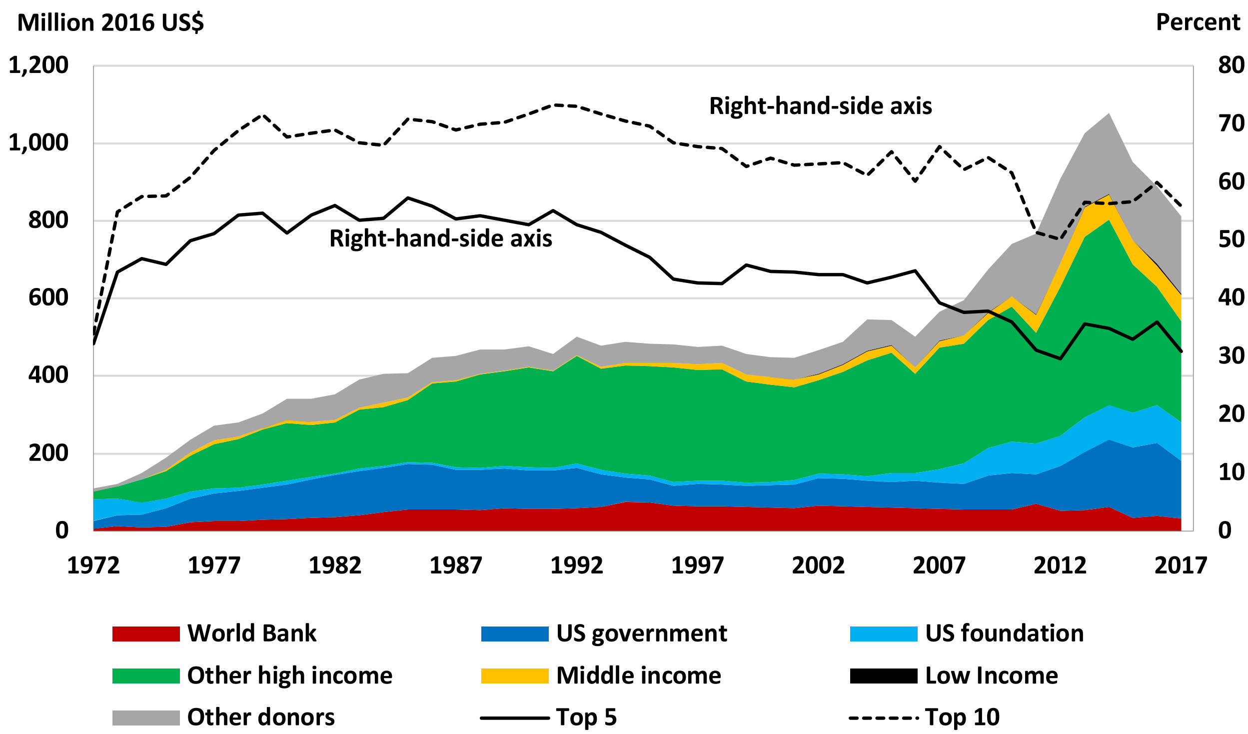
Table 3. CGIAR donor funding 1972, 1990, and 2017

	1972			1990			2017			1972–2017		
Rank	Donor	%	US$M	Donor	%	US$M	Donor	%	US$M		%	US$M
1	Ford Fdn	28.8	31.9	USA	21.0	99.8	USA	18.5	149.9	USA	17.6	4,034
2	USA	18.7	20.7	World Bank	12.0	57.0	BMGF	12.0	97.6	World Bank	9.8	2,252
3	Rock. Fdn	17.3	19.2	Japan	8.6	40.8	UK	6.1	49.6	UK	6.0	1,369
4	World Bank	5.2	5.8	Canada	6.9	32.8	Netherlands	4.4	35.9	Canada	5.1	1,172
5	Canada	5.1	5.6	EC	5.7	26.9	World Bank	3.9	31.8	Japan	4.9	1,127
6	Sweden	4.0	4.4	Switz.	5.3	25.3	Germany	3.7	29.9	EC	4.4	1,008
7	UNDP	3.5	3.9	Germany	5.0	23.9	Australia	3.6	29.3	Germany	4.2	961
8	Kresge	3.0	3.3	UK	4.2	20.2	Mexico	2.9	23.7	Switzerland	3.8	870
9	Norway	3.0	3.3	IDB	3.7	17.5	India	2.5	20.3	Netherlands	3.7	854
10	UK	2.8	3.1	Netherlands	3.0	14.2	EC	2.4	19.7	BMGF	3.7	853
	Top 10	**91.4**	**101.2**	**Top 10**	**75.4**	**358.6**	**Top 10**	**60.1**	**487.7**	**Top 10**	**63.1**	**14,500**
	Others	8.6	9.6	Others	24.6	117.1	Others	39.9	324.4	Others	36.9	8,462
	Total	**100.0**	**110.8**	**Total**	**100.0**	**475.7**	**Total**	**100.0**	**812.1**	**Total**	**100.0**	**22,962**

Sources: Authors' estimation based on data from *CGIAR Annual Report 1986/87* and *CGIAR Financial Reports* (various years). Data in nominal U.S. dollars were deflated to 2016 prices using the U.S. GDP deflator from Williamson (2019).

Notes: See notes to figures for additional details.

Figure 7: Total CGIAR funds by source of funding, 1972-2017



Sources: Authors' compilation using data *CGIAR Annual Report 1986/87* and *CGIAR Financial Reports* (various years). Data in nominal U.S. dollars were deflated to 2016 prices using the U.S. GDP deflator from Williamson (2019).

Notes: See notes to figures for additional details. Top 5 and top 10 country shares are in terms of their total contribution to the CGIAR in constant (2016 dollar value) terms for the period 1972 to 2007.

conducted by the post-1980 expansion centers may reflect a lack of measurable impact, but it may also reflect conceptual and empirical challenges in measuring the benefits—for instance, as the studies reported by Pardey and Smith (2004) describe regarding policy-oriented R&D (POR) conducted by IFPRI, other CGIAR centers, and other policy researchers (e.g., Pannell et al. 2018).

Writing in 2003, Barrett pointed to evaluation complexities as one explanation for "…a dearth of ex post impact assessment of CGIAR NRM [natural resource management] research" (p. 25). Barrett (2003, p. 24) also noted:

> … given the relatively recent launch of most of the CGIAR's NRM research and the excessively diffuse nature of some of the early research in this area in the early-to-mid 1990s, it seems unreasonable to expect to see significant aggregate level evidence of any impact just yet. The absence of clear, quantitative evidence of impact to date does not imply the absence of current, much less likely future impact; it merely means we simply do not know yet.

More recently, the CGIAR Standing Panel on Impact Assessment (SPIA) commissioned various studies seeking to rectify the dearth of evidence of impact in certain understudied areas, including NRM and policy-oriented research. Subsequently, Stevenson and Vlek (2018) reviewed nine studies of the adoption of NRM practices commissioned by SPIA. In a foreword to that review report (p. iv), Karen Macours, the chair of SPIA, noted that the adoption rates for NRM practices were consistently and surprisingly lower (often much lower) than expected, and accordingly expressed some pessimism about the associated flows of benefits.

3.3 Previous Evaluation Reports

Later in this report we present evidence that research undertaken by the CGIAR has been intensively evaluated, compared with agricultural R&D more generally—perhaps with a view to encouraging donors to sustain or increase their funding support, which is a requirement peculiar to CGIAR research given its reliance on short-term (and often piecemeal or project rather than programmatic) funding commitments. The CGIAR evaluation studies have been scrutinized in periodical meta-reviews, perhaps for similar funding-related reasons. This might help account for the fact that a number of the 18 meta-review studies listed chronologically in Table 4 cluster in the same or nearly concurrent years, while for other long intervals no meta-reviews were conducted. Three of these studies were published before 2003 (1988, 1999, and 2001); in 2003, five were published; then three during 2006–2008, three during 2010–2012, and three in 2018.[23]

The meta-review studies listed in Table 4 vary considerably in scope and style. They include reports from broad-scale system reviews (i.e., those by Anderson and Dalrymple 1999 and World Bank 2003b), as well as other major, multi-year, big-budget projects (such as that by Anderson et al. 1988), along with more focused efforts (e.g., Pingali 2001, Barrett 2003, Gardner 2003, and Stevenson et al. 2018). Some refer to reviews of research impact *assessments*, as distinct from research *evaluations*, and some do not review any studies that report estimated rates of return (RORs) or equivalent measures such as BCRs, which is our interest here.

Most of the 13 meta-studies in Table 4 that do review ROR studies encompass only a few ROR studies in their assessments, and only four of them encompass 15 or more ROR studies: Maredia and Raitzer (2012 and 2010) review 42 and 23 studies, respectively; while Raitzer (2003) and Raitzer and Kelley (2008) each review just 15. The meta-studies may have been actively partial or selective in their coverage because of concerns over the relevance or quality of some of the evidence (like Raitzer 2003 and Raitzer and Kelley 2008) or because they were taking a narrower perspective (like Maredia and Raitzer 2006, 2010, and 2012, focused on impact in Africa).

23 In our experience of the agricultural R&D world generally, evaluation studies are used more for justifying and shoring up funding support than for setting research priorities, and the demand for such studies by research agencies is more pronounced at times when funding is shrinking or threatened than in times of plenty. From a loose inspection of the evidence, we can see some correspondence between the intensity of CGIAR research evaluation studies and the funding cycle. The same may be true of the meta-studies, for similar reasons.

Table 4. Prior meta-reviews of CGIAR-oriented research evaluation studies

Pub. Year	Authors	Title	ROR studies reviewed	ROR estimates reviewed
1988	Anderson, Herdt and Scobie	Science and food: The CGIAR and Its partners	4	27
1999	Anderson and Dalrymple	The World Bank, the grant program, and the CGIAR: A retrospective review	1	2
2001	Pingali and Feldmann	Milestones in impact assessment research in the CGIAR, 1970-1999	9	15
2003	Barrett	Natural resource management research in CGIAR: A meta-evaluation	1	1
2003	Gardner	Global public goods from the CGIAR: Impact assessment	12	23
2003	Hossain, Gollin, Cabanilla, Cabrera, Johnson, Khush and McLaren	International research and genetic improvement in rice: Evidence from Asia and Latin America	0	0
2003	Raitzer	Benefit-cost meta-analysis of investment in the international agricultural research centers of the CGIAR	15	unclear
2003a	World Bank	The CGIAR at 31: An independent meta-evaluation of the Consultative Group on International Agricultural Research: overview report. Part 1	0	0
2003b	World Bank	The CGIAR at 31: An independent meta-evaluation of the Consultative Group on International Agricultural Research: technical report. Part 2	1	1

Table 4. Prior meta-reviews of CGIAR-oriented research evaluation studies (continued)

Pub. Year	Authors	Title	ROR studies reviewed	ROR estimates reviewed
2006	Maredia and Raitzer	CGIAR and NARS partner research in Sub-Saharan Africa: Evidence of impact to date	23	0
2007	Pingali and Kelley	The role of international agricultural research in contributing to global food security and poverty alleviation: The case of the CGIAR	5	5
2008	Raitzer and Kelley	Benefit-cost meta-analysis of investment in the international Agricultural Research Centers of the CGIAR	15	unclear
2010	Maredia and Raitzer	Estimating overall returns to international agricultural research in Africa through benefit-cost analysis: A "best-evidence" approach	23	0
2010	Renkow and Byerlee	The impacts of CGIAR research: A review of recent evidence	7	11
2012	Maredia and Raitzer	Review and analysis of documented patterns of agricultural research impacts in Southeast Asia	42	0
2018	Garbero, Marion and Brailovskaya	The impact of the adoption of CGIAR's improved varieties on poverty and welfare outcomes	0	0
2018	Herdt	Documenting the impact of widely-adopted CGIAR research innovations	0	0
2018	Stevenson, Johnson and Macours	Estimating ex post impacts and rates of return to international agricultural research for development	2	unclear

Sources: Compiled by the authors.

Notes: Maredia and Raitzer (2012) reviewed 42 studies, not necessarily all of which reported ROR estimates.

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As is typical in this context, individual studies often include multiple estimates of RORs, and some contain none—though they might report a measure of benefits without tying it to a corresponding measure of costs. Eight of the tabulated meta-studies document reported ROR estimates (or equivalent), and in total they encompass just 85 ROR estimates (no doubt with some double-counting), most of these in four studies: (a) Anderson, Herdt and Scobie (1988), 27 estimates; (b) Pingali (2001), 15 estimates; (c) Gardner (2003), 23 estimates; (d) Renkow and Byerlee (2010), 11 estimates.

In some meta-studies, the authors deduced RORs or BCRs by combining the reported measures of benefits with extraneous estimates of corresponding costs (Raitzer 2003; Maredia and Raitzer 2006 and 2010; Raitzer and Kelley 2008). Still, the total number of ROR estimates encompassed by any of these meta-reviews is small compared with the total number pertaining to CGIAR research included in the InSTePP dataset and encompassed by our review (115 studies reporting 363 estimates, or 78 studies reporting 203 estimates in our filtered dataset).

The work in this report is based on a comprehensive compilation of CGIAR-related ROR studies, which was developed in a series of steps using multiple sources.[24] A key question concerns the selection of studies to be included in the analysis. Prior meta-reviews of the consequences of CGIAR research have drawn from limited subsets of evidence on the returns to investments in CGIAR-related R&D (Table 4). As discussed by Alston et al. (2000a, 2000b) a comprehensive review of the evidence reduces the risk of the selection bias inherent in partial, qualitative summaries and allows a comparative assessment of the relative returns among subsets of the portfolio. In addition, a comprehensive analysis of the literature can provide a basis for understanding *why* RORs differ among studies, over time, among research fields, and so on.

Many studies of returns to research report their results in terms of internal rates of return (IRRs). However, for the reasons raised by Alston et al. (2000, 2010) and elaborated by Hurley et al. (2014a, 2014b, 2017), we have reservations about the use of IRRs (see Box 3). In this section, we present the available evidence on the payoff to CGIAR research, with rates of return restated as standardized benefit-cost ratios (BCRs). Next, we analyze and interpret this evidence relative to the overall evidence on rates of return to research and the past patterns of CGIAR research investments. In later sections, we extrapolate from this partial evidence to develop a more complete sense of the payoff to the portfolio. Before going into those details, drawing heavily on Alston et al. (2000a, 2000b), we briefly review some conceptual issues and challenges that arise in conducting a study of this nature applied to evidence on the returns to agricultural R&D.

24 As discussed in detail below, the coverage is nonetheless still partial in terms of the CGIAR research represented by the evidence.

THE RETURNS TO CGIAR RESEARCH

Credit: G. Smith (CIAT)

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4. Concepts, Methods, Measures and Data for the Analysis

4.1 Concepts and Challenges

Alston et al. (2000a, 2000b) discussed in detail various conceptual and measurement issues that can arise in conducting a meta-analysis (or statistical research synthesis) of evidence on returns to agricultural R&D (see, also, Rao et al. 2019 and the CGIAR review studies listed in Table 4). Two main concerns are measurement error bias in the individual ROR studies and selection bias in the choice of studies to encompass in the review. A related concern may be representativeness of the sampled studies and their measured returns compared with the portfolio as a whole.

Various factors might cause an estimate to depart systematically from the true ROR. Some problems relate to measuring the streams of benefits and costs in ways such that the measures match up to the concepts they are meant to represent—for instance, dealing appropriately with overhead costs or having an accurate measure of adoption. Alston and Pardey (2001) discuss the related set of "attribution problems" in terms of matching a stream of measured benefits to the corresponding stream of costs. This encompasses issues associated with appropriate allowance for interspatial and inter-industry knowledge spillovers; the overhead cost of basic research to support applied research, or extension effort to support adoption; institutional sharing of project costs (say between a NARS and a CGIAR center); accurately representing the timing of the research expenditures and the consequential research benefits; taking appropriate account of complementary private-sector roles; and so on. Alston et al. (2000a, 2000b) detail various characteristics of the ROR study, including characteristics of the analyst as well as the methods of analysis and critical modeling assumptions that can have implications for the measured ROR.

In addition to measurement error biases, we must consider selection biases in terms of the choice of projects and programs to evaluate. Within any large portfolio of research projects a wide range of RORs, including some failures, is likely to be found. In ex post evaluation, it is natural for some to focus on the successful projects or programs. This is a problem only if the ROR to the "winners" is misinterpreted as representing the overall ROR to the broader portfolio. Similarly, ROR estimates can be biased up if overhead costs are not appropriately shared or if benefits are double-counted (e.g., if two competing varieties are treated as having been adopted on the same area). An institution-level or programmatic evaluation is less vulnerable to the problem of project selection bias, in which only the successful projects are evaluated (i.e., counting all of the benefits against a fraction of the costs), but may have the opposite problem if some benefits are not easily quantified.[25] Less than one-quarter of CGIAR RORs (22% of the 235 ROR estimates) refer to

25 Another set of problems arises in institutions that have multiple roles—such as CGIAR centers with their roles in technology creation, scientist training, germplasm preservation, and institution building. When measuring the returns to the R&D activities, we should count an appropriate part, but not all, of the total costs, and some of the costs are hard to apportion appropriately. On the other hand, if we are assessing the entire set of the institution's investments, how do we measure the benefits from institution-building programs, say? See, for example, Evenson and da Cruz (1992) and Behrman (2010). In principle, what to do is clear. In practice, the benefits and attributable costs are diffuse and difficult to measure.

institution-level or programmatic evaluations, similar to the share for the broader body of ROR evidence (about 23% of the 2,242 ROR estimates).

At the level of the meta-review, we must consider two types of sample selection bias and representativeness. First, as discussed above, the choice of projects and programs to evaluate may be biased: projects that have been evaluated might not represent the total portfolio either because of cherry-picking bias or because some types of R&D are more amenable to analysis or for some other reason. Second, possibly for similar reasons, bias may enter the selection of ROR studies to include in the meta-review. In any event we have grounds for being concerned about the quality of the available "data" in the published evidence on RORs to agricultural R&D and its representativeness relative to the portfolio of CGIAR R&D investments. We have these considerations in mind in what follows as we document the details of the data sources and discuss the filters applied to the data to develop subsets for the analysis, as well as in the analysis and interpretation of the results.

4.2 Overview of the Evidence

Our major source of evidence on CGIAR ROR studies is Version 3 of the InSTePP returns-to-research database developed and periodically updated by the University of Minnesota. Across all ROR studies, not just those pertaining to CGIAR research, this database includes 2,829 ROR estimates from program or project evaluations reported in 492 separate studies published between 1958 and 2015, including 93 separate studies reporting 310 ROR estimates for CGIAR research (Hurley et al. 2016).[26] Nearly three-quarters of these studies (and 65% of the ROR estimates) were published since 1990. Our second source of evidence was a listing of impact studies compiled by the CGIAR System Management Office to support the preparation of *CGIAR System Annual Performance Reports* (CGIAR 2017 and 2018) and related data products. This yielded an additional 13 ROR estimates taken from seven studies. Third, in the course of the research for this project, in early 2020 we identified a further 15 studies reporting 40 ROR estimates for CGIAR research. The estimates from these additional 22 studies were combined with the InSTePP data into a unified database, with comparable data details (InSTePP RoR data Version 3.5).

Combining the evidence from all sources yielded 363 ROR estimates from 115 studies of CGIAR-related research listed in Annex Table 1. For comparative purposes, in this report we also juxtapose the CGIAR-related research evidence against ROR evidence for non-CGIAR research taken from the InSTePP database, which consists of 2,600 ROR estimates taken from 403 studies. The updated InSTePP database includes details regarding the technical aspects of each ROR study (e.g., the methodology used to estimate the returns to research, the nature and length of the cost and benefit lag structures), the publication of the study (e.g., date, author affiliation), the research itself (e.g.,

26 Version 1 of the data set included 292 studies reporting 1,886 rates of return estimates and underpinned the work reported in Alston et al. (2000a and 2000b). Version 2 includes 2,681 evaluations from 372 studies published between 1958 and 2011. Details of this version of the database are summarized in Hurley et al. (2014a) and were used for work reported by Hurley et al. (2014b).

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timing of costs and benefits, commodity and country focus, institutional attributes of the research performers), and the types of rate-of-return estimates (i.e., whether IRR, BCR, or both).

Research performed in one location can affect agriculture in that location or elsewhere. Figure 8, Panel a shows the geographic scope of where in the world the evaluated research was performed, with the caveat that the evaluations tagged "multinational" report studies of research oriented to more than one country, irrespective of the geographic location of the agency or agencies carrying out the research. The database includes studies of the impact of agricultural R&D for 85 countries. Around 35% of the ROR estimates refer to research performed by federal or state agencies (including Land Grant universities) in the United States. Institutions from Asia-Pacific, Latin America & Caribbean, and sub-Saharan Africa account for 13%, 15%, and 12% of the ROR estimates, respectively.

Figure 8, Panel b identifies the region-by-region shares of agricultural R&D evaluations (from Figure 8, Panel a) that refer to research conducted by CGIAR centers, which account for 363 ROR estimates (10% of the overall total) drawn from 115 evaluation studies. A large share (47%) of the 140 ROR estimates designated "multinational" refer to CGIAR center research. A sizable share of the CGIAR's research is focused on sub-Saharan Africa, and 23% of the evaluations for that region pertain to research carried out by the CGIAR.

4.3 Standardizing the ROR Metric

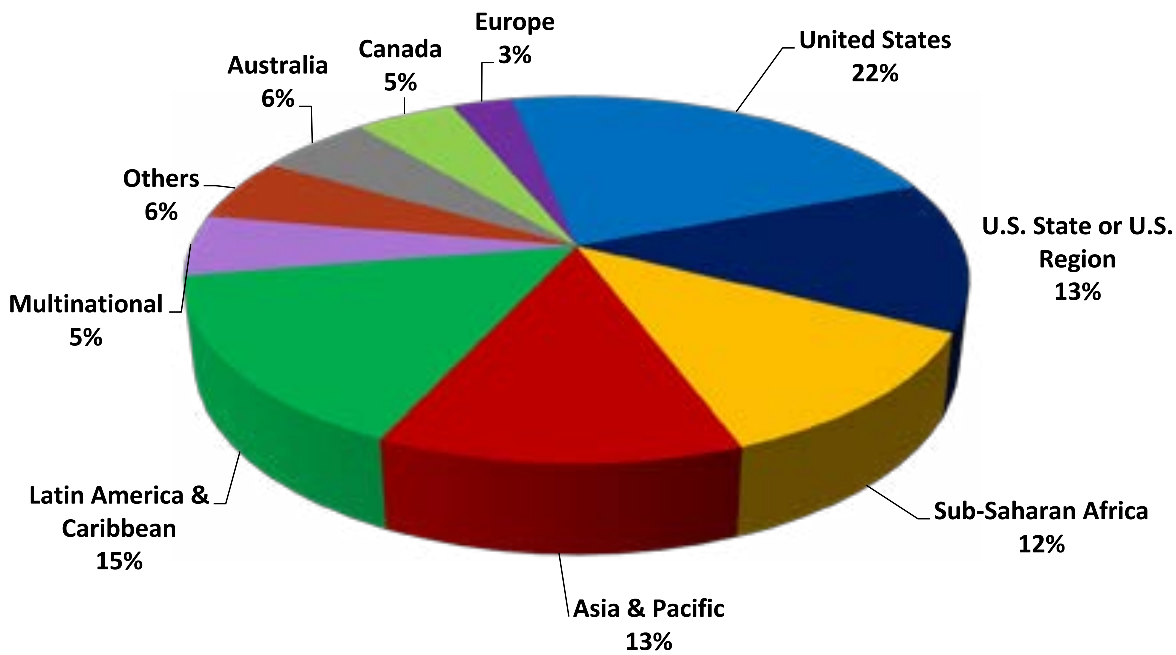
In the economic evidence on the payoffs to investment in R&D, various summary statistics have been used to summarize the streams of costs and benefits associated with R&D activities that typically take (sometimes considerable) time to conduct, followed by lags of years if not decades before the resulting innovations are diffused and their economic consequences fully realized. In the majority of studies, the IRR has been used as the summary statistic of choice, and this is also true of the primary data assembled for this study, which includes 2,672 IRRs (90.2% of the total) and 924 BCRs (31.2%). We question the use of the IRR as a suitable summary statistic for R&D evaluations and reject it for the present purpose.[27] Although the IRR is merely a breakeven interest rate, equating the present values of costs and benefits, many policymakers (and even some economists!) treat IRRs as compounding rates of interest, analogous and comparable to the returns reported for financial products (e.g., mortgages, mutual funds, and certificates of deposit). However, Hurley et al. (2014) showed that it is generally incorrect to treat an estimated IRR as an annualized percentage rate of return, and doing so can lead to incredible implications when applied to agricultural R&D given the typical lag structure and highly profitable payoffs.[28]

27 Some of these same concerns were shared by the instigator of the research evaluation literature, Zvi Griliches, who in 1958 wrote "My objection to this procedure is that it values a dollar spent in 1910 at $2,300 in 1933. This does not seem very sensible to me. I prefer to value a 1910 dollar at a reasonable rate of return on some alternative social investment" (p. 425).

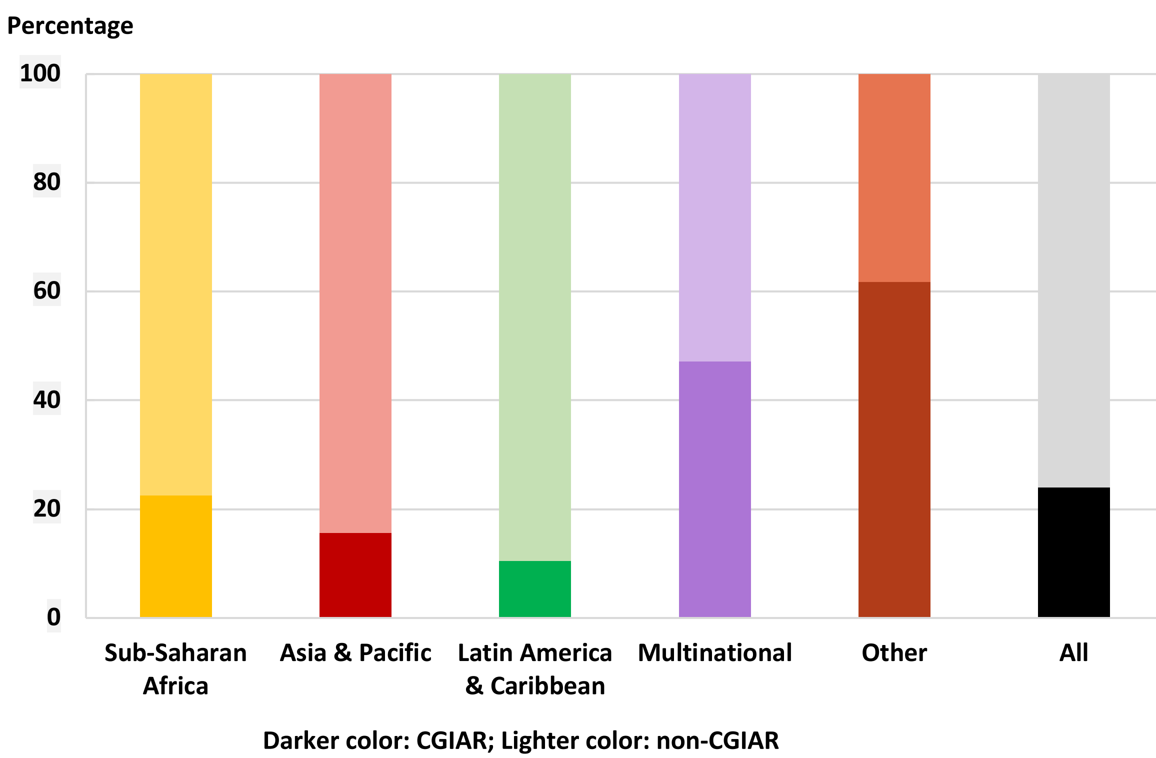
28 As Alston et al. (2011, pp. 1271-2) showed, "… if the roughly $4 billion invested in [U.S.] public agricultural R&D in 2005 earned a return of 50% per annum compounding over 35 years, by 2040 the accumulated benefits would be worth $5,824,000 billion (2000 prices)—more than 100 times the projected U.S. GDP in 2040 and more than 10 times the projected global GDP in 2040."

Figure 8: Research evaluation studies and ROR estimates

Panel a: Region-specific evaluations (total ROR estimates: 2,963)



Panel b: CGIAR research (total ROR estimates: 363 for CGIAR, 2,600 for non-CGIAR)



Sources: InSTePP (2020) RtR Database ver. 3.5.

Notes: See supplemental notes to figures for more details. ROR estimates include reported IRRs and BCRs.

Using the BCR-IRR relationship elucidated by Hurley et al. (2014), Rao et al. (2020) developed and deployed a procedure to recalibrate the reported IRRs into a standardized set of imputed BCRs and modified internal rates of return (MIRRs), where the discount rates and (for imputing MIRRs) research evaluation timelines are held constant, thus improving comparability among the estimates. We draw on that recalibration methodology for this study to recast all the CGIAR-related IRR and BCR estimates into a standardized set of BCR estimates (see Annex B). Reported BCRs use a variety of discount rates to derive the present values of costs and benefits used to form the ratio. To improve the comparability of our estimates, we used a standardized discount rate of 5% to form the imputed BCRs that underpin the analysis presented in this report.[29] The resulting recalibrated database comprises 235 standardized, imputed BCRs from 90 studies for CGIAR research and 2,007 standardized, imputed BCRs from 341 studies for non-CGIAR research (most, but not all of the estimates in the database could be converted to standardized BCRs).

4.4 Selecting Data for the Analysis: Filtering

The essential idea of meta-analysis is to combine findings from multiple studies and thereby increase understanding about the evidence and the relationships to which it refers. In narrowly focused contexts, like repeated drug trials for aspirin (e.g., Zheng and Roddick 2019), meta-analysis is a way of combining data from different studies pertaining to a specific question in a way that effectively increases the relevant sample size and therefore increases the signal-to-noise ratio such that findings can be stated with more precision and greater confidence. This strategy works best when we can presume that the "data" (in our case, observations of RORs to research) refer to the same concept of ROR and are drawn from the same distribution—i.e., with a common mean and independent and identically distributed measurement errors (and without any systematic measurement-error biases) such that, absent measurement errors, the estimates would all converge to the same number.

When we pool estimates referring to different concepts (e.g., research conducted at a different time or place referring to production of a different farm commodity or some other research subject), we should be conscious that some of the variation among the estimates reflects differences in the expected value of the ROR among projects. In this context, increasing the sample size might not improve precision if the observations are not all drawn from the same distribution: combining estimates of RORs to rice-breeding research with estimates of RORs to wheat-breeding research may yield a more precise estimate of the ROR to wheat- and rice-breeding research if the underlying distributions are similar, but it could equally reduce the signal-to-noise ratio if the underlying distributions are dissimilar. The latter seems more likely as we combine results from increasingly dissimilar topics of study and fields of science. Similarly, when we combine results from poorly conducted studies with well-conducted studies, we can diminish the information content of the aggregated data.

29 The rate of 5% was used because this was consistent with the majority of the reported evidence.

Box 3: Problems with the IRR as a Measure of Research Returns

Consider a debt-financed investment made in 1951, C_{1951} yielding a stream of annual flows of benefits over the 50 years, 1951–2000, being evaluated ex post in 2000. Suppose we wish to solve for the break-even interest rate, at which we could afford to borrow to finance this investment. The conventional IRR computation procedure solves for the interest rate (*irr*) that equates the present value of costs in 2000 (PVC_{2000}) with the present value of benefits in 2000 (PVB_{2000}).

$$PVB_{2000} = \sum_{n=1}^{50} B_{1950+n}(1+irr)^{51-n} = PVC_{2000} = C_{1951}(1+irr)^{50} \quad (1)$$

We could equivalently define this same equation in terms of present values of costs and benefits defined in 1951, simply by dividing throughout by the 50-year discount factor, $(1 + irr)^{50}$.

$$PVB_{1951} = \sum_{n=1}^{50} B_{1950+n}(1+irr)^{1-n} = C_{1951} \quad (2)$$

These two equations are clearly equivalent, but equation (1) is more convenient for what follows.

In equation (1), the flow of benefits in 1951, B_{1951} yields a contribution to the final PVB_{2000} equal to $B_{1951} \times (1 + irr)^{50}$. This can only be so if the beneficiary, in 1951, could invest that amount, B_{1951} in an asset that would earn a *compounding rate of interest* equal to *irr*. That is an unreasonable assumption in the context of agricultural R&D projects for which the beneficiaries (consumers and producers of farm products) are unlikely to have a personal rate of time preference approaching the typically measured IRRs or face investment opportunities that would earn anything like the typically measured IRRs.

The computed IRR will accordingly overstate the break-even interest rate. If you cannot reinvest the proceeds at a rate, *irr*, you cannot afford to borrow at that rate to finance the investment. Such reinvestment might be possible within a firm (e.g., by paying off the loan) but not in the case of publicly funded R&D.

A more reasonable approach would be to assume beneficiaries can reinvest their income resulting from the investment at a lower external rate, *r*, and this is the rate at which benefits should be compounded forward (or discounted back). Then we can solve for the modified internal rate of return, MIRR (*mirr*):

$$PVB_{2000} = \sum_{n=1}^{50} B_{1950+n}(1+r)^{51-n} = C_{1951}(1+mirr)^{50} \quad (3)$$

Or, equivalently:

$$PVB_{1951} = (1+mirr)^{-50} \sum_{n=1}^{50} B_{1950+n}(1+r)^{51-n} = C_{1951} \quad (4)$$

If *r* is less than *irr*, so too will be the *mirr*.

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These comments lead to the issue of making decisions about which studies to include in the analysis, which to drop, and how to aggregate the information. Raitzer and Kelley (2008), following Raitzer (2003), took the approach of establishing a specific set of criteria against which to score and select studies to be included in their analysis.[30] Specifically, Raitzer (2003, pp. 10–17) proposed a set of selection criteria related to the extent to which studies had adopted a defined set of best practices in impact assessment, organized under two main headings (which he referred to as "principles"): (a) transparency and (b) demonstration of causality. Then, under each heading, he defined a set of indicators for rating studies.[31] The same indicators were also used to define five scenarios, ranging from more- to less-conservative, for assessing and aggregating benefits.

Like Raitzer (2003), Raitzer and Kelley (2008, p. 190) began by applying a scale criterion:

> The initial selection of publications for review was based upon a comprehensive inventory of impact assessment literature. A minimum cumulative ex post benefit estimate of US$50 million was set as the cut-off value as benefit estimates below that were insignificant compared to the total investment (US$8 billion in 1990 dollars). Although necessary for the efficiency of the review process, this criterion alone was heavily restrictive and excluded many published smaller-scale epIAs [ex post impact assessments]… .

They did not provide details on the inventory of studies from which they drew their subset for analysis. Instead, they presented the outcome from that selection process. As they said, the literature survey, in combination with the criteria for selecting plausible analyses, resulted in a selection of 15 epIA studies. But they also excluded epIA studies published after 2002, leaving only eight studies for detailed analysis. Combining the measures of benefits from a handful of these studies (including five with the greatest total benefits and a further dozen with sizable payoffs) with measures of the total costs of the CGIAR research program, Raitzer (2003) (and Raitzer and Kelley, 2008) was able to infer lower-bound measures of the BCR for CGIAR research under five scenarios ranging from 1.94 (in the most conservative scenario) to 17.26 (in the least-conservative scenario). Later in this report we revisit, refresh, and extend that careful analysis.

This type of detailed assessment is reasonable to contemplate when the total number of studies is small and the indicators are reasonably objective and straightforward to apply, and if we can have a clear sense of the implications of the procedure and understand the implicit tradeoffs. In our context, we have a great many studies to consider. More importantly, though, we have reservations about the appropriateness of the selection criteria and the indicators, and their implications for the evidence—which are not clearly apparent to us.

30 Maredia and Raitzer (2010) subsequently employed a "best-evidence" approach to reviewing returns to international agricultural research in Africa. See, also, Maredia and Raitzer (2006, 2010).

31 These criteria relate to, but are not the same as, "replicability," which might be a more appropriate concept. We found it difficult (or impossible) to confidently replicate the analysis of some studies that satisfied Raitzer's selection criteria.

We opted to take a different approach. Specifically, since we did not have a basis in prior information that would enable us with confidence objectively to discount particular studies (or estimates) as being less accurate or less informative than others based on the observable attributes of the studies or the estimates, we opted to take the approach of including all seemingly relevant studies and estimates. We considered the possibility of discounting (or dropping) studies based on prior views about the consequences of particular methodological approaches or based on knowledge of how particular individuals go about doing cost-benefit analysis. But we were concerned that the application of arbitrary rules of thumb to eliminate studies or estimates from the data base could result in bias or reduced precision, potentially making matters worse, one way or another. In particular, dropping studies risks making the database less representative in its coverage of CGIAR research across centers, commodities, places, and time.

We did end up dropping some studies from the analysis based on concerns over the relevance and likely empirical realism of their estimates. First, we opted to exclude ex ante assessments and restricted attention to the results from ex post assessments for which it is easier to define the relevant counterfactual and where observational data can be used to estimate the rate and timing of the adoption process. Second, we also dropped one CGIAR study (Dey et al. 2007) from those that remained on grounds of questionable relevance. Third, we dropped studies focused on high-income countries such that our comparison non-CGIAR group was developing-country NARSs. In addition, for parts of the analysis we tried dropping extreme values of the standardized, imputed BCRs to examine the likely influence of outliers on our understanding of the central tendency of the distribution of estimates.[32] These details are discussed in the next section (see, also Annex Figure 1, which describes the data-selection process).

32 Alston et al. (2000a, 2000b) noted that narrative reviews of returns to agricultural R&D tended to heavily discount the tails of the distribution of the evidence and to err in the direction of emphasizing more plausible (lower) values for rates of return. Thus, it is common in policy contexts to see reports of IRRs in a narrow range when the unfiltered data had a much wider range and a higher mean, as documented by Alston et al. (2000a, 2000b). For example, Pardey and Alston (2011, p. 1) said: “Surveys of the hundreds of studies quantifying the returns from agricultural research suggest rates of return in the range of 40–60 percent per year.” More recently, Clancy et al. (2016) wrote: “… agricultural R&D has a very large rate of return—on the order of 20 to 60 percent with a median rate of return of 40 percent.” This kind of filtering distorts the information content of the data unless we have real grounds for dismissing estimates outside the reported range.

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5. Evidence on the Returns to Investments in CGIAR Research

The CGIAR is a unique, and highly successful, institutional arrangement for directing development aid dollars to increase food production throughout the developing world through agricultural research. With around 2% of global *public* spending on agricultural R&D (or 3.7% of public agricultural R&D spending in developing countries), by most accounts the CGIAR has had a disproportionately large impact on improving productivity for large numbers of the world's farmers, increasing global food supplies, and lowering the cost of food for all the world's consumers. This impact has come mainly from the release and widespread adoption of the yield-enhancing crop varieties bred by CGIAR scientists; but also involved are R&D addressing pest and disease problems and, more recently, research directed toward natural resource management or policy-oriented social science research. The CGIAR has also trained thousands of scientists and research technicians and assembled one of the world's largest holdings of agricultural genetic resources, which also has economic value that is not well measured (Koo et al. 2004).

Many of these accomplishments and their consequences are not reflected in the available measures of benefits from CGIAR research, which predominantly refer to genetic innovations, especially for wheat, rice, pulse crops, and maize, but also for other crops and livestock. The coverage is partial, and even within the research that has been evaluated, the evidence is disproportionately weighted toward improvement for a few crops. One of the challenges for evaluators is to determine how to interpret this partial evidence and draw inferences regarding the payoff to the broader portfolio.

One approach may be to presume that managers within the CGIAR have allocated resources among projects to maximize the total benefits. If so, anticipated BCRs for incremental investments should be approximately equal among projects, and in this sense the returns to evaluated projects could be taken as also representing those that have not been evaluated. However, the evaluated projects might not be representative of the broader portfolio for various reasons, including the fact that evaluators may consciously or unconsciously tend to cherry pick for evaluation projects or programs known to have been highly successful (as discussed by Alston et al. 2000a, 2000b).

In addition, the preponderance of the funding made available to the CGIAR is earmarked by donors for specific applications, leaving little if any discretion for CGIAR centers or the system as a whole to optimize the portfolio of research projects in light of emerging scientific or economic opportunities. An alternative approach, as applied by Raitzer (2003), for example, is to charge the costs of the broader portfolio against the benefits from the narrower subset for which benefits have been measured. If the benefits have been measured reasonably well for the evaluated projects or programs, then these two methods might be expected to provide upper and lower bounds for the returns to the portfolio as a whole.

In what follows, we first describe and interpret the meta-evidence in two ways:

- Using tabulations, characterizing the overall distribution of BCRs for CGIAR research compared with their counterparts for non-CGIAR research and among CGIAR centers.
- Using regression models to account for the influence of detailed aspects of the evaluation study that gave rise to each particular estimate.

We conclude this interpretation with a finding that the overall BCR for CGIAR research is comparable to that for non-CGIAR research performed by (and for) developing countries.[33] In brief, the evidence from the tabulations, graphs, and regression analysis is broadly consistent with an overall BCR for CGIAR R&D spending in the range of 10:1.

5.1 Distribution of Estimated BCRs

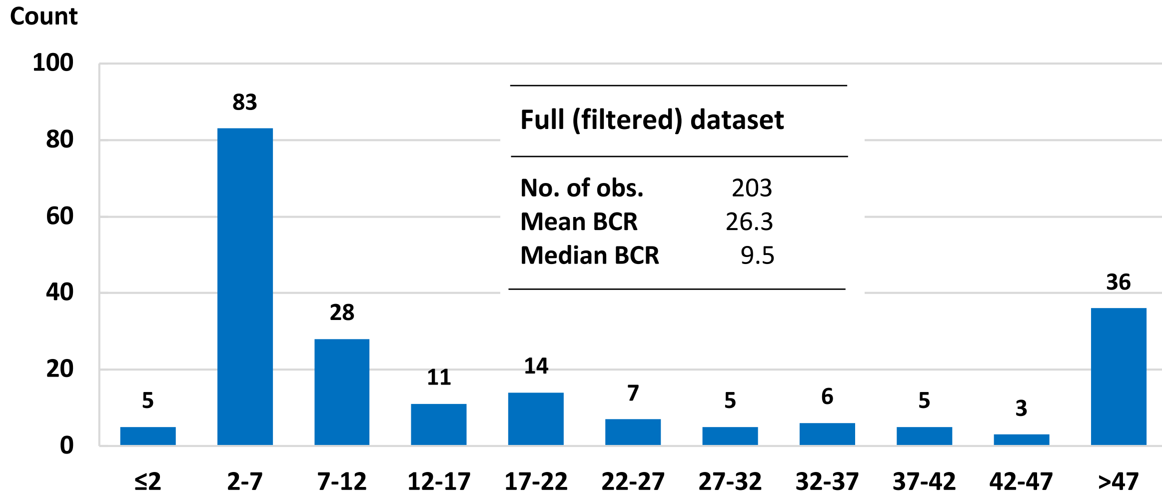
Figure 9 shows the distributions of standardized estimates of BCRs for both CGIAR research (Panel a) and non-CGIAR research performed by (and for) developing countries (Panel b). Table 5 includes summary statistics for the data underlying these plots. For CGIAR research, the BCRs are generally well greater than 1.0, but they range widely (from 0.6 to 230.0), with some very large estimates such that the distribution is skewed heavily to the right (Figure 9). Consequently, the overall mean BCR for CGIAR research, 26.3, is more than twice the median, 9.5. Similarly, for non-CGIAR research the overall mean BCR is 23.9 and the median is 8.3. Even if we drop the lowest and highest 10% of observations, the estimates range from 2.6 to 68.0 for CGIAR research and from 2.4 to 49.4 for non-CGIAR research (Table 5).

At first glance, these plots and the data in Table 5 might suggest that the distributions for CGIAR and non-CGIAR research are quite similar. However, the CGIAR sample is much smaller (203 estimates from 78 studies, compared with 577 estimates from 144 studies for the non-CGIAR sample). Also, the coverage is somewhat different. In the CGIAR sample, 188 of the 203 estimates are for crops, the other 15 are for livestock (1), natural resources topics (5), or policy-oriented research (9). The non-CGIAR sample is also heavily crops-oriented, but now 6.4% of the estimates are for livestock or natural resources compared with 0.4% of the CGIAR sample. The CGIAR sample includes a larger share (indeed a larger number) of studies that are multinational or "global" in scope. The range of estimates tends to be large relative to the measures of central tendency (mean or median) for each of the categories in Table 5 (e.g., crops) or sub-categories (e.g., wheat within crops) such that it is not possible to make confident statements about differences in BCRs across sub-categories based on the data in this table. This is the low signal-to-noise ratio problem encountered by Alston et al. (2000a, 2000b), for example, in a similar context. In general, however, for every category and subcategory of CGIAR research, the results of ROR studies have been favorable: across categories and subcategories both the mean and median BCRs are almost all greater than 5:1, with the median BCRs clustered around 10:1.

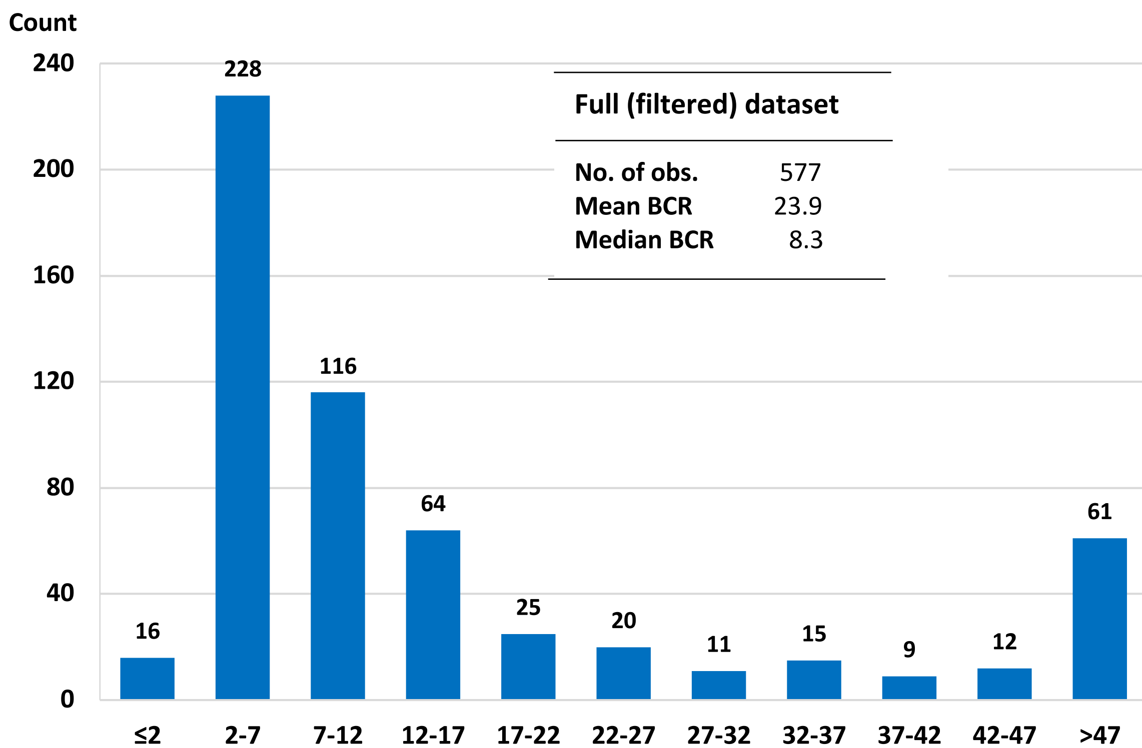
33 Rao et al. (2019) compare estimates from a broader definition of the ROW, including both developed and developing countries. Here we have confined the comparison group to developing countries.

Figure 9: Distribution of imputed BCR estimates for CGIAR and non-CGIAR

Panel a: CGIAR BCRs



Panel b: Non-CGIAR BCRs



Source: Authors' construction using full filtered dataset extracted from InSTePP (2020) RtR Database ver. 3.5. See Table 5 for additional details.

Notes: BCR groupings such as "2-7" indicate greater than 2 and less than or equal to 7, and so on.

Table 5: BCR estimates for CGIAR and non-CGIAR agricultural R&D

	Number of		BCR estimates						
	studies	est.	mean	st.dev.	min	10%	median	90%	max
	count		*ratio*						
CGIAR R&D									
All estimates	**78**	**203**	**26.3**	**39.6**	**0.6**	**2.6**	**9.5**	**68.0**	**230.0**
Crops	68	188	26.2	39.8	0.6	2.6	9.3	68.0	230.0
Wheat	12	25	22.6	22.5	2.4	2.8	19.0	63.4	86.0
Maize	5	15	17.6	19.7	2.5	2.7	12.0	28.0	84.0
Rice	9	37	34.3	50.2	0.6	2.4	7.0	99.0	229.0
Millet & sorghum	7	17	12.6	13.8	2.5	2.7	5.6	37.8	39.9
Roots & tubers	22	33	14.0	16.0	2.0	3.3	8.2	42.7	68.0
Other crops	14	52	39.5	54.4	1.2	2.3	11.8	124.8	230.0
Livestock	1	1	26.5	na	26.5	26.5	26.5	26.5	26.5
Natural resources	4	5	4.4	3.5	2.3	2.3	2.9	10.6	10.6
Policy-oriented research	5	9	39.3	46.4	1.0	1.0	19.6	144.0	144.0
Developing countries	65	145	30.4	44.8	0.6	2.7	9.6	88.9	230.0
Sub-Saharan Africa	16	47	40.9	51.3	2.4	2.7	17.3	124.8	230.0
Multinational & Global	17	58	16.0	18.4	2.0	2.5	8.8	39.6	84.0
Non-CGIAR R&D									
All estimates	**144**	**577**	**23.9**	**63.6**	**0.0**	**2.4**	**8.3**	**49.4**	**1008.2**
Crops	133	540	23.9	64.9	0.7	2.4	8.4	48.9	1008.2
Wheat	24	71	22.1	46.3	0.7	2.4	9.1	43.7	339.7
Maize	27	107	21.3	27.3	2.3	3.1	11.4	49.4	200.6
Rice	21	32	86.3	218.4	1.5	3.0	12.4	186.0	1008.2
Millet & sorghum	10	65	16.5	23.7	1.9	2.2	4.3	65.1	77.9
Roots & tubers	12	36	10.2	37.4	2.3	2.3	2.4	9.3	227.9
Other crops	60	205	22.0	39.8	1.4	2.9	9.0	47.2	215.7
Livestock	13	33	26.3	42.7	0.0	2.4	8.9	55.0	178.6
Natural resources	2	4	2.8	1.0	2.3	2.3	2.4	4.3	4.3
Developing countries	140	558	24.5	64.6	0.0	2.4	8.6	50.2	1008.2
Sub-Saharan Africa	40	140	14.9	17.6	1.4	2.3	6.0	46.8	66.5
Multinational & Global	5	19	5.5	5.4	2.1	2.2	3.0	10.0	25.0

Source: Authors' construction using full filtered dataset extracted from InSTePP (2020) RtR Database ver. 3.5. See Table 5 for additional details. Developing countries denote low- and middle-income countries classified into 2018 income classes using World Bank (2019).

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5.2 Regression Analysis

The same filtered, imputed BCR data were used in a meta-regression analysis of the type undertaken by Rao et al. (2020) and previously by Alston et al. (2000a and 2000b). The dependent variable in these regressions is the BCR in logarithms, and the regressors include variables (mostly indicator variables) characterizing the evaluation study from which the estimate was drawn, the research project or program being studied, and whether it was performed by the CGIAR (including details on which CGIAR center was involved) or by others, and when (see Annex A for details).

These regressions allow us to estimate the expected value of the BCR for R&D—conditional on whether it was done by a CGIAR center, for example—with measures of statistical confidence around those conditional estimates (or predictions). To assess whether the returns to agricultural R&D vary between CGIAR centers and NARSs in developing countries (non-CGIAR), *ceteris paribus*, requires that we also control for differences in the attributes of the BCR evidence between these two groups of researchers. The measures of explanatory variables are derived from factors that represent characteristics of the ROR measure, as well as attributes of the analysts who performed the ROR evaluations, the R&D projects being evaluated, and the evaluation methodology (see Annex C for details). Setting aside those observations that lack complete details for all the explanatory variables, the *regression sub-sample* contains 722 observations of BCR estimates (compared with 780 in total) including 170 BCRs for CGIAR R&D (compared with 203 in total) and 552 BCR estimates for non-CGIAR (public developing country) R&D (compared with 577 in total).

We specified a linear regression model in which the dependent variable is the logarithm of the estimated BCR, and the explanatory variables are indicators of various characteristics of the study that gave rise to the estimate.[34] Two variants of the same model (Model 1 and Model 2) were defined by imposing different sets of restrictions on regression coefficients (see below for details).[35] Our detailed estimation results are reported in Annex C. In the present context, we are not much interested in the detail of the estimated model parameters—except, perhaps, as a check on the implications for the validity of the model. Rather, we are mainly interested in the implications for the expected values of the conditional predicted BCRs and the precision of those conditional predictions, which we characterize with 95% confidence intervals. These are the focus of the results reported below. In each instance, the conditional prediction is defined as the expected value of the BCR for the respective aggregate, conditional on the values of the explanatory variables all having been set at the means for the relevant subset of the data (e.g., the expected value for the BCR for

34 This semilogarithmic functional form makes sense given the nature of the data: BCRs are strictly positive numbers and the distribution is highly skewed to the right. The fact that the BCRs are all strictly positive numbers means we have a limited dependent variable with attendant implications for the error distribution. The logarithmic transformation removes that limitation on the range of the residuals; that almost all of the BCRs are all greater than 1.0 means the observed ln(BCRs) are almost all greater than zero.

35 We also tried a model with the dependent variable in levels rather than logarithms. This model did not fit the data very well, and it yielded conditional predicted values for BCRs with wide confidence intervals (i.e., low precision), in several instances including zeros or, implausibly, negative numbers. The logarithmic transformation of the dependent variable resulted in much more acceptable regression results, but it did mean that recovering predicted BCRs in levels entailed more complicated procedures.

IRRI R&D is evaluated at the means of the explanatory variables for the observations of BCRs pertaining to IRRI).[36]

Below, three sets of results are presented referring to those from the analysis using the full regression data set and two alternative trimmed data sets, created by dropping 20% of the observations: either the highest and lowest 10% of the observations or just the highest 20% (Table 6).[37] The statistical analysis supports using the results from the model estimated using the full sample. The results using the trimmed data sets were generally quite similar, though setting aside the highest 20% of BCRs considerably reduced the mean and median and closed the gap between them in ways that had direct implications for the predicted BCRs. Still, across the subsamples in Table 7, the (conditional) predicted BCRs and confidence intervals in any row are quite similar. The preferred results from the full regression data set are discussed in detail next.

As noted, results are presented for each of the two models, Model 1 and Model 2, obtained by applying alternative restrictions on the coefficients representing the CGIAR center-specific fixed effects. First, in Model 1, we included individual center-specific indicator variables for each of the seven listed (crop-related) CGIAR centers (IRRI, CIMMYT, ICARDA, IITA, CIAT, CIP, and ICRISAT), and these indicators took the value of 1 (otherwise zero) if the reported BCR was derived from that center; an additional indicator variable was equal to 1 (otherwise zero) if the BCR was derived from one of the other five CGIAR centers for which we have sufficient BCR estimates (ILRI, ICRAF, CIFOR, AfricaRice/WARDA, or WorldFish); and finally, a separate 0-1 indicator was set equal to 1 if the BCR was for policy-oriented research (POR).[38] The default category applied for non-CGIAR BCRs, such that the coefficients on the indicator variables measured differences relative to the default category. Hence, we were able to derive straightforwardly from the regression model conditional predicted values and confidence intervals of the BCRs for (a) each of the seven listed centers, (b) any of the "Other Five" across which the measure was the same, (c) POR (policy-oriented research) projects, (d) the default, non-CGIAR category, and (e) all estimates.[39]

In Model 2, the CGIAR indicator variable was set equal to 1 (otherwise zero) if the BCR referred to <u>any</u> CGIAR center, which facilitated computing a measure of the average conditional predicted

36 This is a somewhat arbitrary choice, but it does mean that the predictions are pertinent. It would be straightforward to compute conditional predictions at any other set of values for the vector of explanatory variables, but some care might be warranted in the interpretation. For example, we could compute an expected BCR for livestock research conducted at IRRI in the year 1900, but that is clearly nonsensical.

37 This was done as a kind of robustness check, since we were concerned that the model might not fit equally well across the wide range of the data, especially with some of the very high values for BCRs, which might be unduly influential outliers. A downside of this approach is that it does potentially entail a loss of information or representativeness, and it is somewhat arbitrary—though transparent, replicable, and easily justified.

38 The full (standardized) data set includes a total of nine estimates of BCRs for POR projects conducted by IFPRI and a few other centers, but only one of those estimates has the full complement of right-hand-side variables, required for inclusion in the regression sub-sample.

39 The delta method was used to compute the standard errors for the predicted values of the dependent variable (i.e., the BCR), conditional on assumed values for the explanatory variables, including the indicator variables. These conditioning variables were set at their mean values for the relevant subsample (i.e., given the value of the indicator variable and the trimming rule that was applied), and the corresponding expected value, standard error (S), and confidence interval for the ln(BCR) were computed. Then these values were transformed to levels. The upper and lower bounds for the confidence interval were computed simply by taking exponents of the logarithmic counterparts. The expected value was computed with a correction for the estimated variance: $\overline{BCR} = \exp\{\overline{\ln BCR} + S^2/2\}$.

Table 6: Filtered and standardized BCRs: Full dataset and subsets used in the meta-regressions

				Regression subsample								
	Full dataset			Total subsample			Trimmed (10%–90%)			Trimmed (< 80%)		
CGIAR centers	*count*	*mean*	*median*	*count*	*mean*	*median*	*count*	*mean*	*median*	*count*	*mean*	*median*
IRRI	58	40.5	21.6	46	43.9	18.7	33	17.3	11.8	26	10.3	9.3
CIMMYT	68	38.7	20.5	66	38.7	20.5	50	19.2	16.3	41	13.6	12.0
CIAT	59	44.8	14.0	57	46.3	16.0	34	17.4	11.3	32	7.7	6.1
IITA	41	50.0	28.0	41	50.0	28.0	28	21.8	16.7	21	14.6	12.7
ICRISAT	52	43.9	21.6	52	43.9	21.6	39	19.1	11.8	27	9.0	6.5
CIP	57	39.1	17.3	57	39.1	17.3	43	18.7	12.2	34	10.4	9.3
ICARDA	36	49.6	21.6	26	64.8	54.0	14	23.3	16.7	10	14.1	13.3
Founding four	96	36.0	15.0	92	36.7	16.3	65	16.8	12.0	61	10.6	9.3
Other five	41	46.0	23.1	41	46.0	23.1	29	18.3	11.8	22	10.2	10.0
POR	9	39.3	19.6	1	19.6	19.6	1	19.6	19.6	1	19.6	19.6
Total CGIAR	203	26.3	9.5	170	26.8	10.0	139	13.9	8.7	128	8.9	6.4
Non-CGIAR	577	23.9	8.3	552	24.7	8.6	440	13.6	9.0	450	8.7	7.0
All Estimates	780	24.5	8.6	722	25.2	9.0	579	13.7	9.0	578	8.7	6.8

Sources: Created by authors.

Notes: "Other five" include ILRI, ICRAF, CIFOR, AfricaRice/WARDA, Worldfish; "Founding four" includes IRRI, CIAT, CIMMYT, and IITA; POR is policy-oriented research. Non-CGIAR includes all 2019 low- and middle-income countries classified with data from World Bank (2019) in InSTePP (2020) RtR Database ver. 3.5.

BCR for all CGIAR research. Likewise, the indicator for the founding four centers facilitated computing a measure of the average difference between the conditional predicted BCR for research from any of that group (IRRI, CIMMYT, IITA, and CIAT) and that for all CGIAR research. Model 2 can be seen as a special case of Model 1 in which the coefficients on the indicator variables were now restricted to be equal (a) among the founding four centers and (b) among all other centers. These differences in restrictions on the measured fixed effects associated with the different centers resulted in (very) small differences in the fit of the model and in the conditional expected value for "All" and "Non-CGIAR" categories of BCRs.

5.3 The BCR for CGIAR Research

If we consider just the preferred (full sample) model results in Table 7, the predicted BCRs (conditional on setting the explanatory variables at their average values) are generally large with an overall value of 10.4 (both Model 1 and Model 2) and, with a relatively narrow 95% confidence interval, between 9.1 and 11.7. The predicted BCR for the non-CGIAR sub-sample, which accounted for a significant majority of the data, was slightly lower at 9.9, and the predicted BCR for the much smaller CGIAR subsample was a bit higher at 12.0, albeit with a wider confidence interval: from 9.0 to 15.8. As we move farther up from the bottom of Table 7, the results for the even smaller subsamples—referring to the "Founding Four," the "Other Five," and individual CGIAR centers displayed more variation in the predicted BCRs and wider confidence intervals. However, the overwhelming conclusion is that the predicted BCRs are all significantly greater than 1 (from the lower bounds for the 95% confidence intervals) and are generally not statistically (nor economically) significantly different from one another—generally on the order of 10:1, and mostly close to 10:1.

In Table 6, as we look across the different sub-samples, in the last three rows of the table, the median BCRs were all in the range of 6 to 10, whether we were referring to the CGIAR, the non-CGIAR, or all of the estimates. In Table 7, the regression analysis has yielded similar results for the estimates of predicted BCRs, after accounting for the influence of various covariates representing measures of factors that could contribute to differences among the studies. Figure 10 combines the key results from Table 7, and the information from Table 6, with linearized representations of the distributions of predicted BCRs. A reasonable inference from the evidence is that the overall BCR for CGIAR (and non-CGIAR) research is on the order of 10:1 (and generally in the range of 5:1 to 15:1), but that we cannot make more precise statements about the differences among centers, nor according to the research focus or other differences among studies.

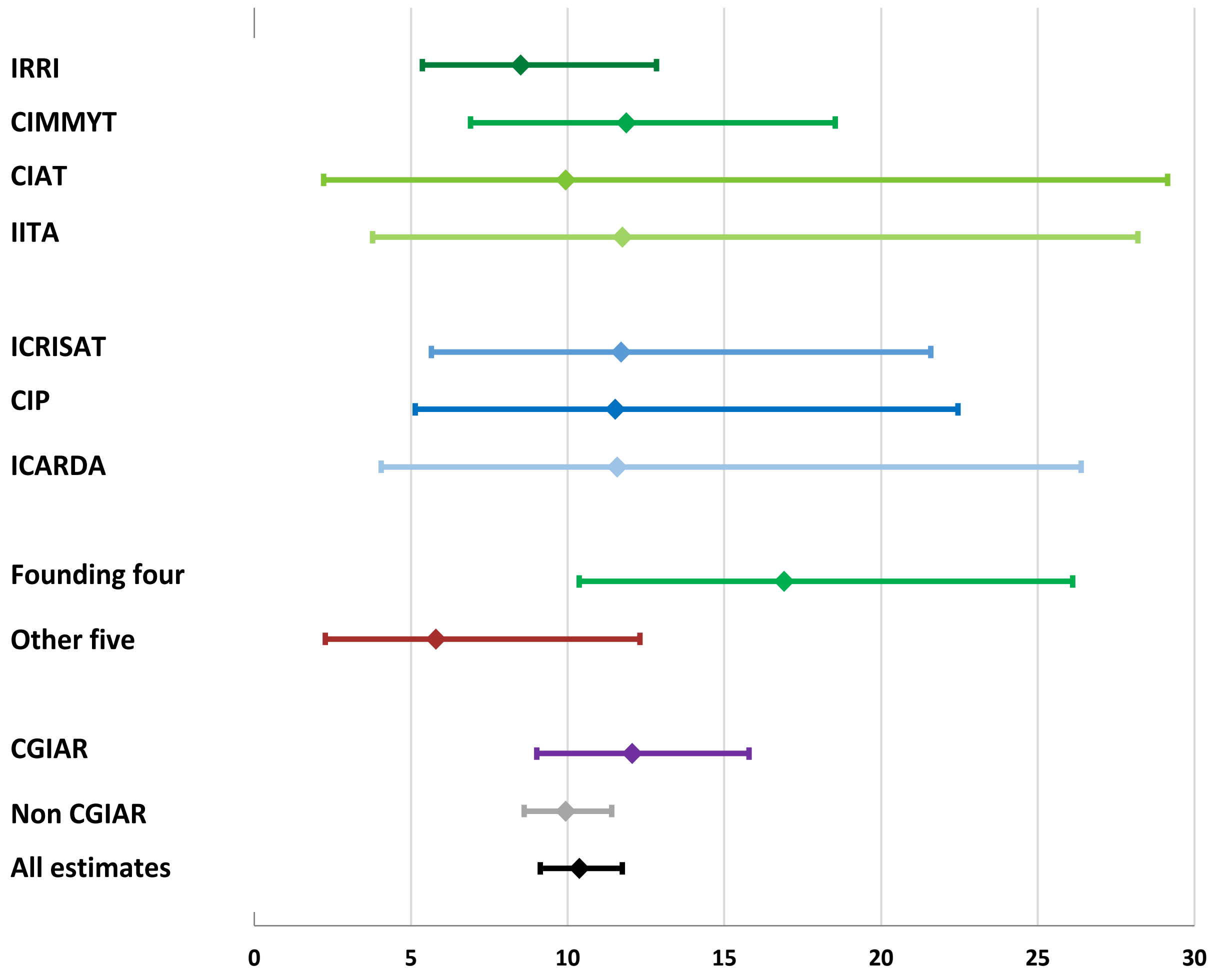
Table 7: Conditional predictions of BCRs for CGIAR centers and other aggregates

	Conditional predictions of BCRs based on different regression sub-samples								
	Full sample			Trimmed (10%–90%)			Trimmed (<=80%)		
	$\widehat{\text{BCR}}$	95% CI		$\widehat{\text{BCR}}$	95% CI		$\widehat{\text{BCR}}$	95% CI	
Model 1									
IRRI	8.5	5.4	12.8	7.8	5.6	10.6	6.6	4.8	8.8
CIMMYT	11.9	6.9	18.5	14.5	9.7	20.9	11.0	7.2	16.0
CIAT	9.9	2.2	29.1	7.3	3.8	12.8	3.8	2.5	5.4
IITA	11.7	3.8	28.2	7.1	2.8	14.8	6.8	3.4	12.2
ICRISAT	11.7	5.7	21.6	11.3	6.0	19.5	5.6	3.7	8.0
ICARDA	11.6	4.0	26.4	5.9	2.3	12.6	4.2	1.6	9.2
CIP	11.5	5.1	22.5	11.6	7.1	17.9	8.7	5.9	12.4
Other five	5.8	2.3	12.3	6.6	3.2	12.0	5.8	2.9	10.5
POR	19.6	19.6	19.6	NA	NA	NA	NA	NA	NA
Non-CGIAR (1)	9.8	8.6	11.2	9.5	8.6	10.6	6.4	5.8	7.1
All estimates (1)	10.4	9.2	11.6	9.6	8.7	10.4	6.5	6.0	7.0
Model 2									
Founding four	16.9	10.4	26.1	11.9	9.6	14.7	7.7	6.0	9.7
POR	19.6	19.6	19.6	NA	NA	NA	NA	NA	NA
Total CGIAR	12.0	9.0	15.8	9.3	8.0	10.8	6.7	5.9	7.7
Non-CGIAR (2)	9.9	8.6	11.4	9.6	8.6	10.8	6.4	5.8	7.1
All estimates (2)	10.4	9.1	11.7	9.6	8.7	10.5	6.5	6.0	7.0

Sources: Created by authors. $\widehat{\text{BCR}}$ is the predicted value of BCR for each grouping (i.e., row) based on the estimated regression model parameters, with explanatory variables set at their respective group sub-sample means.

Notes: "Other five" include ILRI, ICRAF, CIFOR, AfricaRice/WARDA, Worldfish; "Founding four" includes IRRI, CIAT, CIMMYT, and IITA. Non-CGIAR includes all 2019 low- and middle-income countries classified with data from World Bank (2019) in InSTePP (2020) RtR Database ver. 3.5.

Figure 10: Conditional predictions of BCRs for CGIAR centers and other aggregates



Source: Created by authors.

Notes: Whiskers denote 95% confidence interval for predicted BCRs, shown by diamonds from the semi-log model, applied to the trimmed sample from which the upper and lower 10% of observations had been dropped. For "Founding four," "Other five," "CGIAR," "non-CGIAR," and "All estimates," the expected value and 95% confidence interval were taken from Model 2 (see Table 7). For all other centers, expected value and 95% confidence interval from Model 1 were used.

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6. The Benefits From Investments in CGIAR Research

BCRs are scale-free numbers. Seeking to add more meaning to those numbers, we undertook to infer measures of the present value of benefits associated with various particular streams of research expenditures to make statements about the past payoffs. For comparison, we also collected measures of total benefits from impact assessment studies that report those indicators or net present values (NPVs) as well as (or instead of) IRRs or BCRs.

6.1 Scaling ROR Evidence: From BCRs to Benefits

Applying a relevant measure of BCR to a quantum, R_t of research spending in a particular year, *t*, we can infer an estimate of the present value in year *t* of the future stream of research benefits from that investment: PVB_t = BCR * R_t. Using this idea, we computed estimates of the present value of (streams of future) benefits corresponding to expenditures by CGIAR centers and by public research agencies in developing countries. One issue in making such calculations is matching the measure of BCR appropriately to an expenditure series. In some cases, we might have information that supports using a specific estimate of a BCR, rather than some more-general estimate, and in some other cases, we might consider adjusting the BCR or the measure of expenditure to which it applies, if the expenditure is not entirely committed to R&D per se (Box 4).

The imputed, standardized BCRs for R&D undertaken either by the CGIAR or by NARSs in low- and middle-income countries are distributed over a wide range, with a central tendency around 10:1 after we discount the effects of extreme outliers and accommodate other peculiarities of the evidence. In what follows we work with round numbers, across a wide range, consciously to signal and reflect the imprecision of these measures and our knowledge in this context. We use a BCR of 10:1 as our base and starting point.

Figure 11, Panel a displays plots of year-by-year measures of the present values of the future streams of benefits from research undertaken by the CGIAR, computed by scaling the total expenditure (as plotted in Figure 3) in each year by each of three BCRs: 5, 10, and 15:1. The middle plot, corresponding to a BCR of 10:1, reflects our best estimates of the stream of observations, year by year, of the present value of future benefits (PVB). After rising from about $1 billion to almost $4 billion in the 1970s, the yearly measure of PVB from the CGIAR floats between $4 billion and $6 billion for some twenty years, until a rapid rise and fall in the final decade, peaking at over $10 billion in 2013, reflecting the surge in funding.

The upper and lower plots in Figure 11, Panel a, corresponding to BCRs of 15 and 5, might be read as representing upper and lower bounds to those annual estimates of total benefits: the 95% (or even 99%) confidence limits implied by the estimated standard errors of our predicted BCR for CGIAR R&D would be well within these bounds. But other interpretations are possible. For instance, the line shown as corresponding to a BCR of 5 could be read as a more conservative estimate of the most likely yearly present values of (future streams of) research benefits, allowing for potential issues associated with attribution and measurement that imply discounting the reported BCRs (see, e.g., Alston et al. 2000a, 2000b; Alston and Pardey 2001, and the discussion below). Or it could be interpreted as reflecting the BCR of 10 if only half of the total CGIAR spending was for research and the BCR should be applied only to that half. Panel b in the same figure represents the corresponding measures of present values of research benefit flows associated with total public expenditures on R&D by middle- and low-income countries. Here the vertical scale is different, as is the shape of the time path of benefits, though it is broadly similar—generally trending up but with some flattening during the 1990s. The present value measure of research benefits rises from less than $100 billion per year in the early 1970s to more than $250 billion per year by 2018 using a BCR of 10:1. The measures of benefits from public agricultural R&D in Panel b are on the order of 100 times their counterparts in Panel a for CGIAR spending.

In Figure 12, we take a more nuanced look at these measures of total benefits from CGIAR spending, paying some attention to the breakdown among different groupings of CGIAR centers. Here the measures are partitioned among three groups:

- The founding four centers.
- The other seven centers added in the first expansion of the CGIAR during the 1970s, still all focused on crop and livestock productivity.
- The six centers added subsequently during the 1980s and 1990s, with various other areas of research focus.

This partitioning allows us to consider measures obtained if we apply the BCR of 10:1 only to the crop research centers—for which relatively more and potentially more reliable evidence on the research payoff has been accumulated—or only to the founding four centers as a subset. Virtually all of the BCRs in our database are for crops research.

The top line of Figure 12 matches the middle line of Panel a in Figure 11, corresponding to a BCR of 10 applied to total spending by the entire CGIAR. The lowest block, tagged "founding centers" represents less than half that total in the most recent years, but it was a larger share in the earlier years. By the late 1970s, these four centers were conducting research with payoffs approaching $2 billion each year (expressed in 2016 dollar values).[40] After a slowdown in the 1990s, this flow surged (briefly) to more than $4 billion in 2014. These payoffs accruing to work by the founding four centers would have been more than enough to cover the full costs of the expanded CGIAR, within which this group came to diminish in relative importance. It may be reasonable to apply the same BCR uniformly to the other crop centers, in which case we can simply add together the parts labeled "founding centers" and "first expansion." The composition of that aggregate may be of interest, but after some years of a relative rise in benefits accruing to the first expansion group, catching up, the two parts have been close to equal since the late 1980s.

40 This is a complicated concept. The payoffs represent the future stream of benefits over future decades (measured in real 2016 dollar values) discounted back and expressed in present values in the year when the corresponding spending takes place.

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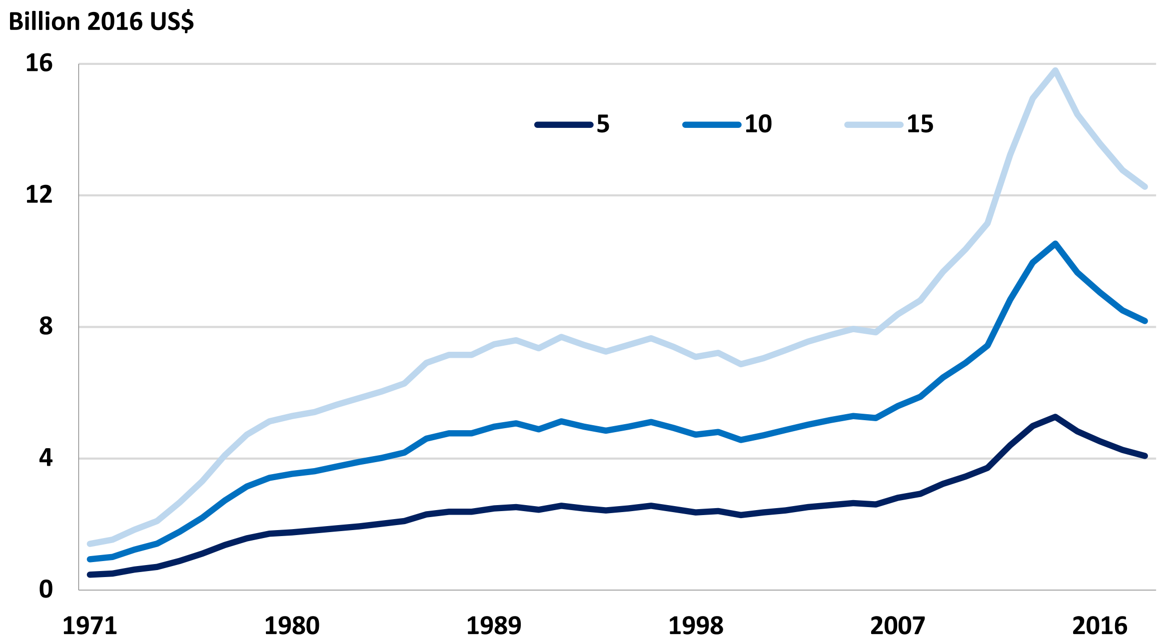
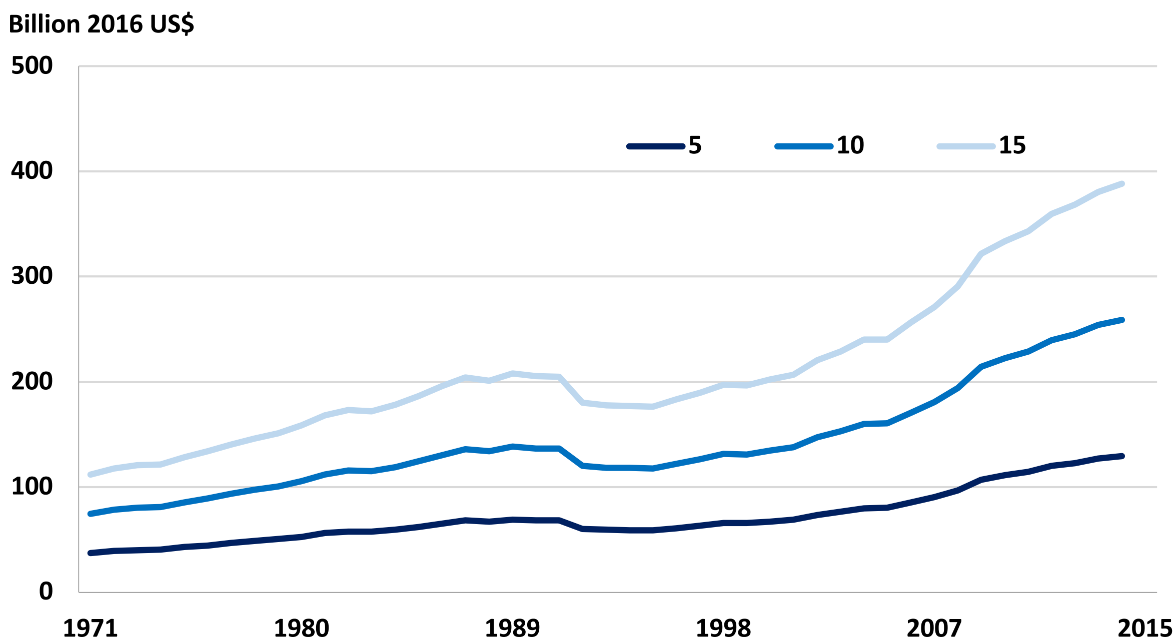
Figure 11: Value of benefits, implied by BCRs, from R&D streams 1971-2018

a. **CGIAR (1971-2018)**



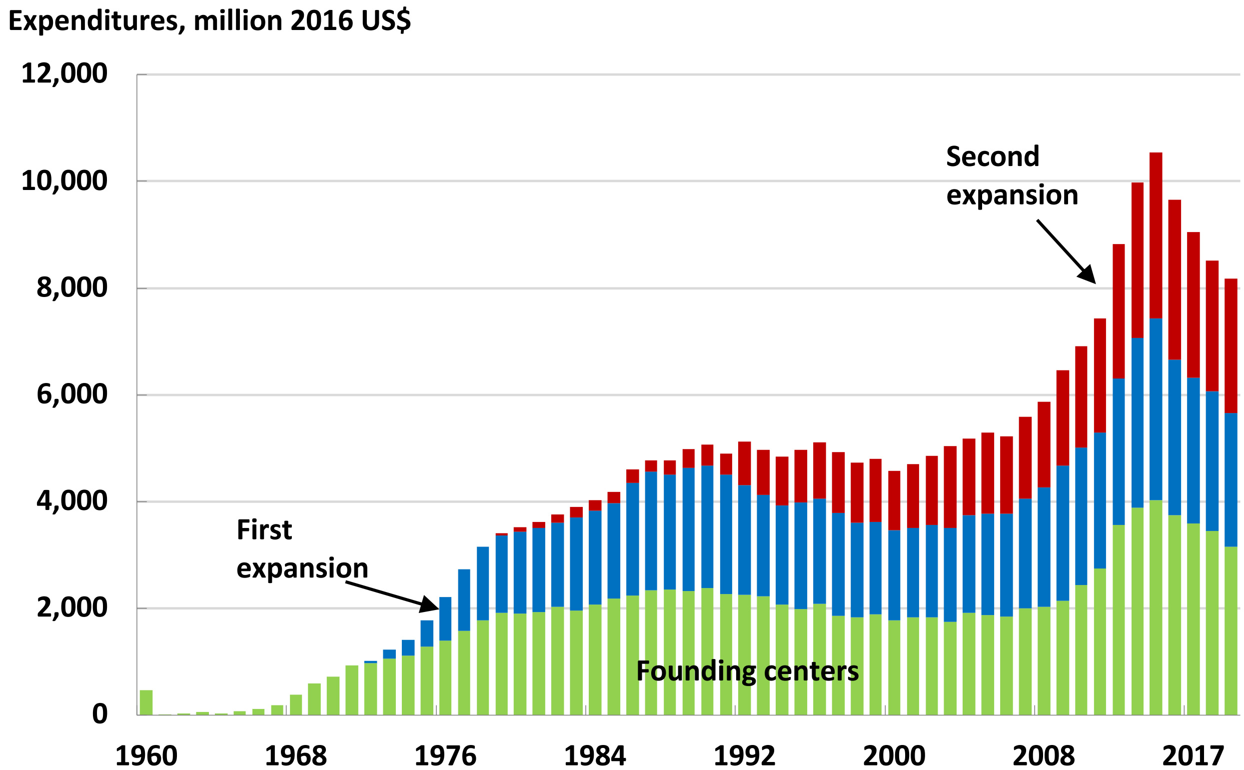
b. **Public agricultural R&D in developing countries (1971-2015)**



Sources: Public agricultural R&D data are from Pardey and Chan-Kang (2020). CGIAR expenditures are authors' compilation based on data from CG Secretariat (1983), MacNeil (1998), and *CGIAR Financial Reports* (various years).

Notes: CGIAR and public agricultural R&D expenditures were scaled up by BCRs equal to 5, 10, and 15.

Figure 12: Value of benefits, implied by BCRs, from CGIAR R&D streams 1971-2018



Sources: See Figure 5.

Notes: Benefits represent CGIAR expenditures scaled by a factor of 10.

To provide alternative insights into the payoff evidence, Table 8 juxtaposes summary measures of the streams of benefits depicted in Figures 11 and 12 against comparable measures of streams of R&D costs. The entries in Table 8 were developed by compounding the streams of implied benefits (in annual present value terms), as displayed in Figures 11 and 12, forward to 2018, using an interest rate of 5% per year. Thus, in the last row of Table 8, compounding forward at a rate of a 5% per year over the period 1971–2018, the stream of R&D spending by the founding four CGIAR centers had an equivalent present value in 2018 of $31 billion. Applying a BCR of 10:1 to that same stream of spending and compounding the implied benefits (in annual present value terms) forward over the period 1971–2018 (or equivalently, applying 10:1 to the compounded present value of that stream of benefits) yields an equivalent present value in 2018 of $314 billion. This benefit is large in absolute terms, but nonetheless is just 0.17% (as shown in parentheses) of the compounded present value in 2018 of the total value of agricultural production in today's low- and middle-income countries over the period 1971–2016 ($183,365 billion). The bottom row of Table 8 also includes comparable estimates implied by using BCR multipliers of 5 and 15 rather than 10 to compute benefits.

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The other rows in Table 8 show comparable measures for different (increasingly larger as we move up the table) streams of research investments, including those for CGIAR crop R&D for the period 1971–2018, all CGIAR R&D for the period 1971–2018, and all public R&D in today's low- and middle-income countries over the period 1971–2015. Applying a BCR multiplier of 10 to the total present value in 2018 of CGIAR R&D over the period 1971–2018 ($64.8 billion in 2016 dollars) implies a present value in 2018 of benefits from CGIAR R&D equal to $648 billion. This benefit is just 0.35% (as shown in parentheses) of the comparable present value in 2018 of the total value of agricultural production in low- and middle-income countries over the period 1971–2016. If we apply BCR multipliers of 5, 10, and 15 to public agricultural R&D in today's low- and middle-income countries over the period 1971–2015, the benefits are equivalent to 5.4%, 10.9%, and 16.3% of the comparable total value of agricultural production in those countries, all computed in 2018 present value terms but expressed in 2016 dollar values for consistency with other measures throughout this report.

Table 8: Present value in 2018 of benefits from various R&D streams implied by BCRs

R&D expenditure Stream	Period covered	Present value in 2016 of R&D stream @ 5%	Benefits computed using an assumed BCR of		
			5:1	10:1	15:1
	Years	*billions, 2016 international dollars (percent of Ag VOP)*			
Public agricultural R&D in ROW LDCs	1971–2015	1,968	9,841 (5.44)	19,682 (10.88)	29,523 (16.31)
CGIAR R&D	1971–2018	65	324 (0.18)	648 (0.35)	971 (0.53)
CGIAR crop R&D	1971–2018	50	248 (0.14)	497 (0.27)	745 (0.41)
Founding four CGIAR centers	1971–2018	31	157 (0.09)	314 (0.17)	471 (0.26)

Sources: Authors' compilation based on R&D spending data from Pardey and Chan-Kang (2020).

Notes: A discount rate of 5% was used to compute present values.

Box 4: Accurately Representing R&D Spending

Data on funding for agricultural R&D agencies rarely translates directly into measures of expenditure on research per se—including appropriate allowance for overhead costs of management, administration, fund-raising, and facilities—when agencies spend significant shares of their resources on non-research activities, such as "strengthening NARS," training, and other types of institution-building activities, or outreach and extension. Measuring R&D spending is conceptually and quantitatively difficult, although there are guidelines for how to do this (e.g., OECD 2015).

In CGIAR financial reports from 1971 through to 1994, the research share of total core CGIAR spending fluctuated between 51% and 63%, with no apparent trend. A change in the expenditure categories reported in the CGIAR *Financial Reports* covering the period 1997–2006 meant we could not recover consistent research spending totals for this period. Recent financial reports, for the years 2016 to 2018, indicate CGIAR research spending as a share of total expenditures was in the 65–67% range. However, across the decades, detailed documentation as to the changing definitions of what constitutes "research" (including the crop, livestock, tree, fish, or policy orientation of that spending) is lacking (see Notes to Figures and Boxes). Given the steady rise in earmarked funding and the shift of the total CGIAR portfolio away from *agricultural* R&D, it seems reasonable to think that a smaller share of the resources has been spent on agricultural research. A good rough guess may be that one-half of the total accumulated CGIAR expenditure since 1971 has gone to agricultural research.

At first blush, 50% may seem to be a small share of the total CGIAR funds going to research per se versus other activities—depending on how, precisely, those distinctions are to be drawn. However, total spending by Land Grant universities in the United States, for example, are split between teaching, research, and outreach activities. Moreover, in public universities, overhead rates of more than 50% are common, with overhead costs not always being spent in the service of the university's research operations. Likewise, charitable foundations and aid agencies incur expenses that reduce the share of donations that reach the poor. At issue, in our context, is to decipher the share of "non-research" costs that is overhead expenses related fairly directly to research, and should be counted as a cost of research, versus activities that are truly separable from research—even if complementary to it.

6.2 Directly Estimated Benefits

The vast majority of economic assessments of returns to research report IRRs or, less often, BCRs as their summary statistics of choice. Relatively few studies report the corresponding measures of total benefits (nor other details that could be used to infer measures of total benefits). Unit-free measures—like BCRs and IRRs—have advantages and disadvantages. An advantage is that, to the extent that they are comparable for such purposes, they can be readily pooled and subjected to statistical analysis to draw inferences about the broader population from which they are drawn.[41] However, in counterpoint, we do not know the scale of the investment to which they apply, nor the

41 In the meta-analysis, all observations of BCRs are treated equally, regardless of both the scale of the investment from which they were derived and the scale of the total benefits that they reflect; it is a *simple average*. However, referring to the portfolio as a whole, the relevant overall BCR would be given by a *weighted average* in which each BCR is weighted by a share of the total research budget it represents. Hence, scaling research investments using the simple average of the BCRs may result in a misleading indicator of total benefits to the portfolio unless the distribution of the BCRs is similar across all scales of investment such that the simple (unweighted) and weighted averages are similar.

scale of the benefits. Consequently, we cannot say confidently how much (or even which parts) of the total research investment is directly represented by the evidence from an examination of the BCRs alone—but we can confidently predict it will not be equally representative of all types of R&D.

In our context, the available BCRs for CGIAR spending mostly refer to particular kinds of research investment (mainly crop improvement, for which returns are amenable to measurement and likely to be worth measuring) and in particular places (where there was capacity available for doing the measurement and interest in the measures). They may also reflect cherry picking or other selectivity or attribution biases and thus not be representative even of the subsample of research investments to which they correspond—say, crop research. Moreover, because of the unit-free aspect, we cannot know how much of the total investment is represented by the BCR—though we might expect to see a propensity for the ROR evidence to be more concentrated among the larger-scale projects for which large absolute payoffs (as measured by total benefits) as well as high proportional payoffs (as measured by BCRs) would be anticipated and to which greater scrutiny would be a natural tendency.

Since the population of BCRs for CGIAR spending is hardly representative of the total CGIAR, we should be cautious about extrapolating from the available evidence. Even within, say, crop improvement R&D, the BCRs might not fully represent the broader portfolio—especially if we extrapolate to livestock, natural resource management, policy-oriented social science research, or even beyond that to non-research activities. Thus, we must exercise due care in extending the average BCR of 10:1 to the broader portfolio—even though we might have good grounds from our broader experience for thinking that 10:1 is probably a good, conservative, and generally representative estimate.

One way to check on the representativeness of the BCRs is to examine the evidence from the subsample of studies that did report (or from which we could recover) measures of total benefits and for which we therefore do know something about scale. If enough of those studies refer to a large enough share of the total research enterprise (either the total costs or the total benefits), we might be able to infer an alternative estimate of the total payoff, which we can usefully compare with that based on applying the BCR estimates to the total investment or parts of it, as discussed above. This is the strategy employed by Raitzer (2003) and Raitzer and Kelley (2008) in their meta-review, which focused on a selected (non-random) subset of specific studies of CGIAR R&D that have presented measures of total benefits and show large payoffs. In what follows, we revisit, revise, and extend that work. As well as five of the studies emphasized by Raitzer (2003) and Raitzer and Kelley (2008), our selected sample of nine studies includes four others identified by the authors or cited in Renkow and Byerlee (2010).

In defining this sample, described briefly in Table 9 (and in more detail in Annex Table 12), we sought to identify billion-dollar studies—i.e., studies for which the total respective reported PVBs attributable to CGIAR and related spending exceed $1 billion in 2016 values—for which enough detailed information could be availed to credibly and competently deduce the relevant measures. These nine studies collectively report benefits from R&D associated with six CGIAR centers (i.e., CIMMYT, CIP, CIAT, IRRI, IITA, and ICARDA) referring to R&D that resulted in substantial gains in productivity for wheat (two studies), rice (two studies), potatoes, sweet potatoes, edible beans, and cassava (two studies)—covering crops that represent a significant share of the main focus of those centers and much of the world's staple food supply, but also with some meaningful omissions. Several of the studies are based on measures of the value of total yield gain for these major crops, only some of which is truly attributable to public agricultural R&D and, within that, CGIAR R&D. A key determinant of the estimates of benefits in those studies, in particular, is their attribution assumptions. We will return to this aspect. First, we summarize findings from our recompilation of their estimates.

The measures of benefits in Table 9 are based on those reported by the authors of the original studies.[42] After estimated streams of benefits were recovered, several steps were taken to express them in comparable terms.[43] First, if benefit streams ended before 2020, we extrapolated the nominal (current purchasing power) values forward to 2020, which meant in real terms the annual stream of measured benefits would be eroded by inflation. This is more conservative than assuming that benefits are maintained in real terms and more realistic than assuming they end abruptly in the last year of data reported. Second, all of the annual flows of benefits, expressed in U.S. dollars, were converted into constant 2016 values using the price deflator for U.S. GDP (and likewise for research expenditures). Third, to compute measures of the present value in 2016 of the stream of benefits from the first year of benefits (the earliest of which was in 1966) to 2020, annual benefits prior to 2016 were compounded forward to 2016 and future benefits were discounted back to 2016 using a constant real discount rate of 5% per year.

Across the nine studies, the present value of benefits (2016 values) accruing from 1966 to 2020 adds up to $1,783 billion—which may seem large, but a great part of these gains is associated with studies based on yield gains for rice and wheat, and we should expect those gains to be highly valuable.[44] It all turns on attribution. What share of the measured gains is attributable to R&D (including CGIAR research and other public and private research) versus other sources of farm productivity gain (increased use of fertilizer and other purchased inputs that contributed to yield gains might be falsely attributed to R&D if not accounted for otherwise)? Of the part that is attributable to R&D, how much is attributable to the CGIAR versus public R&D in developing

42 In the original studies the measures of benefits were reported variously as either streams, single values, or (sometimes) present values. In each case, study-specific transformations (based on details reported in the respective studies) were applied to express the reported measures as equivalent flows of annual benefits (in 2016 dollar values).

43 An issue of potential concern is double-counting of benefits across these studies. Among these studies, two deal with rice, and two deal with cassava—but in each case they report benefits for different regions of the world. We have two studies on wheat varietal improvement—one specifically on rust resistance. These studies report benefits for overlapping regions of the world, and some share of the benefits may have been counted twice.

44 Notably, 70% of the total across the nine studies comes from just one study (Hossain et al. 2003), for which the projected benefit through 2020 is valued here at $1,173 billion. Importantly, this study does account for additional input costs offsetting some of the benefits from the yield gains being evaluated. However, like the other studies in the table, it does not go far with identifying benefit shares attributable to the CGIAR.

Table 9: Nine billion-dollar studies of returns to CGIAR and related spending

			Research benefits			
Study	**CGIAR centers(s)**	**Technology/ geography**	**Reported period of research benefits**	**Attribution of benefits**	**Present value for reported period**	**Present value to 2020**
					(billions 2016 US$)[a]	
Byerlee and Moya (1993)	CIMMYT (plus joint ICARDA/CIMMYT wheat improvement program)	Wheat varieties, 37 developing countries (incl. south China).	1977-1990	Benefits attributed based on varietal pedigrees. CIMMYT and NARS costs combined.	150	301
Sanint and Wood (1998)	CIAT (linked to IRRI)	Rice varieties, Latin America & Caribbean.	1967-1995	No benefit attribution.	112	173
Fuglie et al. (1999)	CIP	Virus "free" sweet potato seed, China (Shandong province).	1988-2020	No benefit attribution. CIP and NARS costs combined.	7	7
Zeddies et al. (2001)	IITA	Cassava mealybug control, W. and E. Africa (27 countries).	1982-2013	No benefit attribution. IITA and NARS costs combined.	41	44
Hossain et al. (2003)	IRRI and CIAT	Rice varieties, S. and S.E. Asia (excl. China).	1999	No benefit attribution.	915	1,173
Johnson et al. (2003a)	CIAT	CIAT bean varieties, 19 developing countries (12 in LAC, 7 in SSA)	1979-1998	No explicit benefit attribution. CIAT costs doubled to impute half the total benefits to the CGIAR	6	13
Johnson et al. (2003b)	CIAT	CIAT cassava varieties, 12 developing countries (4 in Asia, 8 in LAC)	1982-1998	No explicit benefit attribution. CGIAR costs doubled to impute half the total benefits to the CGIAR	2	6
Marasas et al. (2004)	CIMMYT	Wheat leaf rust resistance; all CIMMYT mega environments; where spring bread wheat is grown at low latitudes.	1973-2007	No benefit attribution.	44	59
Myrick (2016)	CIP	Potato variety, *C88*, late blight and virus resistant. China (Yunnan province).	1996-2015	No benefit attribution.	4	5
Total Across Nine Studies					**1,280**	**1,783**

Source: Developed by authors based on details gleaned from the sources cited in the table. See Johnson (2020) for additional details regarding CIAT cassava and edible beans evidence. See notes to tables for more details.

Notes: Present value of benefits calculated using a 5% discount rate and taken from Annex Table 12. Present values all expressed in 2016 dollar values.

[a] Benefit values rounded to whole numbers.

countries? This is especially pertinent as all of the benefit estimates in Table 9 (and in Annex Table 12) refer to CGIAR research carried out jointly with NARS partners.

These attribution questions are difficult. In the broader literature, some studies have been able to address these questions directly with information on who conducted and paid for the research leading to a new crop variety (using genetic attribution rules), and information on the extent to which the new variety would provide cost savings relative to the relevant counterfactual alternative varieties (see, e.g., Pardey et al. 1996, 2006). Our nine billion-dollar studies for the most part had much-less detailed information available and had to rely on ambitious assumptions about shares of credit—between the CGIAR and other contributors—for the observed streams of benefits, or said nothing informative regarding partitioning of benefits. It seems a common approach, absent other information, is to assume that one-half of the measured benefits in such studies are attributable to CGIAR research.[45]

As noted above, it is challenging to distinguish roles (and responsibility for outcomes) between the CGIAR centers and their counterparts in developing country NARSs, especially when so much of the relevant research is conducted jointly or separately but in complementary fashion, such as where the NARSs are doing the work required to adapt CGIAR releases to their local conditions. Moreover, from our analysis of the spending streams, CGIAR R&D is dwarfed by public agricultural R&D conducted in medium- and low-income countries, to an extent that it seems adventurous to give half the credit for all the gains to the CGIAR as studies often do. Against that background, in Table 10, we display the results from applying various alternative attribution rules to the benefits from Table 9 (over the period 1966–2020), combined with different cuts on measures of the total cost of CGIAR R&D and non-CGIAR public agricultural R&D in developing countries (over the period 1960–2010), expressed in comparable 2016 dollar values and in 2016 present value terms.

In Table 10, the columns refer to various measures of benefits, reflecting alternative attribution rules, and the rows refer to various different elements of costs. The upper part of the table refers to estimates computed with a discount rate of 5% per year; the lower half uses 3% per year for purposes of comparison. Column 1 refers to total benefits ($1,783 billion in Panel a); Column 2 refers to the case where half of those benefits are assumed to be attributed to other causes and what remains ($891 billion) is the benefits attributable to CGIAR R&D and non-CGIAR public R&D; Column 3 refers to benefits attributable to the CGIAR ($446 billion) if (as in many studies)

45 For example, Byerlee and Moya (1993, p. 48) apportioned benefits to CIMMYT from varietal improvement undertaken jointly with NARSs using a modification of the weighting scheme devised by Brennan (1989) based on crop varietal pedigrees. Thus "[V]arieties from CIMMYT crosses were given a weight of 0.85, based on the share of wheat breeding expenditures incurred up to advanced generation selection... [while] varieties with CIMMYT parents were given a weight of 0.5, assuming that half of the germplasm came from CIMMYT." Using these attribution rules, averaging over all the mega-environments included in their study, Byerlee and Moya (1993, Table 34) assign 49% of the total benefits attributable to varietal improvement to CIMMYT. Johnson et al. (2003a, pp. 270–71 and 2000b, p. 353) implemented an assumed 50:50 assignment of benefits between the CGIAR and NARS by doubling the CGIAR costs associated with the respective benefit streams from jointly developed varietal improvements. This benefit attribution approach has a long history in the research evaluation literature. For example, Griliches (1958, p. 427) assumed private R&D spending on U.S. hybrid corn research was about the same magnitude as public spending, while Evenson (1967, p. 1424) noted "…one-half of the benefits should be attributed to private sources" when estimating the aggregate returns to agricultural research in the United States.

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Table 10: Benefit-cost comparisons for the billion-dollar studies

		Present value of costs 1960-2010	Present value of benefits from billion-dollar studies 1966-2020		
			100 % attribution (1)	50% attribution (2)	25% attribution (3)
			billions US$ in italics, BCR in bold roman		
a. 5 % discount rate					
			1,782.5	*891.3*	*445.6*
Centers in evaluations	(1)	*44.5*	**40.1**	**20.0**	**10.0**
Crop CGIAR centers	(2)	*47.7*	**37.4**	**18.7**	**9.3**
Total CGIAR centers	(3)	*59.7*	**29.9**	**14.9**	**7.5**
NARS in LDCs	(4)	*2,568.6*	**0.7**	**0.4**	**0.2**
NARS and CGIAR	(5)	*2,628.3*	**0.7**	**0.3**	**0.2**
b. 3 % discount rate					
			1,129.9	*525.8*	*262.9*
Centers in evaluations	(1)	*25.3*	**44.7**	**20.8**	**10.4**
Crop CGIAR centers	(2)	*27.5*	**41.1**	**19.1**	**9.6**
Total CGIAR centers	(3)	*35.4*	**31.9**	**14.9**	**7.4**
NARS in LDCs	(4)	*1,347.0*	**0.8**	**0.4**	**0.2**
NARS and CGIAR	(5)	*1,382.4*	**0.8**	**0.4**	**0.2**

Source: Authors computations. Table 9 and Annex Table 12.

Notes: Present value in 2016 of benefits and costs in all expressed in 2016 dollar values.

the CGIAR is given credit for half of the total benefits in Column 2 attributable to CGIAR R&D and non-CGIAR public R&D, combined. For the costs, each part of Table 10 has five rows. Row 5 refers to total cost of CGIAR R&D and non-CGIAR public R&D in developing countries combined, over the period 1960–2010 ($2,626.3 billion in Panel a); as subsets, Row 4 refers to total spending by developing country NARS ($2,568.6 billion) and Row 3 refers to total CGIAR spending as a subset of that total ($59.7 billion), Row 2 refers to spending by the 9 crop-oriented centers ($47.7 billion), and Row 1 refers to spending by the six CGIAR centers associated with the studies summarized in Table 9 (i.e., CIMMYT, CIP, CIAT, IRRI, IITA, ICARDA).

The entries in the (shaded) body of the table refer to the BCRs obtained by dividing the benefit for the respective column by the cost for the respective row. Thus, for example, in the cell for Row 1 and Column 1 in panel a, when we compare the total benefits (Column 1) with the costs for only the six directly related centers (Row 1), the implied BCR is 40.1:1—more consistent with the broad evidence from the ROR studies, albeit at the high end. This ratio changes as we move to Column 2, allowing for a half-share attributable to causes other than R&D, and to Column 3, giving credit for half of that reduced total to the CGIAR. Now the BCR in Column 3 is 10.0:1, comparable to the results from the meta-analysis, perhaps serendipitously. Within the body of Table 10, the other BCRs vary, reflecting the different attribution assumptions. At the farthest extreme, the BCR of 0.68:1 results if we charge all of the costs of spending by CGIAR and public R&D agencies in developing countries, combined, against the benefits given in the billion-dollar studies alone. As this comparison reveals, the measured benefits from these few studies are quite large—sufficient to cover almost seven-tenths of the total cost of all spending by CGIAR and public R&D agencies in developing countries, including non-research activities and spending on R&D that has nothing to do with crop yields such as livestock research, policy-oriented social science research, or research into forestry, aquaculture, water resources, or human nutrition.

The second half of Table 10 shows the consequences of using a lower discount rate—3% per year rather than 5%—to compute the present values of costs and benefits. This results in slightly more favorable BCRs in every case, reflecting the different timing of the streams of benefits and costs. In present value terms, the total benefits are on the order of one-third less than their counterparts with a 5% discount rate, but the costs are reduced by a greater share: 40–50%.

6.3 Ground-Truthing Benefits

Spending on agricultural R&D is closely linked to the productivity performance of agriculture (see, e.g., Craig et al. 1997, Alston et al. 2010, Fuglie et al. 2020). With this in mind, as a further frame of reference and check on plausibility, we computed estimates of the total value of agricultural productivity growth worldwide and by region, expressed as present values in 2016. Then we contrasted this measure of benefits with the present value of total expenditure on R&D by the CGIAR and governments in developing countries, also expressed as present values in 2016, as another kind of BCR measure—drawing on and extending ideas from Alston and Pardey (2015). To begin, let us consider the counterfactual consequences in 2016 if we were to revert to the patterns of agricultural productivity that existed in 1961, holding input use constant.

The (approximate) value of productivity growth

In Table 11 the first column is the index of total factor productivity (TFP) in region j in 2016 ($TFP_{j,2016}$), given a base of $TFP_{j,1961} = 100$ in 1961, aggregated into regions we have defined, using country-specific estimates from USDA-ERS (2019), which we take at face value for this purpose. For the world as a whole, this index is 217, meaning the quantity of output per unit of input has increased by a factor of 2.2 from 1961 to 2016.[46] For the Asia & Pacific region the ratio is much higher at 264, and for sub-Saharan Africa it is much lower at 129. In Column 3 we report an approximate money measure of benefits foregone if we were to revert from actual 2016 to much lower counterfactual 1961 productivity levels—computed as $k_j * AgVOP_{j,2016}$—where $k_j = (TFP_{j,2016} - TFP_{j,1961})/TFP_{j,2016}$ and $AgVOP_{j,2016}$ (in Column 2) is a measure of value of agricultural production for

46 The USDA-ERS (2019) reports a TFP index for the world as a whole of 173 in 2016, much lower than our estimate of 217. We computed regional measures of TFP growth using different aggregation procedures and for different aggregates than those reported by USDA-ERS (2019). The differences were very small for some aggregates but more pronounced for some others, and (remarkably) most pronounced for the global aggregate, for reasons we do not fully understand. These differences in regional and global TFPs are not relevant for our computation of regional and global benefits from TFP growth, which are all computed by adding up the country-specific benefits, computed using the country-specific TFPs from USDA-ERS (2019).

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2016 from the FAOSTAT (2020) measured in 2016 international (PPP) dollars.[47] For the world as a whole, this total benefit from farm productivity growth is estimated to be $1,690 billion. Arguably, half or more of this total can be attributed to public and private investments in agricultural R&D, though precise attribution is impossible, and the attributable share will vary among countries and regions.[48] For developing countries, the corresponding total benefit from farm productivity growth is estimated to be $1,281 billion—almost three-quarters of the global total.

Table 11: The value in 2016 of agricultural TFP growth since 1961

Region	TFP in 2016 (1961=100)	AgVOP 2016	Total gains 2016	Present value of gains in 2016	
				1961–2016	1961–2026
	index		*billion 2016 PPP$*		
a. 5% discount rate					
Asia & Pacific	264	1,441	884	29,460	36,286
EE & FSU	142	263	81	-3,655	-3,030
High income	213	777	409	27,640	30,801
LAC	224	387	212	8,691	10,326
MENA	262	106	65	3,461	3,962
SSA	129	212	40	125	431
World	**217**	**3,185**	**1,690**	**65,723**	**78,775**
Developing countries	**211**	**2,408**	**1,281**	**38,082**	**47,974**
b. 3% discount rate					
Asia & Pacific	264	1,441	884	21,405	28,945
EE & FSU	142	263	81	-1,375	-685
High income	213	777	409	17,878	21,370
LAC	224	387	212	6,030	7,837
MENA	262	106	65	2,319	2,872
SSA	129	212	40	394	731
World	**217**	**3,185**	**1,690**	**46,650**	**61,069**
Developing countries	**211**	**2,408**	**1,281**	**28,772**	**39,700**

Sources: Authors' calculation based on value of production data from FAOSTAT (2020) and TFP estimate from USDA, ERS (2019).

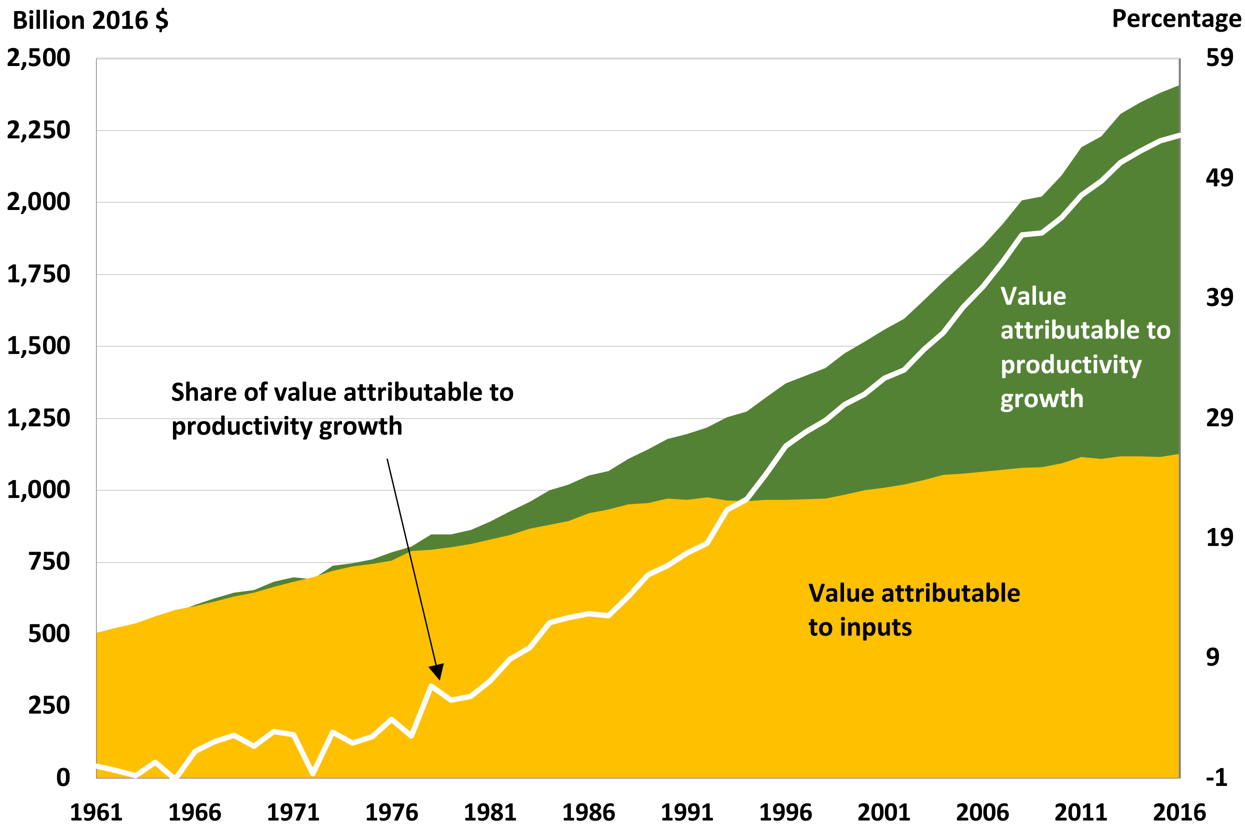
Notes: See supplemental notes to tables.

Applying the same approach, we measured the value of benefits from productivity gains, relative to 1961, for every year 1961–2016, all expressed in constant 2016 dollar values. Figure 13 represents the corresponding ideas and measures graphically over the period 1961–2016 for developing countries as a group. If productivity had stayed constant at the 1961 value of 100, the actual pattern of total output would have followed the pattern of total input (i.e., in every year, the index of output would be equal to the index of input). Figure 13 shows the actual value of output ($AgVOP_t$) divided into two parts: (a) the lower part representing what the value of output would have been, holding the input quantities constant, if productivity had not grown since 1961—i.e., counterfactual value, $CV_t = AgVOP_t * (100 / TFP_t)$; and (b) the upper part, a residual representing the value of additional output that is attributable to productivity growth—i.e., residual value, $RV_t = AgVOP_t - CV_t = AgVOP_t * (TFP_t - 100) / TFP_t$. As productivity increases over time, the share of the value of production that is attributable to productivity growth increases; after 2012 it represents more than half the total value of production.

Simple approximate benefit-cost ratios

Alston et al. (2010) used measures like these, of benefits from productivity growth over past decades, to estimate indicative measures of BCRs for U.S. public agricultural R&D. This required making attribution assumptions. Likewise, here we can juxtapose the present value of the stream of benefits from agricultural productivity growth against the present value of spending by the CGIAR

Figure 13: The benefits from agricultural TFP growth in developing countries, 1961-2016



Sources: Authors' calculation based on value of production data from FAOSTAT (2020) and TFP estimates from USDA, ERS (2019).

Notes: $AgVOP_t$* (100/TFP_t) measures the counterfactual value of agricultural production (holding prices constant) in any year, *t,* if TFP reverted to that of 1961. The share here refers to gains attributable to productivity growth divided by the value of agricultural production.

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and public agricultural R&D agencies in developing countries, combined—recognizing that it would be impossible to identify a separate CGIAR role in this context and noting that our meta-analysis would support combining them—expressed in 2016 dollar values and in 2016 present value terms.

Table 12 includes various alternative approximations of benefit-cost ratios using the method described above, reflecting combinations of assumptions about attribution of benefits, the timing of the matched streams of benefits and costs, and the discount rate. The benefits refer either to the value of productivity gains since 1961 compounded forward to 2016 or to the same amount augmented with the value of gains from 2017 to 2026 (given by projecting the real gains in 2016 forward) discounted back to 2016. Whether the benefits were accrued over the 55 years (1961–2016) or the 65 years (1961–2026), we allow for two alternative attribution assumptions: either 50% or 100% of the benefits attributable to the CGIAR and public agricultural R&D agencies in developing countries. The costs refer to spending by the CGIAR and non-CGIAR public agricultural R&D agencies in developing countries over the period 1960–2015 or, to further examine the effects of R&D lags, 1960–2006. We also tried two discount rates for the stream of benefits and costs, 5% versus 3% per year, in Panel a and Panel b, respectively.

The BCR estimates in Column 1 (13.7 in Panel a, 18.9 in Panel b)—comparing benefits accumulated over 1961–2016 with costs over essentially the same period, 1960–2015—are biased estimates of the true BCRs. First, R&D lags mean that we have left out some of the relevant costs: research expenditures prior to 1960 will have contributed to productivity growth between 1961 and 2016. Second, for similar reasons, we have left out some of the relevant benefits: research expenditures between, say, 2006 and 2015 will generate benefits for many years after 2016. Depending on the pattern of benefits and costs over time and the effects of discounting, these two sources of bias could be offsetting. However, given the generally rising pattern of research expenditures and the annual flows of benefits from productivity gains, we would expect the effect of the understatement of benefits to outweigh the effect of the understatement of costs, biasing the BCRs down on balance. This conjecture is confirmed when we extend the period of benefits from 2016 to 2026 (in Row 1, Column 2): the BCRs increase to 17.3 and 26.1 (Panel a and Panel b). Likewise, when we truncate the period of costs from 2015 to 2006 (Row 2, Column 1), the

BCRs increase to 15.2 and 22.5 (Panel a and Panel b). The BCRs are even larger when we combine the extended benefits (1961–2026) with the truncated costs (1960–2006). The more reasonable combinations are in the "off-diagonal" cells (1,2) and (2,1), which have the stream of costs ending 10 years before the end of the stream of benefits.

Columns (3) and (4) of Table 12 show the BCRs that are implied if we assume only one-half of the total productivity gains are attributable to CGIAR R&D and non-CGIAR public agricultural R&D, and we compare with total spending by the CGIAR and non-CGIAR public agricultural R&D

Table 12: Simple, approximate benefit-cost ratios

		Present value of costs, 2016	Present value of benefits in 2016			
			100% attribution		50% attribution	
			1961–2016 (1)	1961–2026 (2)	1961–2016 (3)	1961–2026 (4)
			billions US$ in italics, BCRs in bold roman			
a.	**5% discount rate**					
			38,082	*47,974*	*19,041*	*23,987*
(1)	*1960–2015*	*2,776*	**13.7**	**17.3**	**6.9**	**8.6**
(2)	*1960–2006*	*2,508*	**15.2**	**19.1**	**7.6**	**9.6**
b.	**3% discount rate**					
			28,772	*39,700*	*14,386*	*19,850*
(3)	*1960–2015*	*1,522*	**18.9**	**26.1**	**9.5**	**13.0**
(4)	*1960–2006*	*1,278*	**22.5**	**31.1**	**11.3**	**15.5**

Sources: See Table 11 and Annex Table 12.

Notes: The benefit-cost ratios were calculated by dividing present value of gains by present value of costs (CGIAR costs plus non-CGIAR costs). Present value in 2016 of benefits and costs, all expressed in 2016 dollar values.

agencies in developing countries (rather than, say, the share of that spending that is directed toward farm productivity improvement, which may be well less than half of the total). The resulting BCRs in Panel a range from 6.9 to 9.6, and their counterparts in Panel b range from 9.5 to 15.5. For the more reasonable combinations in the "off-diagonal" cells (1,2) and (2,1), the approximate BCRs are 7.6 or 8.6 with a discount rate of 5% per year, and they increase to 11.3 or 13.0 with a discount rate of 3% per year. These results from "back-of-the-envelope" calculations are quite crude as estimates of the true BCRs for investments in CGIAR and non-CGIAR public agricultural R&D in developing countries, and we do not offer them to be taken literally for that purpose. Rather, they are offered here as a check on the plausibility of estimates obtained by more specific, detailed, and direct assessments of the payoffs to investments in agricultural R&D. Happily, the results are very much in the ballpark: a plausible set of attribution assumptions (both temporal and institutional) for matching streams of benefits and costs results in BCRs quite similar to those from the published work.

6.4 Reservations About the ROR Evidence

Thus far we have set aside any reservations we may have about the available benefit-cost evidence, though we have mentioned potential causes for concern. In their meta-review Alston et al. (2000a, 2000b) detailed a long list of reasons for skepticism about published measures of research payoffs,

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concluding that, on balance, studies had tended to overstate rates of return, though the true rates of return were nonetheless high. We refer the interested reader to that meta-review (i.e., Alston et al. 2000a, 2000b) for those details; see, also Alston et al. (2009). In what follows we consider some key points, illustrated with some selected examples, as they pertain to our interpretation of the evidence we have assembled.

Estimating research payoffs is never easy. Usually the available data are inadequate to the task (Griliches 1994). And even when data resources are abundant, inevitably those who would measure research benefits are obliged to make a host of modeling and measurement assumptions. Potentially important—perhaps crucially important—assumptions are imposed as untested (and untestable) restrictions on the analysis and thus condition the findings, but this aspect is not always acknowledged and rarely highlighted in the evaluation reports. These conditioning assumptions can enter the analysis in various ways, depending on the approach being taken to measure research benefits, which is governed largely by the data and the purpose of the analysis.

In studies that involve direct econometric estimation of links from R&D to productivity, a host of econometric modeling decisions must be made, chief among them being how to model R&D lags and technology spillovers. Conceptual errors are part of the story, especially as they relate to the stock-flow relationships in how research affects technology and productivity; Alston et al. (1995, pp. 104–107) laid out the pertinent ideas. Many studies have imposed unduly short lags and failed to adequately represent spillovers, often owing to data limitations. One of the consequences has been a systematic upward bias in the estimated rates of return, as discussed by Alston et al. (2000a, 2000b) and illustrated in Alston et al. (2010) in one of the few studies for which data resources were sufficient to model long lags and spillovers comprehensively. To illustrate these potential measurement and attribution problems as they arise in studies that involve direct econometric estimation, we briefly review three recent high-quality studies, done by able economists.

Alene and Coulibaly (2009) estimated rates of return to agricultural R&D undertaken by 27 countries in sub-Saharan Africa (SSA). There is much to admire about this study, but inevitably data restrictions came into play, manifest as restrictive modeling assumptions:

- "Productivity" is measured as value-added per hectare.
- To create an agricultural knowledge stock, the "polynomial distributed lag structure" is in practice a quadratic form with end-point restrictions, imposed on the data with a total length of 17 years after a 5-year gestation lag—a one-parameter representation of the complex, dynamic R&D-productivity linkages.
- The production function model is a highly restrictive Cobb-Douglas form on which the authors impose constant returns to scale.
- Although an attempt is made to control for CGIAR influence, no allowance is made for the effects of private R&D nor for spillovers between countries within SSA or from countries outside SSA.

The upshot is that the authors estimate a very high elasticity of GDP per capita with respect to agricultural research (0.36) as the product of the elasticity of GDP per capita with respect to agricultural productivity (0.95) and the elasticity of agricultural productivity with respect to agricultural research (0.38), giving rise to an aggregate IRR of 55% per annum (46% as an average across the 27 countries).[49] It seems likely that the modeling assumptions we have highlighted—especially the treatment of spillovers but also the very short R&D lag—would have biased the estimated R&D impacts up.

Building on Alene and Coulibaly (2009), Fuglie and Rada (2013) used a broadly similar modeling approach and some of the same data to estimate returns to research for 34 countries in SSA. They had TFP rather than value-added as the dependent variable in their regressions, and they included a separate agricultural knowledge stock for CGIAR research in addition to the one for NARS research, with a creative econometric effort to identify the separate effects, but they used the same (Alene and Coulibaly 2009) R&D lag structure imposed on both.[50] Like Alene and Coulibaly (2009), Fuglie and Rada (2013) made no allowance for international agricultural technology spillovers either among countries within SSA or into SSA from outside or for private agricultural R&D. They obtained generally large estimates of IRRs (and more modest BCRs) for both investments by the NARSs in SSA (an IRR of 24% or 29% per year and a BCR of 2.2:1 or 2.8:1 with a large real discount rate of 10% per year) and by the CGIAR (an IRR of 58% per year and a BCR of 6.2:1). We suspect these estimates may be biased up owing to the restrictive and questionable (but largely unavoidable) modeling assumptions imposed on the analysis.

More recently, Nin-Pratt and Magalhães (2018) modeled returns to public agricultural R&D for 71 low- and middle-income countries throughout the world. Like Alene and Coulibaly (2009) and Fuglie and Rada (2013), they used a Cobb-Douglas production function model on which they imposed constant returns to scale to derive their TFP measures. But unlike both Alene and Coulibaly (2009) and Fuglie and Rada (2013), they employed a more-flexible model of the agricultural R&D knowledge stock, with longer lags, and they allowed for international spillovers from public agricultural R&D in other countries, private biotech firms, and the CGIAR. Across the 71 countries, the average elasticity of TFP with respect to the agricultural knowledge stock is 0.23, the average of the implied BCRs is 4:1, and the average of the implied MIRRs is 6% per year. These estimates are much more modest than those of both Alene and Coulibaly (2009) and Fuglie and Rada (2013)—and, while many other aspects also differ among these studies, it seems reasonable to suppose that the differences in assumptions related to the R&D lag relationship and spillovers could account for a significant part of the differences.

To be clear, it is not our purpose here to criticize any of these studies or their authors. All three studies are relatively recent, using up-to-date methods; they have all satisfied rigorous peer review

49 An elasticity of 0.36 means doubling the relevant measure of agricultural R&D would cause a 36% increase in GDP per capita. That seems implausible to us, even in places where agriculture is a very big share of the economy and where agricultural productivity is highly responsive to agricultural R&D.

50 The CGIAR knowledge stock was modeled as affecting TFP indirectly through its influence on the area of crops affected by CGIAR.

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processes; their methods and assumptions are clearly described and documented; their authors are known for their relevant expertise and knowledge and professional seriousness, and well regarded. Much of the ROR evidence is from studies that are not nearly so well-credentialed; the three we have cited are from the higher-quality end. Rather than offer criticism, our purpose is to demonstrate that published BCRs are conditioned by often untested modeling assumptions that we suspect have contributed to a tendency to overstate BCRs. It is hard to say much more than this. We cannot say for sure if any of the estimates we review is biased, up or down, let alone make a confident empirical claim about the extent of the bias that we suspect is present.

Relatively few of the studies of returns to CGIAR research have used this type of direct econometric approach (37 in our full sample of 363 ROR estimates), but some that have done so have generated numerous estimates of RORs, as in the three examples cited above, and may be influential for that reason. Moreover, some of these studies go beyond RORs to estimate effects of agricultural R&D by the NARSs or the CGIAR on other economic variables of interest. For example, jointly with their estimates of the impacts on productivity and the implied RORs, Alene and Coulibaly (2009) also estimated impacts of agricultural R&D on per capita income and poverty rates using the same elasticity estimates. Clearly, these estimates of income and poverty impacts are also likely to be overly optimistic for the same reasons.

In some other studies, estimates of elasticities from econometric models are used to parameterize simulations in structural economic models, ranging from small-scale bespoke models to larger sector models, such as IFPRI's IMPACT model (https://www.ifpri.org/publication/ifpri-impact-webtool) all the way up to global CGE models such as GTAP (https://www.gtap.agecon.purdue.edu/). It is not always easy for us to see how these simulation models work in translating research expenditures into measures of research-induced productivity growth and ultimately impacts on economic outcomes of interest, and we are left with some reservations.[51] In many cases, it appears that the estimated impacts are exaggerated, perhaps because of attribution errors of the types mentioned above or because of other conceptual and measurement errors, including double-counting. The same may be true of other studies that attempt to estimate impacts of R&D on broader measures of wellbeing and attribute shares to the CGIAR.[52]

51 For example, in an unpublished paper, Laborde et al. (2020) used IFPRI's global computable general equilibrium (CGE) model, MIRAGRODEP, to simulate productivity impacts of CGIAR research. They assumed elasticities of 0.04 and 0.11 from the CGIAR R&D stock to productivity to generate estimates of annual research benefits attributable to the CGIAR: $281 billion per year in 2011. They calculated a benefit-cost ratio of more than 200:1 by comparing those benefits with the annualized costs of the R&D, allowing for an average lag of 15 years between investment and productivity. This seems high to us, but to say more than that will require some deeper detective work.

52 For example, using econometric models designed to take advantage of the natural experiment created by the Green Revolution, Gollin et al. (2019) found that, during their sample period (1960–2010), a 1% increase in aggregate crop yields caused GDP per capita to increase by 1% in developing countries. Scaling up, they compute that high-yielding varieties (HYVs) contributed growth of 38% to GDP (relative to a counterfactual of no HYVs) during the period 1964–2010 and, in 2010 alone, HYVs added $14 trillion to GDP in the developing world. This is 20 times greater than our estimate of the value of TFP growth (from <u>all</u> sources) in developing countries as a share of GDP (see Annex Table 13). Implicitly, they attributed all of this (remarkably large) benefit from HYVs to the CGIAR when they wrote: "By any plausible estimate, the cumulative expenditure on the international centers since 1960 is several orders of magnitudes smaller than the US$14 trillion—let alone the dollar value of the accumulated GDP effects over the entire sample period. So in cost-benefit terms, the return on investments in the IARCs has been remarkable" (Gollin et al. 2019, p. 28). We suspect that the estimated elasticity of GDP with respect to crop yields is much too high, that too much of the crop yield increase has been attributed to HYVs (rather than cooperating factors like fertilizer, water, mechanization, and know-how), and too much credit has been given implicitly to the IARCs (rather than the NARSs) as sources of HYVs.

Studies of returns to CGIAR research have more often been focused on varietal innovations for particular crops. Here the critical modeling and measurement issues are related to (a) attribution of institutional responsibility for a particular varietal release (or set of releases) and the costs associated with the development of that variety (or varieties), (b) measurement of varietal adoption patterns over time, and (c) measurement of yield gains or unit cost reductions attributable to specific varieties per se (taking account of any additional use of fertilizer, irrigation water, and labor) where the gains are relative to the appropriate counterfactual alternative varieties that would have been grown otherwise. These questions take different form depending on whether the study begins with a particular institution and sets out to measure the benefits associated with its releases of improved varieties (e.g., as by Pardey et al. 2004, 2006 in their study of releases from Embrapa in Brazil, taking account of spillins from the CGIAR and from other countries) or begins instead with aggregate yield changes and seeks to measure the value of those changes and attribute them among sources—e.g., as by Byerlee and Moya (1993) for wheat or by Evenson (2003) for a range of staple food and feed crops.

In any such studies, it is often necessary to make bold assumptions about sources of yield gains (new varieties versus other reasons), adoption rates, and attribution among institutions, with little if any real data to justify the particular assumptions; likewise, on the cost side, it is easy to leave out some elements of costs (a) contributed by other institutions, (b) involved in enabling the research being evaluated, or (c) incurred in facilitating the adoption of results. On the whole, across the literature, our sense is that the assumptions have tended to be overly favorable and optimistic, especially in ex ante analyses—i.e., tending to bias the estimated RORs and BCRs up—but this varies from study to study and analyst to analyst and over time. In particular, it is common to attribute a large share of the credit for benefits from varietal improvement to the CGIAR if the varieties were released by the CGIAR or had any CGIAR ancestry. Appropriate attribution rules cannot both (a) give 100% credit to the CGIAR for benefits from its varietal releases, regardless of the source of the parental lines (and thus no credit to the sources of the parents), and (b) at the same time give a large share, if not 100%, of the credit to the CGIAR for varieties released by a NARS if those varieties have any CGIAR germplasm in their makeup.

How to appropriately apportion credit is somewhat arbitrary, but this choice matters for the answers, and there is some basis in science for using a geometric attribution rule, as applied by Pardey et al. (1996, 2006). Unfortunately, many studies do not make clear how they treat this important aspect for the analysis, and often it is not possible to determine the basis for the particular attribution rule applied. Over time, the prevailing practice appears to have been improving in this regard. Nonetheless, for example, it is difficult to find any *real* evidence to justify the widespread practice of giving exactly equal credit to the CGIAR and the NARSs for productivity improvements in developing countries, when the NARSs are outspending the CGIAR by a factor of 15:1, and many public agencies have been contributing to the process for much longer—e.g., in the USDA.

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Where does that leave us in our assessment of the evidence? In simple terms, the main issue in ex post analysis of research returns is attribution: which research, conducted when, and by whom was responsible for the observed productivity gains? In our own experience, in situations when we had good data and a clear understanding of the quantitative issues, by making appropriate attribution allowances, compared with naïve attribution assumptions, we were able to significantly reduce measures of benefits and BCRs; but nonetheless, the measures of payoffs were strongly supportive (see, e.g., Pardey et al. 1996, 2006; Alston et al. 2010). We expect this is a fairly general phenomenon. In most contexts, the annual value of agricultural productivity growth is orders of magnitude greater than the annual value of expenditure on agricultural R&D by all agencies. Because of this gross fact, agricultural R&D has surely paid off even if it has only been a part of the story. The main issues are attribution between R&D and other factors contributing to productivity growth; below that, attribution of the part of growth that is attributable to R&D among (often interconnected) sources of R&D and timing—how long is the lag between spending on R&D and realizing the benefits in farmers' fields? A propensity for studies to overstate the payoffs to particular sources of R&D—such as the CGIAR—adds noise that weakens the signal from the body of evidence that supports the case for not just sustaining spending, but doubling down on it.

7. The Bottom Line

The CGIAR is a small but significant part of the global agricultural R&D enterprise, these days spending around $800 million per year (2016 dollar values), compared with total global public and

Credit: G. Smith (CIAT)

private investments in agricultural and food R&D of around $95 billion per year. Compared with other fields of science and other areas of industrial or public R&D, agricultural R&D has been subject to intensive scrutiny, yielding a great many estimates of RORs—more than for all other areas of the economy combined. But R&D undertaken by the CGIAR has been even more intensively evaluated—perhaps reflecting its unusual financial foundations (based on annual donor allocations), institutional arrangements, and incentive structures. The upshot is that a relatively rich resource of past evaluation efforts—albeit still incomplete and partial in its coverage—is available for assessing the past payoff to CGIAR spending, both directly and compared with other investments in agricultural R&D.

Most of this ROR evidence had already been compiled in the InSTePP data base (Version 3.0), and for this study, we augmented that resource with the results from a few additional impact assessment reports (making Version 3.5), all expressed where possible as comparable standardized BCRs. We began with a large database of 235 standardized, imputed BCRs from 90 studies for CGIAR research and 2,007 standardized imputed BCRs from 341 studies for non-CGIAR performers of agricultural R&D. From this set we dropped some studies because of concerns over the relevance and likely empirical realism of their estimates. In particular, we restricted attention to the results from ex post assessments, and we dropped studies focused on high-income countries such that our comparison non-CGIAR group was research performed in and for developing countries. The resulting filtered sample contains 780 observations of BCR estimates, including 203 BCRs for CGIAR R&D and 577 BCR estimates for non-CGIAR (public, developing country) R&D. Some of these observations could not be used in the meta-regression analysis. In addition, for parts of the analysis we trimmed the sample to reduce the influence of outliers.

The distributions of these BCRs for both CGIAR research and non-CGIAR research are heavily skewed to the right, such that in each case the mean (on the order of 25:1) is much greater than the median (on the order of 10:1). Some of the BCR estimates are very large numbers, which we might wish to discount for that reason, and these outliers can have disproportionate effects on our sense of the distribution and its central tendency. For CGIAR research almost every BCR is greater than 1. The BCRs for both CGIAR research and non-CGIAR research are predominantly for crops, emphasizing a small number of staple crops in particular. The commodity focus and other aspects of the research, and the research evaluation process, are potentially important factors to take into account since they can influence both the measured BCR and its relevance for other contexts.

We first examined the differences in estimates of BCRs across various subsets of the data. Next, we employed a meta-regression analysis to more formally explore the extent of systematic differences in BCRs between CGIAR and non-CGIAR R&D investments and among CGIAR centers, after accounting for the influence of the covariates. These regression results were used ultimately to derive a predicted BCR for CGIAR R&D, conditioned on the covariates, for making statements about the past payoffs. The main alternative would be to rely on the information about the distribution of the estimated BCRs, and we compare results from these two alternative approaches.

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Our overall assessment of the evidence is that the BCRs are generally large with an overall average in the range of 10:1 (whether we are contemplating conditional means from the tables or conditional expected values derived from the regressions). The regression results indicate that we can be highly confident about the expected value of the overall BCR for CGIAR research or for non-CGIAR research (the 95% confidence intervals are narrow), and the results for both the non-CGIAR subsample and the CGIAR subsample are essentially the same. However, this high precision notwithstanding, we cannot make specific statements about any differences among centers, nor according to research focus or other differences among studies. The predicted BCRs for these and other sub-categories are all significantly greater than 1:1 and are generally not statistically (nor economically) significantly different from one another—generally on the order of 10:1. In sum, the evidence supports a view that the overall BCR for CGIAR (and non-CGIAR) research is on the order of 10:1.

One potential concern with using reported or imputed BCRs to draw inferences about the payoffs to investment in CGIAR and other research, in the ways that we have been doing, is that for the most part we do not have any information on the scale of investment to which a BCR applies. To address this concern, we set out to replicate, refresh, and extend the work done by Raitzer (2003) and Raitzer and Kelley (2010), explicitly focused on a selected small subset of large-scale studies which reported measures of total benefits from CGIAR R&D. In 2016 dollar terms, after projecting gains to 2020, the present value of benefits across our nine billion-dollar studies totals $1,783 billion. These benefits may be owed to many sources, not just the CGIAR, but perhaps half may be attributable to joint work by the CGIAR with public research agencies in developing countries and half of that again to the CGIAR alone: a total benefit of $445.6 billion. On that basis, the BCR would be 7.5:1 if we count all CGIAR expenditure and 10:1 if we count just the expenditure by the centers included in our nine billion-dollar evaluation studies.

A further plausibility check is provided by our assessment of the total value of agricultural productivity growth attributable to agricultural R&D by the CGIAR in conjunction with the public research agencies in developing countries. Again, the evidence reinforces the findings from our meta-analysis: our most-plausible combinations of assumptions and attribution rules yield approximate BCRs very close to 10:1.

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Supplemental Notes to Figures and Boxes

All per capita income groupings of countries formed using 2019 World Bank classification based on 2018 GNI per capita data taken from World Bank (2019). The same source is used for our regional classification, with the exception that we designate an EE&FSU (Eastern Europe and Former Soviet Union) region. This is equivalent to the World Bank's "Europe and Central Asia" region minus the high-income countries in Western Europe, which in our schema are included in a "high-income" aggregate. Similarly, other high-income countries (such as Japan, Singapore, Uruguay, Qatar, Saudi Arabia, and Seychelles) are excluded from their respective geographical regions and included in our high-income region.

Box Figure 1

The regional average life-expectancies plotted here were formed as weighted averages of the country-specific average life-expectancies, where the weights were the respective population shares of countries within their regions.

Box Figure 2

No additional notes.

Figure 1

The global value of agricultural production for 1961 and 2016 was taken from FAO (2020). The annual values for each country are reported in international average commodity prices expressed in 2004-2006 PPP dollars, which we rebased to 2016 PPP dollars using the ratio of the 2016 US GDP deflator to the 2005 US GDP deflator taken from Williamson (2019).

Figure 2

The denominator used to calculate the CGIAR spending shares is total (i.e., national research agencies and CGIAR) expenditures.

Figure 3

Expenditures series

Founding centers are IRRI, CIMMYT, CIAT, and IITA. First-expansion centers focused on crop and livestock productivity and include ICRISAT, CIP, ILRI (formed by the 1995 merger of ILRAD and ILCA), Biodiversity/IPGRI, African Rice/WARDA, and ICARDA. Second-expansion centers focused on issues other than crop and livestock productivity and include IFPRI and ISNAR, World Agroforestry/ICRAF, IWMI, WorldFish/ICLARM, and CIFOR.

Restricted versus unrestricted funds

Prior to 1988, funds are not split into "restricted" and "unrestricted." Rather they are split into "agenda" and "non-agenda." Therefore, we used the rate of change of "agenda" and "non-agenda" funds to backcast the "restricted" and "unrestricted" series for the years prior to 1988. From 1988 to 2010 data are split into "restricted" and "unrestricted."

In 2011, the CGIAR Research Programs (CRPs) became the main organizational mechanism for planning and conducting research and a new funding mechanism was introduced. Donors fund the CRPs by way of three funding windows:

(1) Window 1 – Contributions are received without donor restrictions. The Fund Council sets overall priorities and makes specific decisions about the use of Window-1 Funds such as allocation to CGIAR Research Programs (CRPs), payment of System Costs, and any other use required to achieve the CGIAR mission.

(2) Window 2 – Contributions are designated by Fund Donors to one or more specific CRPs. Once Window 2 funds are allocated to a given CRP, they flow to the Lead Center implementing the CRP.

(3) Window 3 – These are contributions Fund Donors wish to allocate to specific Centers. Neither the Consortium nor the Fund Council make decisions about the use of Window-3 funds. Within two years after the CGIAR Fund's establishment, the Fund Council will review the use of Window3 funds in consultation with the Consortium Board. (*CGIAR Financial Report 2011*, 2012).

Total CGIAR revenue is the sum of CRP and non-CRP revenue. CRP revenue comes from CRP Windows 1, 2, and 3 as well as from bilateral funds. Non-CRP revenue comes from Window 3, bilateral, system entities, special initiatives, and other partner programs (see, e.g., CGIAR 2015, Tables 11 and 12).

From 2011 onward, we estimated unrestricted funds as follows.

Version 1: Data on revenues from CRPs and non-CRPs were taken from *CGIAR Financial Reports* 2011-2016. Non-CRP revenue was further split into "restricted" and "unrestricted." Restricted funds were calculated by subtracting "Total Grant Revenue" (i.e., the sum of CRP revenue and non-CRP grant revenue) from non-CRP unrestricted funds). Therefore, restricted funds include CRP revenue and non-CRP restricted revenue. This concords with the view of Denyse Faulkner from the CGIAR secretariat, who noted that "All CRP funds are restricted."

Version 2: "Unrestricted" funds are the sum of W1 funds that we estimated and unrestricted non-CRP funds that were reported in *CGIAR Financial Reports* 2011–2016.

Version 3: Table 12 in the *CGIAR Financial Report* 2016 reports expenditures split into restricted, unrestricted, system entities and special initiatives, and extraordinary expenditures. We assumed that the sum of "system entities and special initiatives," "extraordinary expenditures," and "unrestricted" represent "unrestricted" funds.

Figure 4

From 2000 onward (see *CGIAR Financial Report* 2004, Table A5.1), the research program categories changed slightly. The new categories are "Germplasm improvement," "Sustainable production," "Germplasm collection," "Improving policies," and "Strengthening NARS." The procedure we used to map the more recent categories into the earlier categories concords with that used by Elven and Krishnan (2018, p. 16).

The numbers on the top of the bars represent average annual total CGIAR expenditures for the respective periods expressed in millions of 2016 U.S. dollars.

Figure 5

In 2016, CRP funds accounted for 84% of CGIAR total revenue. Cereals are the sum of the funds from the following CRPs: rice, wheat, maize and dryland cereals.

The numbers on the tops of the bars represent average annual total CGIAR expenditures for the respective periods in millions of 2016 US dollars.

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Figure 6

CWANA denotes Central and West Asia and North Africa, SSA is Sub-Saharan Africa, LAC is Latin America and the Caribbean. Spending amounts represent the average annual expenditures across centers for the respective periods.

Figure 7

U.S. foundations include the Bill and Melinda Gates Foundation, Ford Foundation, Rockefeller Foundation, Kresge, and Kellogg Foundations.

Other donors include "Other foundations and organizations," "Challenge program," "multi donor programs" "private donors," "academic and research," "non-member and miscellaneous donors," "2020 Resilience Conference," "Global Nutrition Report," "West Africa Agricultural Productivity Program," and "World Congress on Agroforestry."

Figure 8

"Other" includes evaluations for "other developed" countries, West Asia, North Africa, and "global" studies. "Multinational" includes observations that span multiple countries and, perhaps, multiple regions.

Figure 9

No additional notes.

Figure 10

See Table 7 for details.

Figure 11

No additional notes.

Figure 12

No additional notes.

Box 3

CGIAR (1973) describes the "Budgeting and Accounting Procedures and Practices of International Agricultural Research Centers." For the period 1971-1993, CGIAR expenditures are broken down into "core" versus "non-core" or "special project" expenditures. CGIAR (1973, p. 2) notes that "The core program of a center or institute is a set of long-term activities designed to progress toward the center's fundamental objectives of research and training, as described in a basic statement approved by the center's governing board (which some centers refer to as their 'mandate'). The core program need not be confined to the headquarters of an institute." CGIAR (1973, p. 3) notes that the recurring (i.e., core) program expenditures are to be reported under the following seven "program" headings: research; conferences and training activities; library, documentation and information services; service operations; general administration; general operating; and all other. "Research" expenditures include "… the cost of study and investigation aimed at the improvement of crops, animals or agricultural systems" CGIAR (1973, p. 2).

CGIAR (1973, pp. 4-5) notes that "Special projects usually are highly specific in purpose and limited to a definite span of time. They are often financed by a single donor, and may or may not be continued or renewed when the donors support comes to an end. In contrast to the content of a core program, the content of a special project is often stipulated by the donor and/or by the client. The project usually consists, basically, of making practical use of a center's research results or its expert staff in a single country (which may or may not be the center's host country. … A large class of special projects is composed of outreach programs. … Another class of special projects is composed of training exercises carried out for the benefit of trainees from a particular country or region…"

In addition, "core restricted grants" consist of "… funds made available [by particular donors] for specific elements in the core program, including the support costs of these elements" (CGIAR 1973, p. 7).

Beginning in 1994 "core" expenditures were designated as expenditures on the "research agenda," while "non-core" or "special project" spending was designated as "complementary" expenditures (see. e.g., CGIAR 1995, Table III-1). This designation persisted in the CGIAR financial reports to 2010. Beginning in 2011 the reports differentiate expenditures into CRP (CGIAR Research Programs) and "Center Own Programs" (see, e.g., CGIAR 2012, Table 1), although spending by center was also reported according to an "agreed agenda" categorization (see, e.g., CGIAR 2012, Table A3.1). The CRP categorization continued to 2018, although phase I of the CRPs ended on December 31, 2016 (CGIAR 2017, p. 1).

Supplemental Notes to Tables

All regional or per capita income groupings of countries formed using the classification based on 2018 GNI per capita taken from World Bank (2019).

Table 1

Poverty Gap (PG) is the mean shortfall of income from the poverty line. The mean is based on the entire population, treating the nonpoor as having a shortfall of zero, and the shortfall is expressed as a proportion of the poverty line. Squared Poverty Gap (SPG) is the mean squared shortfall of income from the poverty line. The mean is based on the entire population, treating the nonpoor as having a shortfall of zero, and the shortfall is expressed as a proportion of the poverty line (and then squared).

Table 2

Pulses include bambara beans, dry beans, dry broad beans, dry horse beans dry, chick peas, dry cow peas, lentils, lupins, dry peas, pigeon peas, pulses nes (not elsewhere specified), and vetches; dairy includes whole fresh milk from buffalo, camel, cow, goat, and sheep; Beef and Pork refer to indigenous cattle meat and pig meat respectively; poultry included indigenous meat from chicken, duck, geese, turkey, bird nes, hen eggs in shell and other bird eggs in shell.

Table 3

In the *CGIAR Financial Reports,* the data from 1972 to 1982 represented agreed research agenda funds. From 1983 to 2010, data represent total funds (i.e., agenda and non-agenda). We estimated the 1972 to 1982 data by backcasting the 1983 total funding to 1972 using the annual rates of change from the 1972-1982 agreed research agenda data.

1983 to 2010 data are taken from various annual *CGIAR Financial Reports*.

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2011-2016 were estimated. Data for these years represent W3 (Window 3) and bilateral funds plus an estimate of W1 and W2 contributions by country. We used the share of each donor contribution in total W1 and W2 on reported grant income to each center's approved research agenda from W1 and W2 funds to estimate W1 and W2 contribution by country. We did this because the donor contribution to W1 and W2 and the reported grant income by centers are not directly comparable due to a difference in accounting method. For example, in the 2014 *CGIAR Financial Report*, total Window 1 and 2 funds as reported in Table A1.1 (a table showing "CGIAR grant income to Centers for the Approved Research Agenda" by donor) was 382 million U.S. dollars in 2014. In Table 3 (showing "Donor contributions to the CGIAR fund") of the same report, the total Window 1 and 2 funds was 300 million U.S. dollars in 2014. According to Albin Hubscher, CGIAR Consortium, the difference came in part from cash versus accrual accounting methods. Donor funds are accounted on a cash basis, whereas centers account on an accrual basis. In addition, Albin Hubscher advised that disbursements of funds made in the current year for the previous year's funding may also explain the discrepancies in the amounts reported in the two tables. For example, an amount of 120.3 million U.S. dollars was paid in 2014 for costs encumbered in 2013 (see 2014 *CGIAR Financial Report,* Table 6).

Table 7

Includes conditional predictions, specifically the expected value of the BCR for the respective aggregate, conditional on the values of the explanatory variables all having been set at their means for the relevant subset of the data (for instance, if it is the expected value for the BCR for IRRI R&D, it is evaluated at the means of the explanatory variables for the observations of BCRs pertaining to IRRI).

Table 8

All data and estimates pertain to year 2016. The aggregated TFP was estimated by weighted averages of country-specific TFP using USDA data (2019). Weights were based on country-specific shares of AgVOP in corresponding region and income groups. The total benefit from TFP growth for each group was calculated by multiplying the respective AgVOP by the change in TFP, from 1961 to 2016, divided by TFP in 2016 (i.e., value foregone if TFP in 2016 were to revert to TFP in 1961). Countries classified as "High Income" are included in that category and are excluded from the totals "By region" (e.g., Japan is excluded from Asia & Pacific and, among others, Slovenia is excluded from EE &FSU).

Table 9

All benefit estimates reported in this table were recovered as a time series in nominal U.S. dollars from the cited studies as described below, deflated to 2016 dollar values using the U.S. GDP deflator from Williamson (2019) and BEA (2020), then expressed in 2016 present value benefit terms, PVB_t^{2016}. For benefits, B_t, in year $t < 2016$, $PVB_t^{2016} = B_t\,(1+r)^{(2016-t)}$, where r is the discount rate (5%), while for benefits, B_t, in year $t > 2016$, $PVB_t^{2016} = B_t / (1+r)^{(t-2016)}$. The table reports the sum of PVB_t^{2016} for the years in the respective periods.

Byerlee and Moya (1993)

Byerlee and Moya (1996) did not report a time-series of research benefits, but Figure 22 of their report plotted *discounted net* benefits (i.e., discounted research benefits minus research costs attributable to CGIAR and NARS research) expressed in millions of 1990 U.S. dollars for the period 1968-1990 attributed to national and international wheat breeding research in developing countries in the post-Green Revolution period. We digitally recovered the discounted net benefit series (1968-1990) from the figure using Engauge Digitizer software. These values were rebased from 1990 to nominal U.S. dollars using the Producer Price Index (PPI) taken from BLS (2020) given Byerlee and Moya's (1996, p. 48) use of a U.S wholesale price index—which was scaled by the factor $1 / (1+r)^{(t - 1990)}$, $r = 0.08$ (Byerlee and Moya 1996, p. 5) to recover an undiscounted series—and then deflated to 2016 U.S. dollars using the US GDP deflator.

Byerlee and Moya (1996, chapter 4) discuss the NARS and CGIAR costs included in their net benefit calculations. To recover an estimate of gross benefit from the net benefit series required estimating the relevant CGIAR and NARS research costs. To do this we used the following information. Heisey et al. (2003, Table 4.2) report an estimate of wheat genetic improvement research expenditures for developing country NARSs for the years 1965, 1970, 1975, 1980, 1985, and 1990 expressed in 1990 U.S. dollar values (see also similar research expenditure estimates for the years mid-1970s and 1990 reported in Byerlee and Moya (1996, Table 1) and for the years 1967-1999 are plotted in Marasas et al. (2004, Figure 6). We linearly interpolated the "world" (actually developing country) research cost data from Heisey et al. (2003, Table 4.2) and rebased the interpolated series from 1990 to 2016 U.S. dollar values using the U.S. GDP deflator. We used the Engauge Digitizer software to recover a 1990 dollar denominated series of CIMMYT wheat improvement expenditures from Byerlee and Moya (1996, Figure 5) for the period 1967-1993, and then used the U.S. PPI and GDP deflators to generate a 2016 U.S. dollar value series. We assumed the discounted net benefits plotted in Figure 22 only netted out CIMMYT (exclusive of ICARDA)-related costs based on the statement by Byerlee and Moya (1996, pp.47-48) that "Costs were based on estimates of research expenditures by NARSs and CIMMYT, discussed in Chapter 4.14." The notes to Byerlee and Moya (1996, Figure 22) indicated that the plotted net benefits (for the period 1968-1990) were based on research costs for the period 1968-1981, and so we recovered a gross benefit series for the period 1977-1990—the period for which Byerlee and Moya (1996, Figure 22) indicated benefits were included in their plotted net benefit series—by adding back research costs for the period 1977-1981 where (gross) costs and benefits overlapped.

Sanint and Wood (1998)

In their regional assessment of the benefits attributable to NARS- and CGIAR-related rice research, Sanint and Wood (1998, Table 7) report a simulated series of gross annual research benefits for Latin America and the Caribbean for the period 1967-1995. The reported series was rebased from a 1995 dollar value to a nominal then 2016 dollar denominated series using the U.S. GDP deflator.

Fuglie et al. (1999)

Fuglie et al. (1999, Table 5) report a series of research benefits and costs for the period 1998-2020 associated with the use of virus free sweet potato seed in Shandong Province, China. We use a "net benefit" series, which is gross benefits minus relevant NARS- and CIP-related research, extension, and seed multiplication costs. The Fuglie et al. series is expressed in 1999 U.S. dollars (Fuglie 2020) and was converted to a nominal then 2016 dollar denominated series using the U.S. GDP deflator.

Zeddies et al. (2001)

Zeddies et al. (2001, Table 2) report a benefit series for 27 African countries associated with the biological control of cassava mealybug (*P. manihoti*). We used their "scenario 1" benefit series, consisting of their baseline benefit estimates for the period 1982-2013 using a farm gate price of U.S.$90 per ton of cassava. Zeddies et al. (2001, Table 2 notes) indicates the series is reported in

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1994 present value terms. To recover an undiscounted nominal U.S. dollar series, we used a U.S. GDP deflator scaled by the factor $1/(1+r)^{(1994-t)}$, $r = 0.06$ (Zeddies et al. 2001, Table 2) for the years prior to 1994, and, in this particular case, by $1/(1+r)^{(t-1994)}$ for the years after 1994. The U.S. GDP deflator was again used to rebase the series in 2016 U.S. dollar values.

Hossain et al. (2003)

Page 96 in Hossain et al. (1999, p. 96) noted that "In the late 1990s … the annual gains from the adoption of modern [rice] varieties now stand at about US$10.8 billion." Gollin (2020) concurred that the $10.8 billion in benefits pertains to a single year, which could be 1999 (and expressed in 1999 dollar values).

To impute a time-series of benefits entailed some projections. Hossain et al. (1999, p. 72) noted that 12 South and Southeast Asian countries were included in their study, specifically Bangladesh, Cambodia, India, Indonesia, Laos, Malaysia, Myanmar, Pakistan, the Philippines, Sri Lanka, Thailand, and Vietnam. We extracted 1999 rice production data for each of these countries from FAO (2020), and using FAO country classifications grouped the countries into a South Asia aggregate (Bangladesh, India, Pakistan, and Sri Lanka) and a Southeast Asia aggregate (Cambodia, Indonesia, Laos, Malaysia, Myanmar, Philippines, Thailand, and Vietnam). Assuming rice benefit and production shares are geographically congruent, we used the respective 1999 production shares to parse the $10.8 billion dollars of benefits into corresponding South ($5.9 billion) and Southeast Asia ($4.9 billion) sub-totals for the year 1999.

Hossain et al. (1999, Table 5.7) also report the estimated rate of varietal adoption (in terms of the share of harvested rice area sown to modern varieties) for South and Southeast Asia for each of the years 1996, 1976, 1981, 1986, 1991, and 1999. We linearly interpolated these adoption rates for the intervening years and used the time-series of adoption percentages to backcast the respective 1999 benefit totals for the period 1966-1999. The resulting 1999 U.S. dollar denominated benefit series was rebased to 2016 using the U.S. GDP deflator.

Johnson et al. (2003a)

Johnson et al. (2003a) provide evidence on the adoption and impact of improved bean varieties (associated with CIAT and NARS research) and report that "In 1998, the gross annual value of increased production [in the Latin American and Caribbean region] was US$177.5 million [1990 U.S. dollars], and the cumulative value since the 1970s is over a billion dollars (p. 269)." The published study does not contain sufficient information for us to recover the underlying time series of benefits, but fortunately the lead author, Nancy Johnson, graciously provided us with the unpublished time-series of country-level estimates used to generate the published benefit aggregates (Johnson 2020). These files included information from which we could recover annual benefit estimates associated with varietal improvements for the period 1979-1998 for 12 Latin American and Caribbean countries, specifically, Argentina, Bolivia, Brazil, Colombia, Costa Rica, Ecuador, El Salvador, Guatemala, Honduras, Nicaragua, Panama, and Peru, and seven African countries, specifically Congo, DR, Ethiopia, Kenya, Malawi, Rwanda, Tanzania, and Uganda. The reported benefits are "net benefits" according to Johnson (2003, p.269), which states "Reported yield gains are net gains associated with improved varieties. Yield gains associated with increased input or other changes in management practices are not included."

The primary benefit data for Latin America were in 1990 U.S. dollar values and for Africa were in nominal dollars. The Latin America data were converted to a nominal time series using a producer price index included in Johnson (2020). Both sets of data were then converted to 2016 U.S. dollar value using the U.S. GDP deflator.

***Johnson et al. (2003b*)**

Johnson et al. (2003b) provide evidence on the adoption and impact of improved cassava varieties (associated with CIAT and NARS research) and report that "The total value of the incremental production due to improved cassava cultivars was estimated at US$327.5 million in 1998. Benefits were highest in the DR Congo, followed by Nigeria (p. 351)" and "[For Asia]… the associated increase in production among the five countries was 1.7 million tons, worth over US$51.2 million at the standard root price. The increased starch content per root, for which farmers received a price premium, was worth an additional US$48.2 million, bringing the total value associated with the new varieties to US$99.5 million in 1998 (p.352)."

The published study does not contain sufficient information for us to recover the underlying time series of benefits, but fortunately the lead author Nancy Johnson graciously provided the unpublished time-series of country-level estimates used to generate the published benefit aggregates (Johnson 2020). These files included information from which we could recover annual benefit estimates associated with varietal improvements for the period 1978-1998 for eight Latin American and Caribbean countries, specifically, Brazil, Colombia, Cuba, Dominica Republic, Ecuador, Haiti, Mexico, and Panama, and four Asian countries, specifically, China, Indonesia, Philippines, and Vietnam. The Asian data included benefits attributable to both root and starch production, while the Latin American data reported only benefits derived from increased root production.

For Latin America the primary benefit data were in nominal U.S. dollars. For Asia, the preponderance of the primary benefit data were in 1990 U.S. dollar values. Data for some Asian countries in Johnson (2020) did not directly reconcile with summary data in Johnson et al. (2003b), and we reconciled these anomalies by consulting with Nancy Johnson. All series were converted to 2016 U.S. dollar values using the U.S. GDP deflator.

Marasas et al. (2004)

Marasas et al. (2004, Table 6) report discounted gross benefits associated with the adoption of leaf rust resistant wheat varieties grown throughout seven CIMMYT mega (and sub mega) environments (spanning the developing world) where spring bread wheats were grown during the period 1973-2007. The reported discounted gross benefits for the period 1973-2007 totaled $7,460.9 million (1990 U.S. dollars). Corresponding totals were also reported for each mega environment. To recover a time series of benefits, we used the following procedure.

We used the Engauge Digitizer software to recover the area shares planted to CIMMYT-related spring bread wheats for each of the seven mega environments plotted in Marasas et al. (2004, Figure 3). A weighted version of these adoption shares was used to parsed the aggregate discounted (present value) benefits into yearly values of undiscounted 1990 U.S. dollar values for the respective mega environments, where for the years prior to 1990 the weights were $(1+r)^{(1990-t)}$, $r = 0.05$ (Marasas 2004, Table 6 notes) for the years prior to 1990 and $1/(1+r)^{(t-1990)}$ for the years after 1990. The U.S. GDP deflator was used to rebase the series to 2016 U.S. dollar values.

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Myrick (2016)

Alwang (2020) provided unpublished data files used to develop the estimates reported by Myrick (2016). The data files report two time-series of benefits for the period 1996-2015—specifically benefit estimates derived by way of a single market model, one open, one closed to trade. We used the open-market benefits series. Cross-referencing this unpublished time series against the total benefit estimates reported in Myrick (2016, Table 11), we determined the published data were incorrectly denominated as constant 2015 priced benefits, whereas they are summed nominal benefits. The nominal benefit time-series expressed in U.S. dollars was deflated to 2016 values using the U.S. GDP deflator.

Table 10

No additional notes.

Table 11

All data and estimates pertain to 2016. Aggregated growth rates in inputs and outputs for regions and income groups were calculated as a weighted average of national growth rates, where the weights are a two-year moving average of current and lagged shares of AgVOP. TFP was recovered as $TFP_t = TFP_{t-1}$*exp(d ln Q_t – d ln X_t), with TFP_{1961} = 100. The total benefit in year *t* (for *t* = 1962–2016) from TFP growth since 1961, for each country, was calculated by multiplying the respective AgVOP by the corresponding change in TFP, from 1961 to year *t*, divided by TFP in year *t* (i.e., value foregone if TFP in year *t* were to revert to TFP in 1961). Regional totals were derived by summing across countries. The present values of gains were calculated by summing up discounted annual total gains (in periods 1961-2016 and 1961-2026, all discounted to 2016) with a 5% (or 3%) discount rate. The TFP data end in 2016. We projected total gains in 2016 forward for years 2017–2026, constant in real terms. The present values of expenditures were calculated by summing up discounted annual expenditures (in periods 1960-2015 and 1960-2006, all discounted to 2016) with a 5% (or 3%) discount rate. Expenditures by the CGIAR and public agricultural R&D agencies in developing countries were included.

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ANNEXES

Credit: CGIAR System Organization

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Annex A: Annotated Tabulation and Listing of CGIAR Studies Included in the Meta-Analysis

Annex Table 1: Characteristics of the source meta-data for CGIAR-related R&D

ID	Pub. Year	Authors	CGIAR Center	Commodity	Country/Region	IRR No. obs	IRR Min.	IRR Mean	IRR Median	IRR Max.	BCR No. obs	BCR Min.	BCR Mean	BCR Median	BCR Max.
						count	*percent per year*				*count*	*ratio*			
1	1978	Evenson and Flores	IRRI	Rice	Africa	11	32.0	79.7	79.0	102.0	11	8.0	58.0	34.3	146.0
2	1978	Flores-Moya, Evenson, and Hayami	IRRI	Rice	Philippines, Asia/Pacific	5	27.0	33.0	32.0	46.0	5	4.0	10.2	6.0	30.0
4	1982	Barker and Herdt	IRRI	Rice	South Asia	4	35.0	50.0	40.0	85.0	4	5.0	7.8	6.6	12.9
7	1986	Unnevehr	IRRI	Rice	Indonesia, Philippines	2	29.0	33.0	33.0	37.0	2	8.0	8.5	8.5	9.0
13	1990	Unnevehr	IRRI	Rice	Philippines	1	61.0	61.0	61.0	61.0	1	49.0	49.0	49.0	49.0
20	1994	Moya et al.	IRRI	Rice	The Philippines	1	177.0	177.0	177.0	177.0	1	5.1	5.1	5.1	5.1
37	1998	Hossain	IRRI	Rice	Bangladesh	0					1	16.6	16.6	16.6	16.6
94	2009	Revilla-Molina	IRRI	Rice	China	1	160.0	160.0	160.0	160.0	1	22.0	22.0	22.0	22.0
100	2010	Templeton and Jamora	IRRI	Policy research	The Philippines	2	57.0	57.0	57.0	57.0	2	56.0	81.0	81.0	106.0
101	2011	Brennan and Malabayabas	IRRI	Rice	Philippines, Indonesia, Vietnam	1	28.0	28.0	28.0	28.0	1	21.7	21.7	21.7	21.7
107	2013	Rejesus, Martin, and Gypmantasiri	IRRI	Rice	Vietnam, Philippines, Bangladesh	5	15.2	42.6	47.4	69.1	6	0.6	10.7	10.0	21.7
15	1993	Byerlee	CIMMYT	Wheat	Pakistan	4	16.0	22.5	23.5	27.0	0				
16	1993	Byerlee and Moya	CIMMYT	Wheat	Developing countries	3	36.0	46.0	48.0	54.0	0				
17	1993	Macagno and Gómez-Chao	CIMMYT	Wheat	Argentina	1	32.0	32.0	32.0	32.0	0				
18	1994	Byerlee and Traxler	CIMMYT	Wheat	West Asia/North Africa	2	53.0	53.5	53.5	54.0	0				
21	1995	Byerlee and Traxler	CIMMYT	Wheat	South Asia	3	37.0	45.7	48.0	52.0	0				
86	1996	Makanda and Oehmke	CIMMYT	Wheat	Kenya	2	3.0	7.5	7.5	12.0	0				
39	1998	Smale et al.	CIMMYT	Wheat	Mexico	1	40.0	40.0	40.0	40.0	0				
40	1999	Byerlee and Traxler	CIMMYT	Wheat	Developing countries, South Asia, Latin America and the Caribbean, West Asia/North Africa, Sub-Saharan Africa	5	23.0	63.8	71.0	91.0	0				
46	1999	Maredia and Byerlee	CIMMYT	Wheat	Developing countries, Global	14	7.0	24.9	22.0	43.0	0				
43	1999	Gomez	CIMMYT	Maize	Central America and the Caribbean	0					9	0.1	12.4	11.1	33.3
59	2001	Zegeye, Tesfahun and Anandajayasekeram	CIMMYT	Maize	Ethiopia	1	29.0	29.0	29.0	29.0	0				

Annex Table 1: Characteristics of the source meta-data for CGIAR-related R&D (continued)

						IRR					BCR				
ID	Pub. Year	Authors	CGIAR Center	Commodity	Country/Region	No. obs	Min.	Mean	Median	Max.	No. obs	Min.	Mean	Median	Max.
						count	*percent per year*				*count*	*ratio*			
66	2002	Tomasini	CIMMYT	Wheat	Brazil, Mexico	2	69.0	73.0	73.0	77.0	2	7.1	10.0	10.0	12.9
73	2003	Marasas, Smale and Singh	CIMMYT	Wheat	Developing countries	1	41.0	41.0	41.0	41.0	1	27.0	27.0	27.0	27.0
80	2006	González-Estrada et al.	CIMMYT	Wheat	Mexico	1	26.9	26.9	26.9	26.9	1	13.5	13.5	13.5	13.5
84	2007	González-Estrada et al.	CIMMYT	Maize	Mexico	1	22.7	22.7	22.7	22.7	1	9.4	9.4	9.4	9.4
89	2008	Barkley, Nalley and Crespi	CIMMYT	Wheat	Mexico	1	51.5	51.5	51.5	51.5	1	15.0	15.0	15.0	15.0
79	2005	Lantican et al.	CIMMYT, ICARDA	Wheat	Global	0					2	50.0	220.0	220.0	390.0
111	2016	Lantican et al.	CIMMYT, ICARDA	Wheat	Global	0					1	73.0	73.0	73.0	73.0
92	2009	Alene et al.	CIMMYT, IITA	Maize	Nigeria, Benin, Togo, Africa, Côte d'Ivoire, Senegal, Ghana, Cameroon, Burkina Faso, Mali	10	28.0	48.8	41.5	74.0	10	10.0	23.0	16.0	84.0
85	2007	Laxmi, Erenstein and Gupta	CIMMYT, Rice-Wheat Consortium	Wheat	India	1	57.0	57.0	57.0	57.0	1	39.0	39.0	39.0	39.0
3	1978	Scobie and Posada-Torres	CIAT	Rice	Colombia	6	79.0	91.0	91.5	101.0	6	35.0	84.5	70.0	148.0
6	1986	Gargiulo	CIAT	Beans	Argentina	6	28.5	40.2	42.6	50.6	6	1.3	2.5	1.9	5.4
11	1990	Jarvis and Sere	CIAT	Pasture	Latin America and the Caribbean	2	16.0	21.0	21.0	26.0	0				
12	1990	Ruiz de Londono and Janssen	CIAT	Beans	Peru	3	15.2	22.2	22.5	29.0	3	1.2	2.3	2.6	3.2
51	2000	Mantilla-Blanco et al.	CIAT	Beans	Colombia	1	47.0	47.0	47.0	47.0	0				
65	2002	Rivas	CIAT	Forages	Brazil	1	29.4	29.4	29.4	29.4	0				
71	2003	Johnson, Pachico and Wortmann	CIAT	Beans	Latin America and the Caribbean	1	18.0	18.0	18.0	18.0	0				
74	2003	Mather et al.	CIAT	Beans	Honduras	1	41.2	41.2	41.2	41.2	0				
82	2007	Dalton et al.	CIAT	Cassava	Vietnam	1	41.2	41.2	41.2	41.2	0				
87	2007	Mooney	CIAT	Beans	Ecuador	3	13.0	29.3	29.0	46.0	0				
103	2012	Reyes	CIAT	Beans	Costa Rica, El Salvador, Honduras, Nicaragua, Ecuador	5	-5.0	29.6	37.0	42.0	0				

Annex Table 1: Characteristics of the source meta-data for CGIAR-related R&D (continued)

ID	Pub. Year	Authors	CGIAR Center	Commodity	Country/Region	IRR No. obs	IRR Min.	IRR Mean	IRR Median	IRR Max.	BCR No. obs	BCR Min.	BCR Mean	BCR Median	BCR Max.
						count	*percent per year*				*count*	*ratio*			
108	2013	Robinson and Srinivasan	CIAT, CIP	Cassava, potato	Vietnam, China	2	57.0	201.0	201.0	345.0	0				
9	1988	Norgaard	IITA	Cassava	Africa	0					1	149.0	149.0	149.0	149.0
24	1995	Lubulwa	IITA	Cassava	Africa	1	12.8	12.8	12.8	12.8	0				
58	2001	Zeddies et al.	IITA and others	Cassava	East Africa	0					1	199.0	199.0	199.0	199.0
91	2009	Akinola et al.	IITA	Maize	West Africa	8	17.0	31.1	30.0	43.0	8	3.0	11.0	8.5	24.0
104	2013	Ayanwale et al.	IITA	Maize, millet, sorghum	Nigeria	6	22.0	30.5	29.5	38.0	6	9.2	24.2	20.0	44.0
106	2013	Oleke et al.	IITA	Coconut	Benin	1	13.2	13.2	13.2	13.2	1	1.0	1.0	1.0	1.0
68	2003	De Groote et al.	IITA, GTZ	Others	Benin	0					1	124.0	124.0	124.0	124.0
61	2002	Bokonon-Ganta, de Groote, and Neuenschwander	IITA, GTZ, CABI, FAO, and others	Mango	Benin	0					1	145.0	145.0	145.0	145.0
64	2002	Kristjanson et al.	IITA, ILRI, NARS	Cowpea	West Africa	1	71.0	71.0	71.0	71.0	1	63.2	63.2	63.2	63.2
14	1993	Ahmed, Masters, and Sanders	ICRISAT	Sorghum	Sudan	9	13.2	25.5	26.0	33.7	0				
23	1995	Joshi and Bantilan	ICRISAT	Groundnuts	India	4	9.9	20.6	17.3	37.9	0				
27	1996	Bantilan and Joshi	ICRISAT	Pigeon, chickpea	India	1	64.8	64.8	64.8	64.8	0				
34	1996	Yapi et al.	ICRISAT	Sorghum, millet	Mali	2	50.0	60.0	60.0	70.0	0				
35	1997	Anandajayasekeram et al.	ICRISAT	Millet and sorghum	Southern Africa	2	5.0	9.5	9.5	14.0	0				
38	1998	Joshi and Bantilan	ICRISAT	Groundnuts	India	1	25.3	25.3	25.3	25.3	1	9.4	9.4	9.4	9.4
48	1999	Rohrbach et al.	ICRISAT	Millet	Namibia	1	50.0	50.0	50.0	50.0	0				
49	1999	Yapi et al.	ICRISAT	Sorghum	Chad	1	95.0	95.0	95.0	95.0	0				
50	1999	Yapi et al.	ICRISAT	Sorghum	Cameroon, Chad	2	75.0	85.0	85.0	95.0	0				
102	2012	Macharia et al.	ICRISAT	Chickpeas	Ethiopia	1	55.0	55.0	55.0	55.0	1	5.0	5.0	5.0	5.0

Annex Table 1: Characteristics of the source meta-data for CGIAR-related R&D (continued)

ID	Pub. Year	Authors	CGIAR Center	Commodity	Country/Region	IRR No. obs	IRR Min.	IRR Mean	IRR Median	IRR Max.	BCR No. obs	BCR Min.	BCR Mean	BCR Median	BCR Max.
						count	*percent per year*				*count*	*ratio*			
109	2014	Bantilan et al.	ICRISAT	Chickpea	India	1	28.0	28.0	28.0	28.0	1	183.5	183.5	183.5	183.5
110	2014	Nedumaran et al.	ICRISAT	Groundnuts	Global	1	50.0	50.0	50.0	50.0	0				
112	2016	Tsusaka et al.	ICRISAT	Groundnuts	Malawi	1	22.0	22.0	22.0	22.0	0				
45	1999	Kristjanson et al.	ICRISAT, ILRI, NARS	Sorghum, millet	India	1	28.0	28.0	28.0	28.0	1	15.0	15.0	15.0	15.0
5	1984	Monares	CIP	Potato	Rwanda	1	40.0	40.0	40.0	40.0	0				
10	1990	Horton et al.	CIP	Potato	Tunisia	1	80.0	80.0	80.0	80.0	0				
22	1995	Fuglie	CIP	Potato	Tunisia	3	45.0	61.0	64.0	74.0	3	6.7	16.3	16.7	25.6
26	1996	Alvarez et al.	CIP	Potato	Dominican Republic	1	27.0	27.0	27.0	27.0	0				
28	1996	Bofu et al.	CIP	Potato	China	2	65.0	83.5	83.5	102.0	0				
29	1996	Chilver and Khatana	CIP	Potato	India	1	22.0	22.0	22.0	22.0	0				
30	1996	Fonseca et al.	CIP	Potato	Peru	1	26.0	26.0	26.0	26.0	0				
31	1996	Khatana et al.	CIP	Potato	India	4	10.0	22.3	23.0	33.2	0				
32	1996	Ortiz et al.	CIP	Potato	Peru	1	30.0	30.0	30.0	30.0	0				
36	1997	Chilver, El-Bedewy, and Rizk	CIP	Potato	Egypt	1	28.0	28.0	28.0	28.0	0				
42	1999	Fuglie et al.	CIP	Sweet potato	China	1	202.0	202.0	202.0	202.0	0				
53	2000	Maza et al.	CIP	Sweet potato	Peru	1	65.0	65.0	65.0	65.0	0				
56	2001	Fuglie et al.	CIP	Potato	Vietnam	3	28.6	36.4	38.9	41.6	3	1.4	2.6	2.6	3.7
60	2002	Barea and Bejarano	CIP	Potato	Bolivia	3	48.0	56.0	50.0	70.0	0				
62	2002	Calderon, Gandarillas, and Zuger	CIP	Potato	Bolivia	1	54.0	54.0	54.0	54.0	0				
63	2002	Fonseca et al.	CIP	Potato	Peru	1	44.0	44.0	44.0	44.0	0				
69	2003	Gabriel, Almanza, and Gandarillas	CIP	Potato	Bolivia	1	47.0	47.0	47.0	47.0	0				
70	2003	Gandarillas	CIP	Potato	Bolivia	1	29.0	29.0	29.0	29.0	0				
75	2003	Walker et al.	CIP	Potato	Developing countries	1	15.0	15.0	15.0	15.0	0				
77	2004	Zuger	CIP	Potato	Peru	1	31.0	31.0	31.0	31.0	0				

Annex Table 1: Characteristics of the source meta-data for CGIAR-related R&D (continued)

						IRR					BCR				
ID	Pub. Year	Authors	CGIAR Center	Commodity	Country/Region	No. obs	Min.	Mean	Median	Max.	No. obs	Min.	Mean	Median	Max.
						count	*percent per year*				*count*	*ratio*			
67	2003	Aw-Hassan et al.	ICARDA	Barley	Algeria, Ecuador, Egypt, Ethiopia, Iraq, Jordan, Morocco, Syria, Tunisia	9	22.0	32.2	31.0	51.0	0				
88	2007	Shideed et al.	ICARDA	Crops & livestock	Tunisia, Morocco	4	7.0	25.5	22.5	50.0	0				
95	2010	Ahmed et al.	ICARDA	Policy research	Syria	1	70.0	70.0	70.0	70.0	1	41.0	41.0	41.0	41.0
47	1999	Ryan	IFPRI	Policy research	Vietnam	0					3	56.0	92.3	77.0	144.0
52	2000	Babu	IFPRI	Policy research	Bangladesh	1	98.0	98.0	98.0	98.0	1	22.2	22.2	22.2	22.2
76	2004	Ryan and Meng	IFPRI	Policy research	Bangladesh	2	64.0	80.0	80.0	96.0	0				
96	2010	Behrman	IFPRI	Policy research	Mexico	4	4.9	21.1	11.1	57.1	0				
81	2007	Ajayi et al.	ICRAF	Maize	Zambia	3	3.2	13.1	15.2	20.8	0				
99	2010	Raitzer	CIFOR	Policy research	Indonesia	0					2	1.0	3.6	3.6	6.2
41	1999	Elbasha, Thornton, and Tarawali	ILRI	Forage	West Africa	1	38.0	38.0	38.0	38.0	1	3.3	3.3	3.3	3.3
44	1999	Kristjanson et al.	ILRI	Dairy and beef	Africa	1	33.0	33.0	33.0	33.0	1	34.0	34.0	34.0	34.0
55	2001	Falconi et al.	ILRI and others	All livestock	Africa	1	32.0	32.0	32.0	32.0	1	5.1	5.1	5.1	5.1
57	2001	Rutherford, Odero, and Kruska	ILRI	Multiple crops	Ethiopia	0					1	0.0	0.0	0.0	0.0
97	2010	Kaitibie et al.	ILRI	Dairy	Kenya	1	55.0	55.0	55.0	55.0	0				
25	1995	Tré	WARDA	Rice	Sierra Leone	4	17.9	19.5	19.2	21.4	0				
78	2005	Briones et al.	WorldFish Center	Natural resources	East Asia, South Asia, Southeast Asia, West Asia/North Africa, Sub-Saharan Africa	0					24	1.3	29.0	22.7	100.0
83	2007	Dey et al.	WorldFish Center	Aquaculture, agriculture	Malawi	1	12.2	12.2	12.2	12.2	1	1.4	1.4	1.4	1.4
90	2008	Briones et al.	WorldFish Center	Aquaculture	East Asia, Latin America and the Caribbean, South Asia, Southeast Asia, Small Island Developing States, Sub-Saharan Africa, West Asia/North Africa	0					40	0.0	2.2	1.3	7.4

Annex Table 1: Characteristics of the source meta-data for CGIAR-related R&D (continued)

						IRR					BCR				
ID	Pub. Year	Authors	CGIAR Center	Commodity	Country/Region	No. obs	Min.	Mean	Median	Max.	No. obs	Min.	Mean	Median	Max.
						count	*percent per year*				*count*	*ratio*			
19	1994	Evenson	IARC	Rice	Global	0					2	25.5	27.0	27.0	28.5
71	2003	Johnson et al.	IARC	Cassava	Asia	2	9.0	15.5	15.5	22.0	0				
54	2000	Ramasamy et al.	IARC	Millet	India	1	27.0	27.0	27.0	27.0	0				
8	1987	Evenson	CGIAR	Maize, maize and staples, maize and cereals, cereals, staple crops	Latin America and the Caribbean, Sub-Saharan Africa, Asia/Pacific	5	35.0	53.0	65.0	65.0	0				
93	2009	Alene and Coulibaly	CGIAR	All crops	Benin, Botswana, Burkina Faso, Burundi, Cameroon, Central African Republic, Cote dIvoire, Ethiopia, Gambia, Ghana, Kenya, Lesotho, Madagascar, Malawi, Mali, Mauritania, Mozambique, Niger, Nigeria, Rwanda, Senegal, South Africa, Swaziland, Tanzania, Uganda, Zambia, Zimbabwe	27	5.0	45.9	50.0	82.0	0				
105	2013	Fuglie and Rada	CGIAR	All agriculture	Global	6	17.0	33.3	29.0	58.0	6	1.6	3.3	2.7	6.2

Source: Compiled by authors.

Notes: Country/region indicates location of performance of the evaluated CGIAR-related R&D, which may or may not concord with the location of the benefits attributable to that R&D.

Annex Table 2: Characteristics of the imputed BCRs for CGIAR-related R&D

ID	Pub. Year	Authors	CGIAR Center	Commodity	Country/Region	Imputed BCRs: No. obs	Min.	Mean	Median	Max.
						count		*ratio*		
1	1978	Evenson and Flores	IRRI	Rice	Africa	11	20.7	125.7	79.8	437
2	1978	Flores-Moya, Evenson, and Hayami	IRRI	Rice	Philippines, Asia/Pacific	5	8.9	23.3	13.6	68.8
4	1982	Barker and Herdt	IRRI	Rice	South Asia	4	11.4	19.4	17.4	31.4
7	1986	Unnevehr	IRRI	Rice	Indonesia, Philippines	2	16.4	20.6	20.6	24.7
13	1990	Unnevehr	IRRI	Rice	Philippines	1	90.5	90.5	90.5	90.5
94	2009	Revilla-Molina	IRRI	Rice	China	1	48.2	48.2	48.2	48.2
100	2010	Templeton and Jamora	IRRI	Policy research	The Philippines	2	17.5	20.1	20.1	22.7
101	2011	Brennan and Malabayabas	IRRI	Rice	Philippines, Indonesia, Vietnam	1	21.7	21.7	21.7	21.7
107	2013	Rejesus, Martin, and Gypmantasiri	IRRI	Rice	Vietnam, Philippines, Bangladesh	5	1.8	12.8	11.5	21.7
15	1993	Byerlee	CIMMYT	Wheat	Pakistan	4	15.7	21.5	20.6	29
16	1993	Byerlee and Moya	CIMMYT	Wheat	Developing countries	3	11.7	21	21.7	29.6
17	1993	Macagno and Gómez-Chao	CIMMYT	Wheat	Argentina	1	7.0	7.0	7.0	7.0
18	1994	Byerlee and Traxler	CIMMYT	Wheat	West Asia/North Africa	2	28.1	28.9	28.9	29.6
21	1995	Byerlee and Traxler	CIMMYT	Wheat	South Asia	3	5.8	10.1	10.9	13.5
86	1996	Makanda and Oehmke	CIMMYT	Wheat	Kenya	2	0.1	0.3	0.3	0.4
40	1999	Byerlee and Traxler	CIMMYT	Wheat	Developing countries, South Asia, Latin America and the Caribbean, West Asia/North Africa, Sub-Saharan Africa	5	4.6	61.1	53.4	136.6

Annex Table 2: Characteristics of the imputed BCRs for CGIAR-related R&D (continued)

						Imputed BCRs				
ID	Pub. Year	Authors	CGIAR Center	Commodity	Country/Region	No. obs	Min.	Mean	Median	Max.
						count		*ratio*		
59	2001	Zegeye, Tesfahun and Anandajayasekeram	CIMMYT	Maize	Ethiopia	1	3.7	3.7	3.7	3.7
66	2002	Tomasini	CIMMYT	Wheat	Brazil, Mexico	2	7.7	14.3	14.3	20.9
73	2003	Marasas, Smale and Singh	CIMMYT	Wheat	Developing countries	1	27.0	27.0	27.0	27.0
80	2006	González-Estrada et al.	CIMMYT	Wheat	Mexico	1	25.4	25.4	25.4	25.4
84	2007	González-Estrada et al.	CIMMYT	Maize	Mexico	1	17.3	17.3	17.3	17.3
89	2008	Barkley, Nalley and Crespi	CIMMYT	Wheat	Mexico	1	21.4	21.4	21.4	21.4
92	2009	Alene et al.	CIMMYT, IITA	Maize	Nigeria, Benin, Togo, Africa, Côte d'Ivoire, Senegal, Ghana, Cameroon, Burkina Faso, Mali	10	10.0	23.0	16.0	84.0
85	2007	Laxmi, Erenstein and Gupta	CIMMYT, Rice-Wheat Consortium	Wheat	India	1	39.0	39.0	39.0	39.0
3	1978	Scobie and Posada-Torres	CIAT	Rice	Colombia	6	50.8	121.7	109	229
6	1986	Gargiulo	CIAT	Beans	Argentina	6	1.4	2.9	2.2	6.7
12	1990	Ruiz de Londono and Janssen	CIAT	Beans	Peru	3	1.2	2.6	3.0	3.6
65	2002	Rivas	CIAT	Forages	Brazil	1	6.3	6.3	6.3	6.3
71	2003	Johnson, Pachico and Wortmann	CIAT	Beans	Latin America and the Caribbean	1	7.8	7.8	7.8	7.8
74	2003	Mather et al.	CIAT	Beans	Honduras	1	16.6	16.6	16.6	16.6
82	2007	Dalton et al.	CIAT	Cassava	Vietnam	1	6.0	6.0	6.0	6.0
87	2007	Mooney	CIAT	Beans	Ecuador	3	1.6	6.8	5.1	13.7
103	2012	Reyes	CIAT	Beans	Costa Rica, El Salvador, Honduras, Nicaragua, Ecuador	5	0.3	7.3	8.3	11.2

Annex Table 2: Characteristics of the imputed BCRs for CGIAR-related R&D (continued)

ID	Pub. Year	Authors	CGIAR Center	Commodity	Country/Region	Imputed BCRs No. obs	Min.	Mean	Median	Max.
						count		*ratio*		
108	2013	Robinson and Srinivasan	CIAT, CIP	Cassava, potato	Vietnam, China	2	0.0	19.3	19.3	38.6
24	1995	Lubulwa	IITA	Cassava	Africa	1	32.7	32.7	32.7	32.7
91	2009	Akinola et al.	IITA	Maize	West Africa	8	3.0	11.0	8.5	24.0
104	2013	Ayanwale et al.	IITA	Maize, millet, Sorghum	Nigeria	6	9.2	24.2	20	44
106	2013	Oleke et al.	IITA	Coconut	Benin	1	1.2	1.2	1.2	1.2
64	2002	Kristjanson et al.	IITA, ILRI, NARS	Cowpea	West Africa	1	63.2	63.2	63.2	63.2
14	1993	Ahmed, Masters, and Sanders	ICRISAT	Sorghum	Sudan	9	2.0	6.5	6.2	10.9
27	1996	Bantilan and Joshi	ICRISAT	Pigeon, Chickpea	India	1	83.6	83.6	83.6	83.6
34	1996	Yapi et al.	ICRISAT	Sorghum, millet	Mali	2	30.5	36.5	36.5	42.4
35	1997	Anandajayasekeram et al.	ICRISAT	Millet and Sorghum	Southern Africa	2	0.9	1.4	1.4	1.9
38	1998	Joshi and Bantilan	ICRISAT	Groundnuts	India	1	14.6	14.6	14.6	14.6
48	1999	Rohrbach et al.	ICRISAT	Millet	Namibia	1	10.7	10.7	10.7	10.7
49	1999	Yapi et al.	ICRISAT	Sorghum	Chad	1	21.4	21.4	21.4	21.4
50	1999	Yapi et al.	ICRISAT	Sorghum	Cameroon, Chad	2	42.7	58.3	58.3	73.8
102	2012	Macharia et al.	ICRISAT	Chickpeas	Ethiopia	1	6.0	6.0	6.0	6.0
109	2014	Bantilan et al.	ICRISAT	Chickpea	India	1	183.5	183.5	183.5	183.5
110	2014	Nedumaran et al.	ICRISAT	Groundnuts	Global	1	43.1	43.1	43.1	43.1
112	2016	Tsusaka et al.	ICRISAT	Groundnuts	Malawi	1	3.0	3.0	3.0	3.0
45	1999	Kristjanson et al.	ICRISAT, ILRI, NARS	Sorghum, Millet	India	1	15.0	15.0	15.0	15.0

Annex Table 2: Characteristics of the imputed BCRs for CGIAR-related R&D (continued)

ID	Pub. Year	Authors	CGIAR Center	Commodity	Country/Region	Imputed BCRs No. obs	Min.	Mean	Median	Max.
						count		*ratio*		
5	1984	Monares	CIP	Potato	Rwanda	1	3.5	3.5	3.5	3.5
10	1990	Horton et al.	CIP	Potato	Tunisia	1	41.4	41.4	41.4	41.4
22	1995	Fuglie	CIP	Potato	Tunisia	3	17.5	42.7	42.7	68
26	1996	Alvarez et al.	CIP	Potato	Dominican Republic	1	8.0	8.0	8.0	8.0
28	1996	Bofu et al.	CIP	Potato	China	2	37.6	55.8	55.8	74.1
29	1996	Chilver and Khatana	CIP	Potato	India	1	6.4	6.4	6.4	6.4
30	1996	Fonseca et al.	CIP	Potato	Peru	1	9.6	9.6	9.6	9.6
31	1996	Khatana et al.	CIP	Potato	India	4	3	15.5	8.7	41.6
32	1996	Ortiz et al.	CIP	Potato	Peru	1	10.6	10.6	10.6	10.6
36	1997	Chilver, El-Bedewy, and Rizk	CIP	Potato	Egypt	1	6.8	6.8	6.8	6.8
42	1999	Fuglie et al.	CIP	Sweet Potato	China	1	101.6	101.6	101.6	101.6
53	2000	Maza et al.	CIP	Sweet potato	Peru	1	21.3	21.3	21.3	21.3
56	2001	Fuglie et al.	CIP	Potato	Vietnam	3	2.7	3.1	3.2	3.3
60	2002	Barea and Bejarano	CIP	Potato	Bolivia	3	27.2	34.8	29.7	47.5
62	2002	Calderon, Gandarillas, and Zuger	CIP	Potato	Bolivia	1	31.1	31.1	31.1	31.1
63	2002	Fonseca et al.	CIP	Potato	Peru	1	11.9	11.9	11.9	11.9
69	2003	Gabriel, Almanza, and Gandarillas	CIP	Potato	Bolivia	1	29.1	29.1	29.1	29.1
70	2003	Gandarillas	CIP	Potato	Bolivia	1	8.9	8.9	8.9	8.9
77	2004	Zuger	CIP	Potato	Peru	1	7.5	7.5	7.5	7.5

Annex Table 2: Characteristics of the imputed BCRs for CGIAR-related R&D (continued)

						Imputed BCRs				
ID	Pub. Year	Authors	CGIAR Center	Commodity	Country/Region	No. obs	Min.	Mean	Median	Max.
						count		*ratio*		
67	2003	Aw-Hassan et al.	ICARDA	Barley	Algeria, Ecuador, Egypt, Ethiopia, Iraq, Jordan, Morocco, Syria, Tunisia	9	3.0	7.0	5.7	18.4
95	2010	Ahmed et al.	ICARDA	Policy research	Syria	1	19.6	19.6	19.6	19.6
47	1999	Ryan	IFPRI	Policy research	Vietnam	3	56.0	92.3	77.0	144
52	2000	Babu	IFPRI	Policy research	Bangladesh	1	9.5	9.5	9.5	9.5
81	2007	Ajayi et al.	ICRAF	Maize	Zambia	3	0.6	2.1	2.4	3.4
99	2010	Raitzer	CIFOR	Policy research	Indonesia	2	1.0	3.6	3.6	6.2
41	1999	Elbasha, Thornton, and Tarawali	ILRI	Forage	West Africa	1	4.6	4.6	4.6	4.6
44	1999	Kristjanson et al.	ILRI	Dairy and Beef	Africa	1	34.0	34.0	34.0	34.0
97	2010	Kaitibie et al.	ILRI	Dairy	Kenya	1	72.8	72.8	72.8	72.8
25	1995	Tré	WARDA	Rice	Sierra Leone	4	2.8	3.1	3.0	3.5
83	2007	Dey et al.	WorldFish Center	Aquaculture, Agriculture	Malawi	1	3.4	3.4	3.4	3.4
19	1987	Evenson	CGIAR	Maize, maize and staples, maize and cereals, cereals, staple crops	Latin America and the Caribbean, Sub-Saharan Africa, Asia/Pacific	5	9.3	28.7	41.6	41.6

Annex Table 2: Characteristics of the imputed BCRs for CGIAR-related R&D (continued)

ID	Pub. Year	Authors	CGIAR Center	Commodity	Country/Region	No. obs	Min.	Mean	Median	Max.
							Imputed BCRs			
						count		*ratio*		
93	2009	Alene and Coulibaly	CGIAR	All Crops	Benin, Botswana, Burkina Faso, Burundi, Cameroon, Central African Republic, Cote dIvoire, Ethiopia, Gambia, Ghana, Kenya, Lesotho, Madagascar, Malawi, Mali, Mauritania, Mozambique, Niger, Nigeria, Rwanda, Senegal, South Africa, Swaziland, Tanzania, Uganda, Zambia, Zimbabwe	27	4.6	120.9	97.5	515.4
98	2010	Maredia and Raitzer	CGIAR	Selected Crops	Africa	1	0.9	0.9	0.9	0.9
54	2000	Ramasamy et al.	IARCs	Millet	India	1	6.5	6.5	6.5	6.5

Source: Compiled by authors.

Notes: Country/region indicates location of performance of the evaluated CGIAR-related R&D, which may or may not concord with the location of the benefits attributable to that R&D.

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Annex Table 3: CGIAR supported centers

Center [a]	CGIAR support begins	Year founded	Location of headquarters	Main areas of focus		Region	2018 expenditures	
				Commodities	Research activities		Amount	Share of CGIAR total
							Million $	*Percent*
IRRI	1971	1960	Los Banos, Philippines	Rice	Rice and rice-based ecosystems	Asia, Africa	64.5	7.6
CIMMYT	1971	1966	El Batan, Mexico	Wheat and maize	Maize research, Wheat research, Genetic resources, Sustainable intensification, Socioeconomics research, Integrated development	World	109.9	12.9
CIAT[i]	1971	1967	Cali, Colombia	*Phaseolus* beans, cassava, tropical forages, rice	Agrobiodiversity, Decision and Policy Analysis, Agroecosystems and Sustainable Landscapes	Africa, Asia, Latin America and the Caribbean	68.4	8.0
IITA	1971	1967	Ibadan, Nigeria	Cassava, cowpeas, maize, plantains and bananas, soybeans, and yams	Biotechnology and Genetic Improvement, Natural Resource Management, Social Science and Agribusiness, Plant Production and Plant Health and Nutrition and Food Technology	Western Africa, Eastern Africa, Central Africa, and Southern Africa	85.9	10.1
ICRISAT	1972	1972	Patancheru, India	Sorghum, millet, pigeonpeas, chickpeas, and groundnuts	Sustainable production systems for the semi-arid tropics	Semi-arid tropics, Asia, Eastern and Southern Africa, West and Central Africa	62.5	7.3
CIP	1973	1970	Lima, Peru	Potato, sweet potato, and other root crops	Potato Agri-Food Systems Program, Sweet Potato Agri-Food Systems Program, Biodiversity	Africa, Asia, Latin America	49.6	5.8
ILRAD [b]	1973	1973	Nairobi, Kenya		See ILRI		NA	NA

Annex Table 3: CGIAR supported centers (continued)

Center[a]	CGIAR support begins	Year founded	Location of headquarters	Main areas of focus: Commodities	Main areas of focus: Research activities	Region	2018 expenditures: Amount	2018 expenditures: Share of CGIAR total
							Million $	*Percent*
ILCA [b]	1974	1974	Addis Ababa, Ethiopia		See ILRI		NA	NA
Bioversity International [c, k]	1974	1974	Rome, Italy		Plant genetic resources of crops and forages, collection and gene pool conservation	Latin America, Sub-Saharan Africa, Central Asia and South Asia, Southeast Asia	31.6	3.7
AfricaRice Center [d]	1975	1971	Abidjan, Cote d'Ivoire	Rice	Genetic Diversity and Improvement; Sustainable Productivity Enhancement; Policy, Innovation Systems and Impact Assessment; Rice Sector Development	Sub-Saharan Africa	17.2	2.0
ICARDA [e]	1977	1977	Beirut, Lebanon	Barley, lentils, faba beans, wheat, kabuli chickpeas, pasture and forage legumes, small ruminants, water	Farming systems	Non-Tropical Dry Areas, North Africa, Middle East, South Asia, Uzbekistan, Sudan, Ethiopia	32.5	3.8
ISNAR [f]	1980	1979	The Hague, Netherlands		Strengthen national agricultural research systems	World	NA	NA
IFPRI	1980	1975	Washington, D.C., USA		Socioeconomic research related to agricultural development, poverty, and malnutrition	World, with primary emphasis on low-income countries and groups	115.7	13.6

Annex Table 3: CGIAR supported centers (continued)

Center[a]	CGIAR support begins	Year founded	Location of headquarters	Main areas of focus: Commodities	Main areas of focus: Research activities	Region	2018 expenditures: Amount	2018 expenditures: Share of CGIAR total
							Million $	*Percent*
World Agroforestry Centre [g, l]	1991	1977	Nairobi, Kenya		Agroforestry, Tree Crop Landscape, Soils, Agricultural Systems with trees, Tree productivity and diversity	Sub-Saharan Africa, Latin America, Asia	58.1	6.8
IWMI [h]	1991	1984	Colombo, Sri Lanka		Irrigation and water resource management, Climate change	Sub-Saharan Africa, North Africa and Middle East, Asia	21.9	2.6
WorldFish Center [i]	1992	1977	Penang, Malaysia		Sustainable aquaculture; Resilient small-scale fisheries; Value chains and nutrition	Africa, Asia and the Pacific	29.9	3.5
CIFOR [l]	1993	1993	Bogor, Indonesia		Forests and human well-being, Sustainable landscapes and food, Equal opportunities, gender, justice and tenure, Climate change, energy and low-carbon development, Value chains, finance and investment, Forest management and restoration	Latin America, Sub-Saharan Africa, Central Asia and South Asia, Southeast Asia, Pacific	36.0	4.2
ILRI [j]	1995	1995	Nairobi, Kenya and Addis Ababa, Ethiopia		Animal and human health; Feed and forage development; Livestock Genetics; Impact at scale; Policies, institutions and livelihoods; Sustainable livestock systems; Bioscience eastern and central Africa (BecA)-ILRI Hub	Sub-Saharan Africa, South Asia, Southeast Asia, China	69.5	8.1

Sources: Alston et al. (2006) and web sites of respective centers.

Notes: NA indicates not applicable.

[a] IRRI: International Rice Research Institute; CIMMYT: International Maize and Wheat Improvement Center; IITA: International Center for Tropical Agriculture; CIAT: International Institute of Tropical Agriculture; ; ICRISAT: International Crops Research Institute for the Semi-Arid Tropics; CIP: International Potato Center; ILRAD: International Laboratory for Research on Animal Diseases; ILCA: International Livestock Center for Africa; ICARDA: International Center for Agricultural Research in the Dry Areas; ISNAR: International Service for National Agricultural Research; IFPRI: International Food Policy Research Institute; IWMI: International Water Management Institute; CIFOR: Center for International Forestry Research; ILRI: International Livestock Research Institute

[b] In 1995, ILRAD and ILCA were merged to form ILRI. ILCA did research on animal feed and production systems for cattle, sheep, and goats for sub-Saharan Africa.

[c] First established in 1974 as the International Board of Plant Genetic Resources (IBPGR). The Board was funded as a CG center but operated under the administration of the Food and Agriculture Organization of the United Nations (FAO), located at FAO headquarters in Rome. In 1991, IBPGR changed its name to IPGRI and in 1994 it was established as a self-administering CG center with headquarters in Rome. The International Network for the Improvement of Banana and Plantain (INIBAP) was established in Montpellier, France, in 1984. In 1992, INIBAP became a CG-sponsored center, but in 1994 operating name to Bioversity International. The new name reflects an expanded vision of its role in the area of agricultural and forest biodiversity and research-for-development activities.

[d] Formerly known as the West Africa Rice Development Association (WARDA). Originally located in Liberia, the organization moved to Bouake, Cote d'Ivoire, in 1987, and has been working out of the IITA station in Cotonou, Benin, since January 2005 because of civil unrest in Cote d'Ivoire.

[e] ICARDA was located in Aleppo, Syria. Following the civil war, ICARDA set up operations in a number of countries across the region in 2012 and relocated its headquarters to Lebanon. Gene bank accessions were safety duplicated in locations outside Syria. All expatriate staff were relocated by July 2012 and continued to work from more than 40 countries. In 2013, new research sites were strategically established in Morocco, Ethiopia, Sudan, Egypt, Turkey/Central Asia and India to allow the Center's scientists to contribute more adequately to 10 CGIAR Research Programs, particularly the Dryland Systems program that ICARDA leads (ICARDA 2012 and 2013 Annual Reports).

[f] Ceased operations in March 2004 and was reconstituted as a division within IFPRI in April 2004.

[g] Known as the International Centre for Research in Agroforestry (ICRAF) until 2002.

[h] Known as the International Irrigation Management Institute (IIMI) until 1998.

[i] Formerly known as the International Centre for Living Aquatic Resource Management (ICLARM); its headquarters were relocated from Metro Manila to Batu Maung, Malaysia, in 2001.

[j] ILRI became operational in January 1995 through a merger of ILRAD and ILCA. ILRAD research focused on livestock diseases (world) and tick-borne disease and trypanosomiasis (sub-SaharanAfrica).

[k] CIAT and Bioversity International formed an Alliance that became fully effective as of January 1, 2020.

[l] CIFOR and World Agroforestry/ICRAF effectively merged as of January 1, 2019.

Annex B: Recalibrating Reported IRRs to Standardized BCRs

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To derive BCR estimates for the evaluations in our sample that report only an IRR estimate, we employed the three-step procedure developed and detailed in Rao et al. (2019). The first step is to use the methods developed by Hurley et al. (2014) to approximate BCRs for the sub-set of 412 evaluations in Version 3.5 of the InSTePP returns-to-research database that reported both a BCR, an IRR, and the time-related information (i.e., starting and ending dates of the cost and benefit streams associated with the R&D projects under evaluation). Hurley et al. (2014) showed that the relationship between the BCR and IRR can be written as

$$BCR = \frac{\sum_{t=0}^{T_c} w_{c_t}(1+IRR)^{-t}}{\sum_{t=T_b}^{T} w_{b_t}(1+IRR)^{-t}} \frac{\sum_{t=T_b}^{T} w_{b_t}(1+\delta)^{-t}}{\sum_{t=0}^{T_c} w_{c_t}(1+\delta)^{-t}}$$

where T_c is the date at which R&D expenditures cease, T_b and T are the dates at which R&D benefits start and end, w_{c_t} and w_{b_t} are the proportions of the total costs and total benefits occurring at time *t*, and δ is the external discount rate. Using these methods we can recover the temporal distributions of R&D costs and benefits (i.e., w_{c_t} and w_{b_t}) that are typically not reported in the original evaluation studies, and thus further approximate various rate-of-return metrics (e.g., the BCR and modified internal rate of return, or MIRR) using the recovered distributions.

In the second step, regression methods were applied to the 1,648 approximated observations to identify the best-fitting relationship between the reported IRRs and the approximated BCRs while accounting for differences in the time-related variables. Rao et al. (2020) showed that the complex mathematical relationship among the BCR, IRR, and time-related variables can inform the specification of the best-fitting regression equation in the following fashion, applying a linear-quadratic functional form:

$$\ln BCR = f(x_1, x_2, T_c, T_b, T),$$

where $x_1(\delta) = \left(IRR\left(\frac{IRR}{2!} - 1\right) - \delta\left(\frac{\delta}{2!} - 1\right)\right)$, $x_2(\delta) = \left(\frac{IRR^2}{2!} - \frac{\delta^2}{2!}\right)$, and δ is the discount rate.

Using their regression specifications, we also assessed the implications of using various robust regression estimators to deal with outlier observations. Like Rao et al. (2020), we found the ordinary least squares (OLS) estimator produced sufficiently robust estimates while at the same time was less likely to produce nonsensically high or low predicted BCRs. For the last step, we used these OLS estimates and the approach developed in Hurley et al. (2014) to estimate the BCRs used in this study assuming a uniform discount rate of 5%. In this way, we derived a total number of 2,137 standardized BCRs consisting of 412 approximated BCRs and 1,725 projected BCRs all generated assuming a uniform discount rate of 5%.

Annex C: Methods, Data and Detailed Results

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Meta-Regression Methods

To derive conditional predictions of BCRs for CGIAR centers and other aggregates, we use meta-regression models with the imputed BCRs (in logarithms) as the dependent variable using two sets of independent variables for the imputed BCRs, and three sample sizes (i.e., the full regression sample and two trimmed versions of the full sample). Both taking logarithms of the imputed BCRs and trimming the full sample address the outlier problem in the observations and help increase the robustness of the regression results. Taking logarithms also helps mitigate heteroskedasticity among observations, an issue raised by Alston et al. (2000a, 2000b) and Rao et al. (2019).[1]

For the independent variables, we include two sets of dummy variables for CGIAR centers in addition to a common set of control variables. Specifically, Model 1 includes seven center-specific dummy variables, one dummy for the "Other Five" CGIAR centers, one dummy for CGIAR "Policy-Oriented" research (mostly from IFPRI but also from some other centers), with the default category being non-CGIAR observations. Model 2 includes one dummy for the Founding Four CGIAR centers, one dummy for CGIAR "Policy-Oriented" research, and one dummy for CGIAR centers, with the default category being non-CGIAR observations. The difference between Model 1 and Model 2 is that Model 1 includes seven center-specific dummy variables and one dummy for the "Other Five" CGIAR centers whereas Model 2 includes one dummy for the Founding Four CGIAR centers and research and one dummy for CGIAR centers. These specifications allow us to detect differences in the imputed BCRs among individual CGIAR centers and between CGIAR centers and non-CGIAR observations.

Finally, both Model 1 and Model 2 include a common set of control variables that are generated from four categories of factors: characteristics of the BCR measure, (2) characteristics of the analysts who perform the BCR evaluations, (3) characteristics of the R&D projects being evaluated, and (4) characteristics of the evaluation methodology. Specifically:

- Characteristics of the BCR measure include whether it was a marginal or average measure, a private or social measure, and whether it was for research, extension or both types of activities.
- Characteristics of the analyst include whether the first author had a government, university, international research center, private organization or other affiliation, and whether the evaluation was self-performed or independent.

1 Alston et al. (2000a and 2000b) and Rao et al. (2019) cautioned that in meta-regression models estimated by OLS, the clustering of observations within groups (i.e., evaluation studies) could entail heteroskedasticity and inter-dependence among individual ROR estimates that will lead to understated standard errors and overstated statistical significance of coefficient estimates, especially of group-level factors (Cameron and Miller 2015). To address this issue, cluster robust standard errors (clustered by evaluation studies) are reported. This does not affect the point estimates of the coefficients, but it does inflate their standard errors.

- Characteristics of the R&D projects being evaluated include whether the performer was a government, university, international research center, international research funding body, or private organization; the focus was crops, livestock, or natural resources and forestry; the scope was basic or applied; the nature was public, private or both.
- Characteristics of the evaluation methodology include whether the institutional orientation was an individual project, program, institution- wide, or multi institution; the evaluation was published in a refereed journal; supply shifts were estimated econometrically; supply and demand shifts were implicit, pivotal, or parallel; the data were industry or experimental; spill-ins, spill-outs or both spill-ins and spill-outs were measured; and farm program, exchange rate, deadweight tax, environmental, or other distortions were considered.

The factors listed above are either dichotomous or categorical and were thus converted into corresponding sets of dummy variables. In addition, we included three variables of general interest: publication date of the BCR evaluation study, year of the R&D project initiation, and a dummy variable for whether or not the beneficiary of the R&D project is classified as a developing country.

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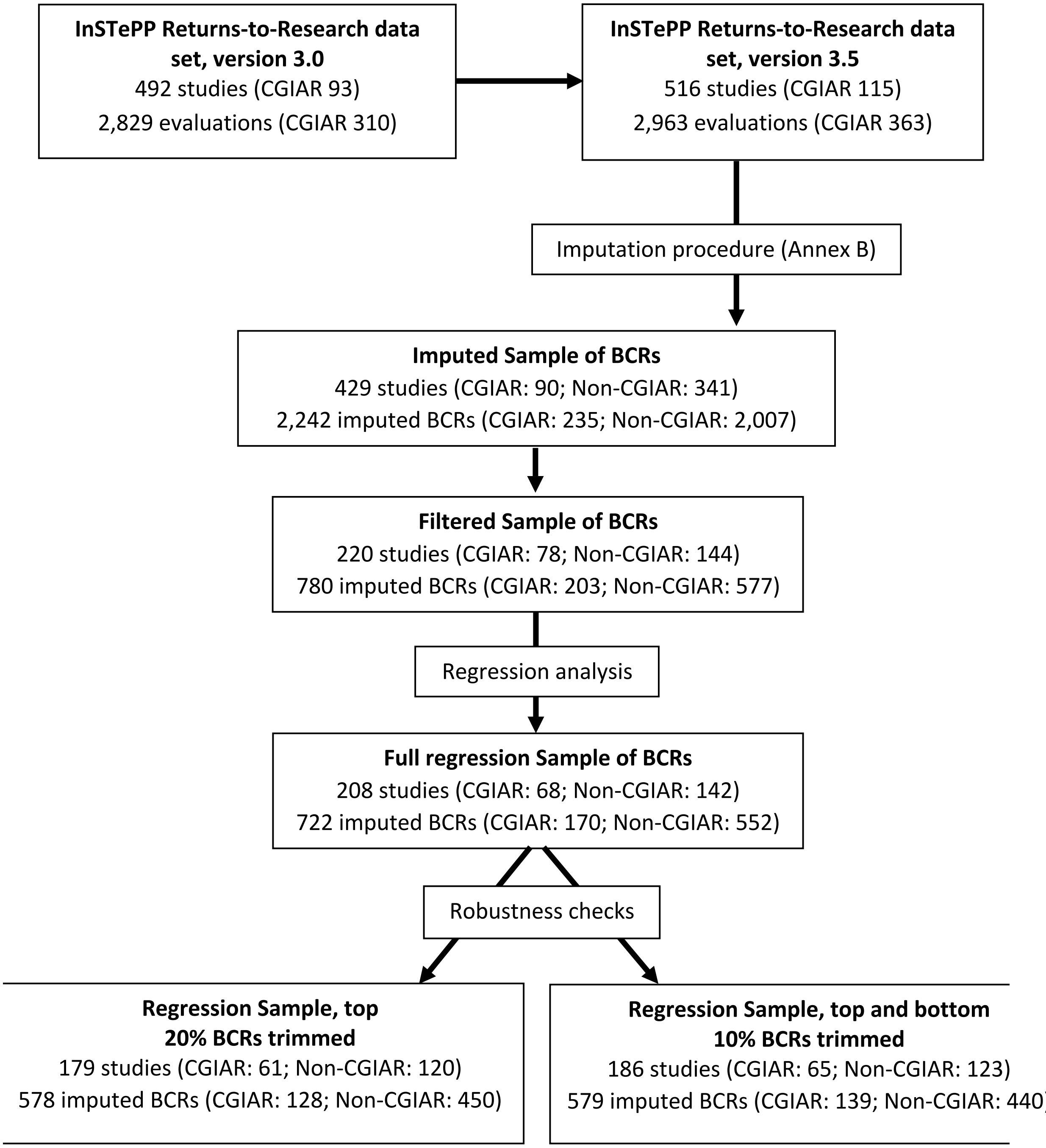
Annex Figure 1: Study Data Sets



Sources: Developed by authors.

Notes: A rate-of-return study may evaluate multiple projects, some of which involve CGIAR participation while some do not. Hence some studies are counted more than once, and the total number of studies is less than the simple sum of the CGIAR and non-CGIAR subsets. Of the total of 2,829 evaluations in the InSTePP Returns to Research data set, version 3.0, two extreme outliers were not used in the analysis in this Report and were dropped from the sample for version 3.5 and subsets thereof as displayed in this Figure.

Annex Table 4: Variables Used in the Regression Analysis

Variable name	Description	All BCR estimates N=2,242		Filtered subset N=780	
		Count	Mean	Count	Mean
		number	*ratio*	*number*	*ratio*
CGIAR	yes=1	2,242	0.10	780	0.26
Time1	Initial year of costs/investments	2,144	1,933.24	755	1,970.50
POR	Policy research=1	2,242	0.00	780	0.01
PubDate	publication date	2,242	1,995.61	780	1,994.54
Developing	yes=1	2,242	0.43	780	1.00
v1_3_1	Marginal ROR	2,232	0.53	780	0.28
v1_4_1	Social ROR	2,241	0.91	779	0.97
v1_5_2	Extension only	2,164	0.03	773	0.03
v1_5_3	Research & extension	2,164	0.52	773	0.50
v2_1_2	University researcher	2,228	0.50	770	0.43
v2_1_3	International researcher	2,228	0.20	770	0.16
v2_1_4	International funder	2,228	0.01	770	0.02
v2_1_5	Private-sector researcher	2,228	0.02	770	0.00
v2_1_6	Unknown affiliation	2,228	0.07	770	0.14
v2_2_2	Self-evaluation	2,230	0.19	770	0.32
v2_2_3	Unclear evaluation type	2,230	0.19	770	0.28
v3_1_2	University research performer	2,242	0.31	780	0.10
v3_1_3	Intl institute research performer	2,242	0.10	780	0.22
v3_1_4	Private research performer	2,242	0.17	780	0.11
v3_1_5	Unknown research performer	2,242	0.09	780	0.02
v3_2_2	Livestock	2,242	0.09	780	0.05
v3_2_3	Natural resource & forestry	2,242	0.33	780	0.00
v3_4_2	Private R&D	2,242	0.02	780	0.04
v3_4_3	Public and Private R&D	2,242	0.18	780	0.07
v4_1_2	Program evaluated	2,239	0.16	779	0.32
v4_1_3	Institution-wide	2,239	0.07	779	0.04
v4_1_4	Multi-institutions	2,239	0.63	779	0.46
v4_2_1	Refereed publication	2,241	0.36	779	0.22
v4_3_1	Econometric supply shift	2,230	0.46	773	0.32
v4_4_2	Pivotal supply shift	2,242	0.15	780	0.26
v4_4_3	Parallel supply shift	2,242	0.18	780	0.29
v4_4_4	Pivotal demand shift	2,242	0.01	780	0.00
v4_5_2	Experimental data for supply shift	2,181	0.30	732	0.35
v4_8_2	Spillins	2,239	0.18	777	0.08
v4_8_3	Spillouts	2,239	0.01	777	0.01
v4_8_4	Both spillins and spillouts	2,239	0.17	777	0.04

Sources: Developed by authors.

Annex Table 5: Regional and Commodity Orientation of BCRs

	All BCR estimates N=2,242		Filtered subset N=780	
Categories	**Count**	**Mean**	**Count**	**Mean**
	number	*ratio*	*Number*	*Ratio*
Regions				
Australia	112	30.74	-	-
Canada	140	27.95	-	-
Europe	74	47.06	-	-
U.S.	518	30.12	-	-
U.S. State or U.S. region	278	42.30	-	-
Other developed	21	6.17	-	-
WANA	28	10.57	22	11.60
SSA	280	19.98	187	21.42
Asia/Pacific	282	26.87	223	29.68
LAC	382	21.20	271	26.62
Multinational	113	21.77	64	13.70
Global	14	12.61	13	12.09
Commodity				
All agriculture	772	33.27	-	-
Natural resources	34	9.10	9	3.72
Aquaculture	9	7.19	-	-
Miscellaneous	130	34.65	-	-
Cereals	579	23.63	390	26.50
Fruits, vegetables and nuts	42	67.48	12	9.73
Fodder crops	29	8.91	3	6.29
Oil crops	37	12.48	18	16.64
Pulses	43	15.62	35	16.37
Roots and tubers	82	14.99	69	11.99
Other crops	202	20.28	140	23.41
All crops	79	43.93	61	39.28
Beef and dairy	46	25.11	9	16.22
Goats and sheep	40	6.65	10	9.01
Poultry	77	37.51	11	54.24
Other livestock	21	7.12	3	9.12
All livestock	11	41.65	1	34.37

Sources: Developed by authors.

Annex Table 6: Regression Results—Full sample, Model 1

	Coefficient	Robust Std. Err.	t	P>|t|	[95% Conf. Interval]	
IRRI	0.16	0.24	0.64	0.52	-0.33	0.64
CIMMYT	0.29	0.26	1.09	0.28	-0.23	0.81
ICARDA	0.27	0.47	0.57	0.57	-0.66	1.19
IITA	0.23	0.54	0.42	0.67	-0.84	1.30
CIAT	0.11	0.57	0.20	0.84	-1.00	1.23
CIP	0.41	0.37	1.09	0.28	-0.33	1.14
ICRISAT	0.49	0.28	1.76	0.08	-0.06	1.05
C5	-0.31	0.39	-0.82	0.42	-1.07	0.45
POR	1.32	0.37	3.58	0.00	0.59	2.04
YearFirstCost	-0.03	0.01	-3.37	0.00	-0.05	-0.01
PubDate	0.01	0.01	0.55	0.58	-0.02	0.03
v1_3_1	-0.22	0.32	-0.70	0.49	-0.85	0.41
v1_4_1	1.55	0.41	3.74	0.00	0.73	2.37
v1_5_2	-0.15	0.25	-0.60	0.55	-0.64	0.34
v1_5_3	-0.42	0.15	-2.79	0.01	-0.71	-0.12
v2_1_2	0.59	0.27	2.23	0.03	0.07	1.12
v2_1_3	0.64	0.29	2.19	0.03	0.06	1.22
v2_1_4	-0.53	0.40	-1.32	0.19	-1.31	0.26
v2_1_5	-0.83	0.25	-3.34	0.00	-1.32	-0.34
v2_1_6	0.45	0.24	1.85	0.07	-0.03	0.92
v2_2_2	0.64	0.26	2.42	0.02	0.12	1.15
v2_2_3	0.13	0.28	0.48	0.63	-0.41	0.68
v3_1_2	0.04	0.21	0.19	0.85	-0.38	0.46
v3_1_3	-0.49	0.26	-1.91	0.06	-0.99	0.02
v3_1_4	-0.88	0.31	-2.83	0.01	-1.49	-0.26
v3_1_5	-0.68	0.23	-2.95	0.00	-1.14	-0.23
v3_4_2	1.19	0.59	2.02	0.05	0.03	2.35
v3_4_3	0.26	0.30	0.87	0.38	-0.32	0.84
v4_1_2	-0.13	0.25	-0.51	0.61	-0.62	0.37
v4_1_3	-0.87	0.56	-1.55	0.12	-1.97	0.24
v4_1_4	-0.12	0.29	-0.41	0.68	-0.68	0.45
v4_2_1	-0.35	0.24	-1.48	0.14	-0.81	0.11
v4_3_1	-0.04	0.33	-0.13	0.90	-0.69	0.61
v4_4_2	-0.23	0.23	-1.00	0.32	-0.68	0.22
v4_4_3	0.15	0.23	0.64	0.52	-0.30	0.59
v4_4_4	1.07	0.53	2.01	0.05	0.02	2.12
v4_8_2	0.43	0.22	1.98	0.05	0.00	0.87
v4_8_3	-0.85	0.31	-2.73	0.01	-1.47	-0.24
v4_8_4	0.08	0.27	0.31	0.75	-0.44	0.61
intercept	48.30	21.60	2.24	0.03	5.71	90.88

N=722
R^2 = 0.3140
Root MSE = 1.0519

Sources: Developed by authors.

Notes: Model 1 using semi-log OLS, 7 center-dummies, C5 for (all other 5 centers).

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Annex Table 7: Regression Results—Full sample, Model 2

	Coefficient	Robust Std. Err.	t	P>|t|	[95% Conf. Interval]	
CGIAR	-0.19	0.34	-0.56	0.58	-0.86	0.48
F4	0.40	0.32	1.28	0.20	-0.22	1.03
POR	0.94	0.37	2.54	0.01	0.21	1.68
YearFirstCost	-0.03	0.01	-3.50	0.00	-0.05	-0.01
PubDate	0.02	0.01	1.12	0.27	-0.01	0.04
v1_3_1	-0.22	0.31	-0.69	0.49	-0.83	0.40
v1_4_1	1.56	0.45	3.46	0.00	0.67	2.44
v1_5_2	-0.19	0.26	-0.72	0.47	-0.69	0.32
v1_5_3	-0.38	0.15	-2.57	0.01	-0.68	-0.09
v2_1_2	0.55	0.26	2.10	0.04	0.03	1.06
v2_1_3	0.72	0.31	2.34	0.02	0.11	1.33
v2_1_4	-0.62	0.41	-1.53	0.13	-1.42	0.18
v2_1_5	-0.75	0.24	-3.06	0.00	-1.23	-0.27
v2_1_6	0.52	0.24	2.18	0.03	0.05	0.98
v2_2_2	0.49	0.25	1.94	0.05	-0.01	0.99
v2_2_3	0.17	0.25	0.69	0.49	-0.32	0.67
v3_1_2	-0.11	0.21	-0.51	0.61	-0.52	0.30
v3_1_3	-0.11	0.34	-0.33	0.74	-0.78	0.55
v3_1_4	-0.80	0.30	-2.63	0.01	-1.39	-0.20
v3_1_5	-0.42	0.29	-1.44	0.15	-1.00	0.15
v3_4_2	1.20	0.60	1.99	0.05	0.01	2.39
v3_4_3	0.11	0.27	0.40	0.69	-0.43	0.64
v4_1_2	-0.14	0.24	-0.61	0.55	-0.61	0.33
v4_1_3	-0.66	0.55	-1.20	0.23	-1.75	0.43
v4_1_4	-0.12	0.29	-0.43	0.66	-0.69	0.44
v4_2_1	-0.27	0.23	-1.20	0.23	-0.73	0.18
v4_3_1	0.08	0.33	0.24	0.81	-0.57	0.73
v4_4_2	-0.26	0.21	-1.19	0.24	-0.68	0.17
v4_4_3	0.04	0.20	0.21	0.84	-0.36	0.44
v4_4_4	1.16	0.52	2.22	0.03	0.13	2.18
v4_8_2	0.39	0.22	1.75	0.08	-0.05	0.83
v4_8_3	-0.92	0.29	-3.16	0.00	-1.50	-0.35
v4_8_4	-0.02	0.27	-0.06	0.95	-0.55	0.52
intercept	34.17	23.55	1.45	0.15	-12.26	80.59

N=722
R^2 = 0.2870
Root MSE = 1.0677

Sources: Developed by authors.

Notes: Model 2 using semi-log OLS, only two dummies: CGIAR and F4 (founding four).

Annex Table 8: Regression Results—Truncated sample (10-90 percentile), Model 1

	Coefficient	Robust Std. Err.	t	P>|t|	[95% Conf. Interval]	
IRRI	0.10	0.21	0.50	0.62	-0.31	0.51
CIMMYT	0.59	0.22	2.73	0.01	0.16	1.01
ICARDA	-0.51	0.43	-1.19	0.24	-1.36	0.34
IITA	-0.37	0.45	-0.82	0.41	-1.26	0.52
CIAT	0.02	0.30	0.08	0.94	-0.56	0.61
CIP	0.45	0.25	1.79	0.08	-0.05	0.94
ICRISAT	0.57	0.27	2.07	0.04	0.03	1.11
C5	-0.13	0.31	-0.42	0.68	-0.74	0.49
POR	1.17	0.27	4.31	0.00	0.63	1.70
YearFirstCost	-0.02	0.01	-2.83	0.01	-0.03	-0.01
PubDate	0.02	0.01	1.46	0.15	-0.01	0.04
v1_3_1	-0.20	0.20	-0.99	0.32	-0.60	0.20
v1_4_1	1.24	0.23	5.31	0.00	0.78	1.70
v1_5_2	0.05	0.18	0.29	0.77	-0.31	0.41
v1_5_3	-0.13	0.13	-1.01	0.31	-0.38	0.12
v2_1_2	0.46	0.23	2.01	0.05	0.01	0.92
v2_1_3	0.30	0.19	1.60	0.11	-0.07	0.68
v2_1_4	-0.70	0.32	-2.16	0.03	-1.33	-0.06
v2_1_5	-0.52	0.19	-2.73	0.01	-0.89	-0.14
v2_1_6	0.41	0.24	1.73	0.09	-0.06	0.87
v2_2_2	0.42	0.23	1.82	0.07	-0.03	0.88
v2_2_3	0.35	0.22	1.60	0.11	-0.08	0.79
v3_1_2	0.06	0.19	0.30	0.77	-0.32	0.43
v3_1_3	-0.46	0.20	-2.31	0.02	-0.85	-0.07
v3_1_4	-0.71	0.27	-2.65	0.01	-1.24	-0.18
v3_1_5	-0.80	0.21	-3.77	0.00	-1.21	-0.38
v3_4_2	1.16	0.31	3.73	0.00	0.55	1.78
v3_4_3	0.30	0.23	1.26	0.21	-0.17	0.76
v4_1_2	-0.16	0.20	-0.77	0.44	-0.56	0.25
v4_1_3	0.11	0.41	0.27	0.79	-0.70	0.91
v4_1_4	-0.03	0.22	-0.13	0.90	-0.45	0.40
v4_2_1	-0.17	0.16	-1.05	0.30	-0.49	0.15
v4_3_1	0.02	0.17	0.14	0.89	-0.32	0.37
v4_4_2	-0.17	0.19	-0.90	0.37	-0.55	0.21
v4_4_3	-0.06	0.17	-0.34	0.74	-0.39	0.28
v4_4_4	0.71	0.33	2.15	0.03	0.06	1.37
v4_8_2	0.35	0.15	2.42	0.02	0.07	0.64
v4_8_3	-0.53	0.29	-1.81	0.07	-1.10	0.05
v4_8_4	0.08	0.25	0.30	0.77	-0.43	0.58
intercept	4.74	15.10	0.31	0.75	-25.04	34.53

N=579
R^2 = 0.2617
Root MSE = 0.7462

Sources: Developed by authors.

Notes: Model 1 using semi-log OLS, 7 center-dummies, C5 for (all other 5 centers).

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Annex Table 9: Regression Results—Truncated sample (10-90 percentile), Model 2

	Coefficient	Robust Std. Err.	t	P>|t|	[95% Conf. Interval]	
CGIAR	-0.03	0.29	-0.11	0.91	-0.60	0.53
F4	0.25	0.20	1.25	0.21	-0.15	0.65
POR	0.99	0.28	3.57	0.00	0.44	1.54
YearFirstCost	-0.02	0.01	-2.97	0.00	-0.03	-0.01
PubDate	0.01	0.01	1.54	0.12	0.00	0.03
v1_3_1	-0.19	0.19	-0.97	0.33	-0.57	0.19
v1_4_1	1.24	0.22	5.64	0.00	0.81	1.67
v1_5_2	0.00	0.19	-0.02	0.98	-0.37	0.36
v1_5_3	-0.08	0.13	-0.61	0.55	-0.34	0.18
v2_1_2	0.40	0.22	1.76	0.08	-0.05	0.84
v2_1_3	0.32	0.20	1.60	0.11	-0.08	0.72
v2_1_4	-0.65	0.32	-2.05	0.04	-1.27	-0.02
v2_1_5	-0.51	0.17	-3.04	0.00	-0.84	-0.18
v2_1_6	0.49	0.22	2.25	0.03	0.06	0.92
v2_2_2	0.35	0.21	1.65	0.10	-0.07	0.78
v2_2_3	0.27	0.21	1.28	0.20	-0.14	0.68
v3_1_2	-0.02	0.19	-0.10	0.92	-0.39	0.35
v3_1_3	-0.18	0.28	-0.65	0.51	-0.74	0.37
v3_1_4	-0.55	0.24	-2.25	0.03	-1.03	-0.07
v3_1_5	-0.53	0.24	-2.19	0.03	-1.00	-0.05
v3_4_2	0.99	0.29	3.44	0.00	0.42	1.55
v3_4_3	0.12	0.20	0.58	0.56	-0.28	0.52
v4_1_2	-0.10	0.20	-0.51	0.61	-0.50	0.29
v4_1_3	0.15	0.40	0.37	0.71	-0.64	0.94
v4_1_4	0.05	0.22	0.21	0.83	-0.38	0.48
v4_2_1	-0.17	0.16	-1.11	0.27	-0.48	0.13
v4_3_1	0.06	0.18	0.35	0.72	-0.29	0.42
v4_4_2	-0.23	0.18	-1.26	0.21	-0.59	0.13
v4_4_3	-0.08	0.14	-0.53	0.60	-0.36	0.21
v4_4_4	0.80	0.33	2.40	0.02	0.14	1.45
v4_8_2	0.32	0.15	2.13	0.04	0.02	0.62
v4_8_3	-0.68	0.35	-1.94	0.05	-1.38	0.01
v4_8_4	0.09	0.23	0.40	0.69	-0.37	0.56
intercept	6.51	13.93	0.47	0.64	-20.97	33.99

N=579
R^2 = 0.2342
Root MSE = 0.7560

Sources: Developed by authors.

Notes: Model 2 using semi-log OLS, only two dummies: CGIAR and F4 (founding four).

Annex Table 10: Regression Results—Truncated sample (<80 percentile), Model 1

	Coefficient	Robust Std. Err.	t	P>|t|	[95% Conf. Interval]	
IRRI	0.17	0.19	0.91	0.36	-0.20	0.55
CIMMYT	0.63	0.20	3.19	0.00	0.24	1.01
ICARDA	-0.56	0.40	-1.38	0.17	-1.36	0.24
IITA	-0.08	0.42	-0.18	0.86	-0.91	0.76
CIAT	-0.29	0.23	-1.26	0.21	-0.74	0.16
CIP	0.57	0.22	2.58	0.01	0.13	1.00
ICRISAT	0.11	0.19	0.60	0.55	-0.26	0.49
C5	0.09	0.30	0.29	0.77	-0.51	0.68
POR	1.76	0.25	7.16	0.00	1.28	2.25
YearFirstCost	-0.02	0.01	-3.56	0.00	-0.03	-0.01
PubDate	0.02	0.01	1.79	0.08	0.00	0.04
v1_3_1	-0.42	0.22	-1.97	0.05	-0.85	0.00
v1_4_1	0.61	0.39	1.55	0.12	-0.16	1.38
v1_5_2	0.24	0.19	1.26	0.21	-0.14	0.63
v1_5_3	-0.13	0.12	-1.07	0.29	-0.36	0.11
v2_1_2	0.37	0.20	1.80	0.07	-0.04	0.77
v2_1_3	0.17	0.17	1.01	0.31	-0.16	0.50
v2_1_4	-0.54	0.30	-1.79	0.08	-1.13	0.06
v2_1_5	-0.29	0.22	-1.33	0.19	-0.73	0.14
v2_1_6	0.12	0.17	0.67	0.50	-0.23	0.46
v2_2_2	0.21	0.18	1.16	0.25	-0.14	0.56
v2_2_3	0.35	0.17	2.06	0.04	0.02	0.69
v3_1_2	-0.16	0.30	-0.53	0.60	-0.76	0.44
v3_1_3	-0.34	0.16	-2.18	0.03	-0.65	-0.03
v3_1_4	-0.33	0.31	-1.07	0.29	-0.94	0.28
v3_1_5	-0.14	0.17	-0.81	0.42	-0.48	0.20
v3_4_2	0.60	0.53	1.13	0.26	-0.45	1.65
v3_4_3	0.20	0.29	0.70	0.49	-0.37	0.77
v4_1_2	-0.16	0.14	-1.09	0.28	-0.44	0.13
v4_1_3	-0.10	0.30	-0.36	0.72	-0.69	0.48
v4_1_4	-0.07	0.19	-0.37	0.71	-0.44	0.30
v4_2_1	-0.19	0.14	-1.34	0.18	-0.48	0.09
v4_3_1	0.18	0.20	0.90	0.37	-0.21	0.57
v4_4_2	-0.34	0.15	-2.31	0.02	-0.63	-0.05
v4_4_3	0.09	0.15	0.61	0.54	-0.20	0.39
v4_4_4	0.88	0.29	3.03	0.00	0.31	1.45
v4_8_2	0.37	0.19	2.02	0.05	0.01	0.74
v4_8_3	-0.19	0.31	-0.61	0.54	-0.81	0.43
v4_8_4	-0.08	0.22	-0.38	0.71	-0.51	0.34
intercept	6.25	13.57	0.46	0.65	-20.53	33.04

N=578
R^2 = 0.2958
Root MSE = 0.7252

Sources: Developed by authors.

Notes: Model 1 using semi-log OLS, 7 center-dummies, C5 for (all other 5 centers).

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Annex Table 11: Regression Results—Truncated sample (<80 percentile), Model 2

	Coefficient	Robust Std. Err.	t	P>|t|	[95% Conf. Interval]	
CGIAR	0.43	0.18	2.40	0.02	0.08	0.78
F4	0.03	0.20	0.13	0.90	-0.38	0.43
POR	1.44	0.24	5.89	0.00	0.96	1.92
YearFirstCost	-0.02	0.01	-3.76	0.00	-0.03	-0.01
PubDate	0.02	0.01	2.19	0.03	0.00	0.04
v1_3_1	-0.53	0.20	-2.67	0.01	-0.93	-0.14
v1_4_1	0.67	0.40	1.68	0.10	-0.12	1.46
v1_5_2	0.23	0.19	1.21	0.23	-0.14	0.59
v1_5_3	-0.13	0.12	-1.05	0.30	-0.37	0.11
v2_1_2	0.31	0.20	1.61	0.11	-0.07	0.70
v2_1_3	0.13	0.18	0.73	0.47	-0.22	0.49
v2_1_4	-0.55	0.28	-1.94	0.05	-1.10	0.01
v2_1_5	-0.34	0.22	-1.53	0.13	-0.78	0.10
v2_1_6	0.23	0.17	1.34	0.18	-0.11	0.57
v2_2_2	0.19	0.16	1.13	0.26	-0.14	0.51
v2_2_3	0.36	0.16	2.28	0.02	0.05	0.66
v3_1_2	-0.24	0.29	-0.83	0.41	-0.81	0.33
v3_1_3	-0.47	0.18	-2.58	0.01	-0.83	-0.11
v3_1_4	-0.30	0.28	-1.08	0.28	-0.85	0.25
v3_1_5	-0.33	0.16	-2.02	0.04	-0.65	-0.01
v3_4_2	0.63	0.53	1.19	0.24	-0.41	1.67
v3_4_3	0.17	0.24	0.71	0.48	-0.30	0.64
v4_1_2	-0.14	0.14	-1.00	0.32	-0.41	0.13
v4_1_3	0.11	0.30	0.36	0.72	-0.48	0.69
v4_1_4	-0.01	0.19	-0.07	0.95	-0.39	0.37
v4_2_1	-0.13	0.14	-0.97	0.34	-0.41	0.14
v4_3_1	0.28	0.20	1.43	0.15	-0.11	0.67
v4_4_2	-0.42	0.13	-3.14	0.00	-0.69	-0.16
v4_4_3	-0.03	0.13	-0.21	0.83	-0.28	0.23
v4_4_4	0.66	0.25	2.65	0.01	0.17	1.15
v4_8_2	0.37	0.18	2.04	0.04	0.01	0.73
v4_8_3	-0.46	0.29	-1.59	0.12	-1.03	0.11
v4_8_4	-0.02	0.16	-0.14	0.89	-0.34	0.30
intercept	-1.77	14.52	-0.12	0.90	-30.43	26.89
N=578						
R^2 = 0.2737						
Root MSE = 0.7324						

Sources: Developed by authors.

Notes: Model 2 using semi-log OLS, only two dummies: CGIAR and F4 (founding four).

Annex Table 12: Benefits and Costs from "Billion Dollar" CGIAR Studies, 1960-2020 (millions of 2016 US dollars)

	Estimated benefits										Costs			
											CGIAR			Public ag R&D in LDCs
Year	Byerlee & Moya	Sanint & Wood	Fuglie et al.	Zeddie et al.	Hossain et al.	Johnson et al. (a)	Johnson et al. (b)	Marasas et al.	Myrick	Total Benefits	Total	Crop centers	Centers in evaluations	
CGIAR Centers	*CIMMYT*	*CIAT (and IRRI)*	*CIP*	*IITA*	*IRRI and CIAT*	*CIAT*	*CIAT*	*CIMMYT*	*CIP*					
							(millions 2016 US$)							
1960											47.1	47.1	47.1	4,358.3
1961											1.2	1.2	1.2	4,592.4
1962											2.7	2.7	2.7	4,815.4
1963											5.4	5.4	5.4	5,016.5
1964											3.4	3.4	3.4	5,387.3
1965											7.5	7.5	7.5	5,716.1
1966					515.9					515.9	11.5	11.5	11.5	5,860.1
1967		34.0			882.8					916.8	19.0	19.0	19.0	6,083.9
1968		70.8			1,249.7					1,320.4	37.8	37.8	37.8	6,439.5
1969		110.4			1,616.5					1,726.9	59.8	59.8	59.8	6,812.1
1970		153.0			1,983.4					2,136.4	72.1	72.1	72.1	7,350.5
1971		198.9			2,350.3					2,549.1	93.7	93.7	93.7	7,457.0
1972		248.0			2,717.2					2,965.2	101.8	101.8	101.8	7,855.3
1973		300.8			3,084.0			0.0		3,384.8	123.1	123.1	123.1	8,044.6
1974		357.2		0.0	3,450.9			0.1		3,808.3	140.5	136.5	134.7	8,111.6
1975		417.6		0.0	3,817.8			0.2		4,235.5	178.1	164.4	160.7	8,563.3
1976		482.1		0.0	4,184.7			1.7		4,668.5	220.7	190.5	184.4	8,928.6
1977	-28.9	551.0		0.0	4,544.8			5.7		5,072.7	273.3	235.0	226.9	9,365.7
1978	173.0	624.5		0.0	4,905.0			12.1		5,714.6	315.4	269.9	259.2	9,718.2
1979	539.8	702.9		0.0	5,265.1	0.1		27.0		6,534.8	341.5	291.5	277.3	10,083.5
1980	1,189.8	786.3		0.0	5,625.3	0.3		55.8		7,657.4	352.7	295.7	279.4	10,576.5
1981	1,725.4	875.1		0.0	5,985.5	0.5		99.2		8,685.6	361.6	303.7	287.6	11,216.6
1982	2,067.5	921.4		22.5	6,314.2	1.8	0.0	161.9		9,489.3	375.5	318.8	301.0	11,545.8
1983	2,861.6	972.1		106.9	6,643.0	4.6	0.2	227.5		10,815.8	389.5	326.6	304.0	11,481.7
1984	3,456.9	1,027.3		127.4	6,971.7	9.5	0.6	286.8		11,880.2	402.8	334.9	314.8	11,893.2
1985	3,408.7	1,087.3		154.9	7,300.5	19.6	1.4	332.8		12,305.2	418.3	348.2	330.0	12,451.7
1986	2,971.5	1,122.9		393.2	7,629.2	32.5	3.1	366.5		12,519.0	460.1	379.4	356.6	13,046.5

Annex Table 12: Benefits and Costs from "Billion Dollar" CGIAR Studies, 1960-2020 (continued)

Year	Estimated benefits: Byerlee & Moya	Sanint & Wood	Fuglie et al.	Zeddie et al.	Hossain et al.	Johnson et al. (a)	Johnson et al. (b)	Marasas et al.	Myrick	Total Benefits	Costs: CGIAR Total	CGIAR Crop centers	CGIAR Centers in evaluations	Public ag R&D in LDCs
CGIAR Centers	*CIMMYT*	*CIAT (and IRRI)*	*CIP*	*IITA*	*IRRI and CIAT*	*CIAT*	*CIAT*	*CIMMYT*	*CIP*					
							(millions 2016 US$)							
1987	3,179.2	1,222.7		494.5	7,898.7	25.9	5.3	394.3		13,220.6	477.4	403.2	382.7	13,619.0
1988	4,294.8	1,298.5	0.0	557.6	8,168.2	46.2	7.3	418.4		14,791.0	477.4	393.2	372.3	13,400.7
1989	4,473.8	1,380.2	0.0	524.9	8,437.7	50.2	9.8	442.2		15,318.7	497.8	404.3	379.6	13,863.0
1990	3,517.1	1,455.8	0.0	714.8	8,707.2	97.6	17.8	466.9		14,977.2	506.2	405.0	378.8	13,685.1
1991	3,402.2	1,535.1	0.0	826.7	8,976.6	137.9	26.4	494.3		15,399.4	489.8	394.5	359.5	13,638.8
1992	3,326.4	1,618.2	0.0	710.0	9,176.2	98.2	35.2	523.9		15,488.1	512.5	378.6	343.4	12,028.8
1993	3,249.2	1,704.9	-0.1	661.8	9,375.7	102.4	39.6	555.5		15,689.0	496.6	372.1	337.2	11,852.9
1994	3,181.3	1,795.1	1.1	679.4	9,575.2	199.2	64.7	589.2		16,085.3	483.8	357.1	319.5	11,816.2
1995	3,115.8	1,889.0	12.3	618.6	9,774.7	223.2	122.8	624.8		16,381.2	497.6	360.4	318.0	11,773.7
1996	3,060.0	1,855.1	61.1	610.8	9,974.3	261.4	133.4	661.4	15.5	16,633.0	511.1	367.7	324.7	12,217.9
1997	3,007.8	1,823.5	122.2	609.0	10,173.8	300.4	164.3	699.0	21.6	16,921.8	492.5	341.0	300.1	12,652.2
1998	2,974.7	1,803.4	183.8	610.2	10,373.3	285.9	157.8	737.1	34.6	17,160.9	473.3	321.6	277.1	13,138.6
1999	2,932.2	1,777.7	201.2	600.3	10,572.9	281.9	155.5	776.2	63.4	17,361.3	480.4	325.3	281.9	13,116.2
2000	2,868.0	1,738.7	201.2	596.2	10,341.3	275.7	152.1	816.6	71.9	17,061.8	457.3	310.3	268.4	13,488.2
2001	2,806.5	1,701.5	201.2	577.9	10,119.7	269.8	148.9	858.5	82.2	16,766.2	470.5	312.9	269.4	13,765.4
2002	2,762.9	1,675.0	201.2	571.9	9,962.4	265.6	146.6	901.7	85.3	16,572.5	497.5	318.9	272.6	14,723.8
2003	2,712.4	1,644.4	201.2	566.9	9,780.1	260.7	143.9	947.2	99.2	16,356.0	505.8	311.5	262.3	15,274.6
2004	2,641.4	1,601.3	201.2	548.2	9,524.0	253.9	140.1	994.7	108.9	16,013.7	529.4	334.8	282.3	15,996.9
2005	2,561.6	1,553.0	201.2	529.8	9,236.4	246.2	135.9	1,044.6	117.9	15,626.6	547.3	338.6	283.6	16,030.0
2006	2,486.2	1,507.3	201.2	514.5	8,964.7	239.0	131.9	1,097.0	149.5	15,291.2	538.1	336.7	282.9	17,087.5
2007	2,421.2	1,467.8	201.2	503.8	8,730.1	232.7	128.4	1,152.0	169.6	15,006.9	578.4	359.3	304.5	18,064.5
2008	2,375.2	1,440.0	201.2	497.3	8,564.4	228.3	126.0	1,130.1	162.8	14,725.4	608.3	379.0	324.2	19,387.6
2009	2,357.2	1,429.0	201.2	487.9	8,499.5	226.6	125.0	1,121.6	153.3	14,601.3	671.6	404.3	341.8	21,429.9
2010	2,330.0	1,412.5	201.2	488.3	8,401.3	224.0	123.6	1,108.6	177.9	14,467.5	723.4	454.2	389.5	22,231.0
2011	2,282.2	1,383.6	201.2	477.9	8,229.2	219.4	121.1	1,085.9	174.4	14,175.0	762.4	483.0	421.1	22,860.1
2012	2,239.3	1,357.6	201.2	465.5	8,074.5	215.3	118.8	1,065.5	282.4	14,020.1	927.9	573.4	511.0	23,977.3
2013	2,200.6	1,334.1	201.2	460.0	7,934.8	211.5	116.7	1,047.1	195.4	13,701.5	1025.1	632.1	561.4	24,548.4

Annex Table 12: Benefits and Costs from "Billion Dollar" CGIAR Studies, 1960-2020 (continued)

	Estimated benefits										Costs			
											CGIAR			
Year	Byerlee & Moya	Sanint & Wood	Fuglie et al.	Zeddie et al.	Hossain et al.	Johnson et al. (a)	Johnson et al. (b)	Marasas et al.	Myrick	Total Benefits	Total	Crop centers	Centers in evaluations	Public ag R&D in LDCs
CGIAR Centers	*CIMMYT*	*CIAT (and IRRI)*	*CIP*	*IITA*	*IRRI and CIAT*	*CIAT*	*CIAT*	*CIMMYT*	*CIP*					
							(millions 2016 US$)							
2014	2,160.7	1,309.9	201.2	451.6	7,790.9	207.7	114.6	1,028.1	225.2	13,490.0	1089.2	662.5	590.0	25,376.5
2015	2,138.4	1,296.4	201.2	447.0	7,710.5	205.6	113.4	1,017.5	260.8	13,390.9	995.2	597.1	534.5	25,884.1
2016	2,116.6	1,283.2	201.2	442.4	7,631.8	203.5	112.3	1,007.1	258.2	13,256.2	930.0	563.0	506.0	
2017	2,088.2	1,265.9	201.2	436.5	7,529.4	200.7	110.8	993.6	254.7	13,080.9	854.6	542.2	488.9	
2018	2,028.0	1,229.5	201.2	423.9	7,312.5	194.9	107.6	965.0	247.4	12,710.0	824.3	500.0	453.3	
2019	1,993.1	1,208.3	201.2	416.6	7,186.7	191.6	105.7	948.3	243.1	12,494.7				
2020	1,954.0	1,184.6	201.2	408.4	7,045.7	187.8	103.7	929.7	238.4	12,253.6				
Present Values (5% discount rate)														
Rep. ben.	**149,695**	**111,604**	**7,324**	**41,220**	**914,784**	**5,577**	**2,179**	**44,082**	**3,921**	**1,280,386**				
Ben. to 2020	**301,153**	**172,982**	**7,324**	**44,126**	**1,173,110**	**13,110**	**6,336**	**59,323**	**5,052**	**1,782,516**				
Costs to 2010											**59,717**	**47,731**	**44,445**	**2,568,588**
Present Values (3% discount rate)														
Rep. ben.	**83,071**	**60,992**	**6,241**	**28,110**	**499,897**	**3,633**	**1,458**	**29,655**	**3,337**	**688,376**				
Ben. to 2020	**197,293**	**110,724**	**6,241**	**31,060**	**721,004**	**9,994**	**4,968**	**44,106**	**4,510**	**1,066,559**				
Costs to 2010											**35,389**	**27,475**	**25,317**	**1,347,017**

Sources: Benefits estimated were recovered by authors using information gleaned from Byerlee and Moya (1993), Fuglie et al (1999), Sanint and Wood (1998), Zeddies et al. (2001), Hossain et al. (2003), Johnson et al (2003a, 2003b and 2020), Marasas et al. (2004) and Myrick (2016). For details on CGIAR spending and agricultural R&D spending for developing countries, see Table 4. Nominal benefits and costs expressed in U.S. dollars were deflated to 2016 values using US GDP deflator from Williamson (2019) and BEA (2020).

Notes: "Rep. ben." indicates Reported benefits. Gray highlighted estimates indicate benefit streams where the last year of reported benefit in nominal (current purchasing power) values was carried forward to 2020. See Table 8 notes in note to tables section at end of main report for details.

Annex Table 13: The value in 2016 of agricultural TFP growth since 1961

	Values in 2016				Per capita benefits in 2016						Benefits as a share of GDP in 2016				
	TFP 1961=100	AgVOP	Pop'n	GDP per capita	Total gain	All countries	Range excluding countries with negative TFP growth				All countries	Benefits as a share of GDP excluding countries with negative TFP growth			
							mean	median	min	max		mean	median	min	max
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
	index	*billion 2016 PPP$*	*million*	*2016 PPP$*	*billion 2016 PPP$*		*2016 PPP$*					*percent*			
By region															
Asia & Pacific	264	1,441	3,859	10,159	884	229	177	122	27	425	2.3	2.3	1.8	0.6	4.8
EE & FSU	142	263	436	19,611	81	185	202	208	25	335	0.9	1.2	1.1	0.1	2.3
High Income	213	777	1,174	47,364	409	349	287	173	1	1392	0.7	0.7	0.5	0.0	3.5
LAC	224	387	598	15,112	212	354	248	171	14	618	2.3	2.3	2.0	0.1	5.0
MENA	262	106	366	13,312	65	177	151	180	0	320	1.3	1.4	1.3	0.0	2.2
SSA	129	212	1012	3,871	40	39	65	55	7	176	1.0	2.4	1.7	0.3	8.2
World	**217**	**3,185**	**7,445**	**16,280**	**1,690**	**227**	**198**	**137**	**0**	**1392**	**1.4**	**1.7**	**1.1**	**0.0**	**8.2**
By income group															
High income	213	777	1,174	47,364	409	349	287	173	1	1392	0.7	0.7	0.5	0.0	3.5
Upper middle	233	1,528	2,771	16,251	911	329	236	188	0	618	2.0	1.7	1.3	0.0	5.0
Lower middle	183	771	2,923	6,573	349	119	121	115	22	304	1.8	2.0	1.7	0.3	4.8
Low income	140	110	577	2,312	21	37	69	55	7	320	1.6	3.2	3.2	0.4	8.2

Sources: Authors' estimations based on TFP data from USDA ERS (2019); value of agricultural production (AgVOP) data are from FAO (2020); GDP data are from UN (2019a) and were converted to PPP$ using PPP conversion factor from World Bank (2019); Population data are from UN (2019b). Additional Population data for Taiwan are from National Statistics, Republic of China (2020). Additional total GDP data for Taiwan, North Korea and New Caledonia are from Rosling (2018a and 2018b).

Notes: See notes to Table 11.

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