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SUMMARY OF A PRODUCTIVE PARTNERSHIP: THE BENEFITS FROM U.S. PARTICIPATION IN THE CGIAR

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ABSTRACT

For more than two decades, the United States has been an important player in a global partnership for agricultural research through its investments in the work of the Consultative Group on International Agricultural Research (CGIAR), a network of 16 agricultural research centers around the world. The primary goal of the CGIAR is to alleviate hunger in developing countries, and it has had some major successes in pursuit of this goal. But the new higher-yielding plants that feed millions in the developing world also yield more for U.S. farmers.

U.S. wheat and rice breeding have accelerated rapidly over the past two decades. From the turn of the century to 1970, an average of 5.1 varieties of wheat and 0.9 varieties of rice were released into U.S. fields each year. Since 1970, the rate has increased to 21.6 new wheat varieties and 3.4 new rice varieties per year. Comparison of experimental-plot yields of new varieties to those in production in 1970 indicates that in the absence of the new varieties, wheat yields would have been 33 percent lower in 1993, and rice yields 19 percent lower. Many of the new U.S. varieties draw on CIMMYT and IRRI research. By the early 1990s, about one-fifth of the total U.S. wheat acreage was sown to varieties with CIMMYT ancestry. Around 73 percent of the total U.S. rice acreage in 1993 was sown to varieties with IRRI ancestry.

The U.S. economy gained at least $3.4 billion and up to $14.6 billion from 1970 to 1993 from the use of improved wheat varieties developed by CIMMYT. In the same 23-year period, the U.S. economy realized at least some $30 million and up to $1.0 billion through the use of improved rice varieties developed by IRRI. U.S. government support of the wheat and rice breeding programs at CIMMYT and IRRI since 1960 has been about $131 million (in present value terms as of the end of 1993). The benefits in the United States of the CGIAR programs have far exceeded the costs of U.S. financial support. Counting only benefits in the United States, the benefit-cost (B/C) ratio of U.S. support to these programs has been greater than 26 to 1. Investment projects whose B/C ratio exceeds 1 are profitable.

Despite its past preeminence as a supporter of the CGIAR, planned U.S. contributions to the CGIAR totaled only $37.2 million in 1996, down sharply from its level in the 1980s and early 1990s. Cutbacks in research investments can undermine the benefits already gained through crop improvement research, as diseases mutate, pest problems recur, populations grow, and climatic conditions shift. Scientific research must continue apace in order to keep ahead of rapid population growth, shifting consumer demands, and other changing conditions that threaten crop yields.

CONTENTS

Page

Synopsis ii

Introduction 1

Agricultural Research Institutions and Investments 4
- The United States 4
- The CGIAR 6

Economics of Varietal Improvement Research 12
- Measuring Varietal Yield Gains 12
- Valuing Industry Yield Gains 14

Varietal Technologies 16
- Varietal R&D 16
- Varietal Releases 23
- Varietal Adoption 27

U.S. Benefits from CGIAR Research 31
- Industry Yield Performance 31
- Benefits from Research 35
- Costs of Research 40
- Benefit-Cost Comparisons 49

Conclusion 56

References 60

List of Boxes

Discovery of *Norin 10* 18

From *Dee-geo-woo-gen* to *IR8* 20

The Complexity of Pedigrees 24

SYNOPSIS

This report describes an investigation into the impacts in the United States of varietal-improvement research performed at the international agricultural research centers funded by the Consultative Group on International Agricultural Research (CGIAR). This investigation focused on two cases: the wheat-breeding work carried out at the International Wheat and Maize Improvement Center (CIMMYT) in Mexico and the rice-breeding program of the International Rice Research Institute (IRRI) in the Philippines. Both of these programs are very well known: they have been at the center of efforts to develop the high-yielding grain varieties whose use in developing countries has contributed to large increases in worldwide food supplies---increases commonly referred to as the Green Revolution.

The U.S. government, through its participation in the CGIAR, has supported these programs for many years. This funding (as well as support for the other international centers) has been a small but significant part of the U.S. international-aid program; its primary objective has been to increase food supplies, fight hunger, and otherwise improve living conditions outside the United States. At the same time, high-yielding, disease-resistant varieties of wheat and rice, although initially intended for use in developing countries, have also been available to both breeders and farmers in the United States. The contributions of these new varieties to farm technology, and to the economic health of farmers in the United States, have been important secondary outcomes of the CGIAR varietal-improvement efforts. In this report, these contributions are evaluated, and compared with the U.S. contributions to the CIMMYT and IRRI wheat and rice breeding programs.

A number of key points emerge from the study:

- New wheat and rice varieties have been introduced into the United States at an increasing rate during the past few decades, and have made a substantial contribution to the maintenance and growth of per-acre yields. Between 1900 and 1970, an average of 5 varieties of wheat and 1 variety of rice were released in the United States every year; since 1970 over 21 wheat varieties per year, and over 3 rice varieties have been released. Even in the absence of increases in biological potential, there is a continuing need for new variety introductions, so that host plant resistance can evolve to respond to the evolution of plant diseases and pests. Comparison of experimental-plot yields of new varieties to those in production in 1970 indicates that in the absence of the new varieties, wheat yields would have been 33 percent lower in 1993, and rice yields 19 percent lower.

- Compared with the size and economic importance of the crops, and in spite of the importance of a continuing flow of new-variety releases, the U.S. effort in varietal improvement in wheat and rice has been quite modest. In 1993, U.S. public institutions (mainly State Agricultural Experiment Stations) spent $28.8 million on wheat breeding research, and $9.5 on rice breeding. Expenditures on all research activities oriented towards the two commodities were $73.8 million in wheat, and $22.2 in rice. Even taking into account U.S. funding of the programs at CIMMYT and IRRI, support of research has been modest: about 70 cents per $100 dollars of wheat production, and $1.40 cents per $100 of U.S. rice production. In comparison, since 1961 the U.S. has spent between 63 cents and $1.52 per $100 of agricultural production on agricultural R&D.

- The CG breeding programs have concentrated on the incorporation of dwarfing genes into disease-resistant strains of rice and wheat. Semidwarf plants have relatively short, stout stalks, and remain upright following fertilizer-induced growth in the grain head. This responsiveness to fertilizers makes the semidwarf grains especially well adapted to economic production on relatively scarce, prime agricultural land, particularly when the fertilizer is applied to grain classes that receive a relatively high price. Thus, almost all California's bread wheat production, which is of high-protein hard red wheats, grown under irrigation, uses semidwarf plants, mostly either bred by CIMMYT breeders or derived from CIMMYT breeds. Semidwarf plants also dominate the production of the high-value bread wheats of the Northern Plains, which also have a significant component of CIMMYT ancestry. In rice, California's japonica rice is mostly grown from semidwarf plants; almost all japonica semidwarfing has roots in the IRRI breeding programs. In recent years, rice production in the southern states has increasingly used semidwarfing technology.

- The benefits in the United States of the programs have far exceeded the costs of U.S. financial support. The additional wheat and rice produced in the United States as a consequence of the CG programs has been worth over $3.4 billion dollars since 1970; U.S. government support of the wheat and rice breeding programs at CIMMYT and IRRI since 1960 has been about $131 million (in present value terms as of the end of 1993). Counting only benefits in the United States, the benefit-cost (B/C) ratio of U.S. support to these programs has been greater than 26 to 1. Investment projects whose B/C ratio exceeds 1 are profitable.

- Grain varieties in production at any point reflect many years of formal and informal breeding and selection efforts. Each step in the process involves selecting parent varieties, based on desirable characteristics, crossing the parents, growing the resulting seed, and selecting from the offspring to identify the ancestors of subsequent generations of the new variety. A number of cycles of growth and selection are typically required before a true variety emerges. The characteristics of the new variety--including yield potential and disease resistance--are due partly to the genetic characteristics of the ancestor plants, partly to the skill and luck of the breeder in recognizing and isolating these traits, and partly to the investment of time and money necessary to carry out the sometimes-lengthy breeding activity.

Different rules to accommodate differing perceptions of the relative importance of earlier and later breeding steps may be used in computing and attributing the benefits from wheat and rice breeding. Our most conservative estimate is $3.4 billion of U.S. benefits from CG wheat and rice research, giving a ratio of U.S. benefits to U.S. costs of 26:1. The upper bound estimate is $14.6 billion of benefits; a benefit to cost ratio of 112:1. So even when the most conservative rule is used to attribute U.S. value to the breeding efforts of the CG, the benefits to the United States are very high.

- The CIMMYT wheat breeding program has made major contributions to the U.S. wheat industry in four areas. First, the CIMMYT program developed many of the early semidwarf varieties. In addition to being directly introduced into U.S. production, particularly in California, these varieties demonstrated the great promise of semidwarf technology, and encouraged work in the United States to develop semidwarf varieties well-adapted to local conditions. Second, the CIMMYT program was very active in using germplasm from exotic locales, especially Brazil and Africa, to create varieties resistant to the rusts that afflict wheat crops in the United States, as elsewhere. Third, by developing the "shuttle-breeding" technique, where selections from one site are grown off-season at another site, CIMMYT breeders not only sped up the breeding cycle, but also demonstrated that varieties could be developed for use in a wide variety of growing conditions. Finally, CIMMYT has been a key institution in an international network of wheat breeders, promoting international sharing of gremplasm, ideas, and information, through both informal means and formal structures such as short- and medium-term employment of U.S. (and other) scientists, germplasm distribution functions, and sponsorship and publication of international testing programs. The calculation of benefits in this report includes only the measurable contributions of CIMMYT varieties and germplasm to varieties in production in the United States; other benefits, less tangible but also important, are not measured.

- The IRRI rice breeding program has been at the center of the development of semidwarf rice varieties, in the United States and elsewhere. In its early years IRRI brought together breeding expertise from the United States and Taiwan and drew on sources of semidwarfness from southern China and Taiwan, as well as genetic material from Indonesia and elsewhere, to develop the widely adapted and adopted IRRI varieties that gave rise to the Green Revolution in Asia and other parts of the developing world. IRRI continues to be a pivotal player in the international exchange of rice germplasm, and sponsors international varietal testing programs that provide valuable performance data for breeders everywhere. U.S. rice researchers typically spend time at IRRI, and have used IRRI expertise extensively in their work. As with the case of the benefits from CIMMYT research, the intangible scientific contributions of IRRI to the United States are not included.

- U.S. Government support for the international agricultural research centers (of which CIMMYT and IRRI are two of the better known) reached a peak in 1985 of about $78 million (in 1993 dollars), and has generally declined thereafter. In 1995, the United States contributed $39.1 million (1993 dollars) to the centers through the CGIAR. The United States accounted for 12 percent of the total CGIAR contributions in 1995, slightly less than Japan, and down from over 28 percent of the budget in the early 1980s.

The original, and principal, basis for U.S. support of CIMMYT and IRRI, and for the other centers, is the foreign-aid rationale. U.S. participation in the CGIAR has been part of the U.S. Agency for International Development (USAID) mission. The contributions of the centers to the well-being of consumers and producers in the less-developed countries amply justify the U.S. participation in the CGIAR. But there are other compelling justifications as well:

- Market failure in the funding of research extends to the international as well as to the national context. Even a country as large as the United States cannot appropriate all the benefits from its own research, even assuming the existence of effective national policy. International cooperative efforts to support public-good research can in part correct the market failure. U.S. underinvestment in wheat research (in particular) is in part corrected by the U.S. support of the international wheat research program.

- The need for constant "maintenance" breeding in response to pest and disease evolution places a premium on the continued collection and study of new germplasms, and on the identification of desirable traits. An active international community of researchers can make key contributions to the maintenance breeding effort.

The existence of rationales beyond the original humanitarian goals of CIMMYT and IRRI make it possible for the United States to "do well while doing good." CIMMYT and IRRI are important parts, in essence, of the U.S. agricultural research system. Support for these centers, and for the other institutes in the CGIAR system, can be justified on grounds of national agricultural science policy, with demonstrable benefits for U.S. producers and consumers, as well as on humanitarian and foreign policy grounds.

It is essential in science policy as in other domains, that ongoing programs be subject to ongoing scrutiny. Scarce taxpayer funds must be spent carefully, and good money should not be sent after bad. But past U.S. research aid, particularly in the form of support to the CG centers, has been anything but "bad": it has supported vital contributions to fields of science of direct and immediate benefit to the United States, and has more than paid for itself in the form of enhanced farm income and less expensive food. Relatively speaking, the United States has pitched pennies at the plant-breeding endeavor; the harvest from these modest sums has been rich indeed.

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1. INTRODUCTION

U.S. taxpayer support for international agricultural research by way of the United States Agency for International Development (USAID) is but a tiny fraction of the U.S. aid budget. From 0.54 percent in 1980, U.S. support to the CGIAR grew to 0.75 percent of U.S. aid contributions by the end of that decade. But the 1990s have witnessed a sharp decline in the U.S. contributions to the CG; a projected $37.2 million in 1996 compared with $60.1 million in 1990. Partly, and perhaps most importantly, this reflects a decline in the United States' overall commitment to foreign aid. But also, as the U.S. government tries to trim its total budget, public support for national and international research has come under closer scrutiny. Budget makers are asking whether the current R&D institutions are still needed, and questioning the basis for increasing upon, or even simply maintaining, past levels of financial support in the future.

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One way to assess the likely benefits from future U.S. support for international agricultural R&D is to evaluate the benefits from past public investments. Decisions on how best to evaluate U.S. contributions to the CG require clarity concerning the basis on which that support is given and justified. The humanitarian rationale is to help the poor; doing well for its own sake. Another, and the most compelling economic justification, is an efficiency rationale; to correct the global underinvestment in agricultural R&D that would occur if each country only invested in programs of domestic research.[1]

A third rationale is enlightened self interest, by which a country seeks to "do well while doing good." This is a variant of the humanitarian rationale where the intent is to give aid to improve the lot of those less fortunate, but choosing the form and direction of aid with an eye to the potential gains to the giver. Those gains can take various forms. For some it is the increased political and economic stability in a region or country that flows from the improved growth and food security prospects that productivity-enhancing agricultural research can bring about. Another dimension of these research benefits is the reduced pressures for immigration from poorer to richer countries. Yet another is the increased demand for imports from the aid-giving countries in response to the productivity-driven increases in the incomes of developing-

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[1]This is an international variant of the economic rationale that justifies federal funding of U.S. research in addition to state sponsorship of the agricultural experiment stations. Just as each state would underinvest in research in the hope of free-riding on the efforts of other states, so would the countries of the world collectively underinvest in research. This occurs when one country's R&D is adapted and applied elsewhere so the country incurring the research costs captures only a fraction of the benefits resulting from it.

country producers and consumers. Or, conversely, the donor country may obtain cheaper imports as a result of improved productivity overseas.

Aid-giving countries may benefit even more directly. The improved germplasm and ideas developed from research conducted by the CGIAR, and carried out partly with U.S. sponsorship, may find their way into U.S. research programs or directly onto the fields of U.S. farmers. It is these spillovers of CGIAR research into the United States that are the basis of the benefit estimates presented here.

The estimated returns are phenomenally large. That could cause some to dismiss the evidence presented here as distorted; a self-serving advocacy exercise. To be sure, this study sought to quantify the economic returns to the United States from investments made by that country in CGIAR research. And this was done in the belief that if the evidence were credible, and understood in the proper context, it could help shore up U.S. support for the CGIAR.[2] But we approached the study taking the view that, unless the evidence is credible, it has little if any advocacy value. Consequently, in assembling and analyzing the large amount of data used in this study, every effort was made to make the analysis as transparent as possible, and to provide a carefully constructed and accurate accounting of the size of the U.S. benefits from varietal improvements in wheat and rice, and the share of those benefits attributable to CGIAR research.

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[2] Certainly if the trends of the recent past are not reversed, and North American support for international agricultural research continues to diminish, a point could be reached where the CG was no longer viable as an *international* enterprise. The results below indicate that this would not be a desirable outcome either for the donors or the developing-country beneficiaries of the research aid.

2. AGRICULTURAL RESEARCH INSTITUTIONS AND INVESTMENTS

By way of background we provide a brief description of the institutional structure of agricultural research in the United States and the CGIAR, and give some indications of the overall quantities of resources committed to the respective undertakings. Greater emphasis is given to the CG because its development and operations are generally less familiar than those of the U.S. system.

THE UNITED STATES

Patterns of funding of agricultural R&D in the United States are summarized in table 1. From modest legislative beginnings in 1862 the public agricultural research system in the United States has grown to a $2.6 billion a year enterprise, involving over 10,700 scientist years employed by state and federal (USDA) agencies. In 1993 the State Agricultural Experiment Station Systems (SAESs) collectively spent $1,980 million on public agricultural research; federal agencies invested a further $692 million in intramural research. The private-sector undertook an additional $3.4 billion worth of agricultural R&D in 1992, the latest year for which estimates are available.

The allocation of research resources among commodity and other research areas has changed considerably over the years.[3] Crop research constitutes a much smaller (and declining) share of total R&D in the United States than in the CG. The United States does more research on livestock and, more noticeably, on noncommodity areas

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[3] Alston and Pardey (1996) document the evolution of public research in the United States. Christian, Pardey, and Alston (1995) provide more detail on the allocation of the funds among different areas of research.

than the CG does. The U.S. public-sector investment in wheat and rice research in 1993 of $96 million was only 3.6 percent of total U.S. public agricultural R&D. This exceeded the CGIAR (specifically CIMMYT and IRRI) investment in 1993 of $60 million in wheat and rice research. A reasonable question to ask is whether the U.S. wheat or rice research dollar would have a bigger U.S. impact if spent in the CG rather than in the United States.[4]

Table 1 Funds for agricultural R&D in the United States

	1950-59	1960-69	1970-79	1980-89	1990	1993	Annual growth rate (1950-93)
			(millions 1993 dollars per annum)				(%)
SAES research	689.1	929.1	1,276.8	1,788.4	1,935.9	1,980.3	2.9
USDA research	352.4	509.7	683.0	748.1	673.1	692.3	2.0
Total public research	*1,014.5*	*1,438.9*	*1,959.7*	*2,536.4*	*2,609.1*	*2,672.6*	*2.6*
Total private research	--	1,374.5	1,973.5	2,985.3	3,154.6	3,365.7[1]	3.7
Total extension	601.4	686.1	929.4	1,104.9	1,084.7	1,090.6	1.5

Source: Reworked version of table 14 in Christian, Pardey, and Alston (1995).

Note: Public expenditures include all USDA agencies and U.S. state agricultural experiment stations for 48 states (i.e., excluding Alaska and Hawaii). Including Alaska and Hawaii increases the 1993 SAES figure to $2024.8 million.

[1] 1992 figure.

In relation to fields of science, U.S. agricultural R&D investments include a large share (over two-thirds) spent on biological sciences (of which genetics and breeding

[4] It is noteworthy that virtually none of the funds currently committed for agricultural R&D in the United States are used to fund CG research. U.S. contributions come from aid funds, managed by an agency of the State Department (USAID), rather than research funds administered by agencies of the federal government (i.e., USDA or other science agencies) or their counterparts at the state level.

takes a significant share). Given the size of the U.S. system, this means the United States makes a very significant annual public-sector investment in science that underpins the types of work being undertaken in the CG.

In typical recent years, the U.S. public agricultural R&D system has spent nearly eight times as much as the CG system does, but with different emphasis. Recent figures may be misleading in relation to the total contributions, however, since the CG system has grown from virtually nothing over the past 25 years while the U.S. system, though growing, has not grown as quickly. The sum of real expenditures by the CG system and its antecedents over the years 1960-1993 was $7.4 billion (1993 dollars) while the sum of U.S. public expenditures over the same period was $65 billion, nearly nine times the comparable CG figure.

THE CGIAR

The CGIAR is an informal association of more than 50 countries, international and regional organizations, private foundations, and representatives from national research systems in the less-developed world, formed to guide and support a system of international agricultural research centers.

Institutions and Policies

The seeds of the CGIAR were sown by private, U.S. foundations.[5] The Ford and Rockefeller foundations pioneered a series of bilateral, commodity-oriented,

[5] More detail on the history of the CGIAR can be found in Baum (1986), Anderson, Herdt, and Scobie (1988), and Gryseels and Anderson (1991).

cooperative research efforts that linked U.S. scientists and institutions with developing-country national agricultural research systems (NARSs). Beginning in the mid-1940s, and accelerating through the 1950s, the foundations placed agricultural staff in less-developed countries (LDCs) to work alongside scientists in the national research organizations on joint-venture projects. The first such venture was the cooperative Mexican government-Rockefeller program, established in 1943 to conduct wheat research. This became the model for many of the subsequent international programs in international agricultural research; it later evolved into CIMMYT. Another notable example was the efforts of the Rockefeller foundation, in partnership with the Ford foundation, to establish the International Rice Research Institute (IRRI) at Los Baños, the Philippines in 1960. Closely following these developments came the establishment of centers at Ibadan, Nigeria in 1967 and at Cali, Colombia in 1968.

The further development of international agricultural research centers (IARCs) took place largely under the auspices of the CGIAR, which was established in 1971. The chronological institutional development of the CG system involved three phases. The first was the pre-CGIAR period when the four founding centers, noted above, developed independently. Baum (1986, chapter 2) describes "mobilizing the aid community" as follows: first, to accept the idea of the role of agricultural R&D in development and the existence of an international market failure in research, and second, to establish the financing and governance mechanisms to do something about it through international collective action. The pivotal decisions were reached at a conference in Bellagio, Italy in April 1969.

The second major development took place in the decade that followed. During the 1970s, seven centers were added dealing with different commodities or the same commodities in different agroecologies. In addition, two social science centers were created and incorporated into the CG. The mid-1980s saw the onset of political pressures to extend the research agenda and place more explicit emphasis on environmental sustainability, nutrition, and equity. There was also a perception, perhaps, that research resources were available so that extending the agenda would not involve much sacrifice of the original goals. This led to a third phase of the evolution of the CG system. Beginning in 1990, the CG establishment was extended to include five more centers, several of which had existed for a decade or more as independent operations. Thus the mandate of the system was extended to include agroforestry, acquaculture, irrigation, and forestry.

Trends in Funding

Total Funding

The CG system began modestly. Between 1960 and 1964, of the institutes that would become the CG only IRRI was operating as such. After an initial funding of $7.4 million (mainly spent on capital) in 1960, total funding rose to $0.6 million per year in 1964. By 1970, the four founding centers were allocated a total of $14.8 million annually. During the next decade, the progressive expansion of the total number of centers, and the funding per center, involved a tenfold increase in nominal funding, to $142 million in 1980. During the 1980s, funding continued to grow, more than doubling in nominal terms to reach $288 million in 1990. The rate of growth had slowed but was still impressive. In the 1990s, however, although the number of centers grew—from 13 to 18 at one point, but now 16—funding did not grow enough to maintain the funding per center, let alone the growth rates.

While the CG system has captured the attention of the international agricultural R&D and aid communities, through the impact of its scientific achievements, and through its pivotal role in the green revolution, it has spent only a small fraction of the global agricultural R&D investment. In 1990, the CG represented 1.7 percent of the annual, global investment of 14.5 billion (1985 international) dollars in public-sector agricultural R&D.[6]

Donor Roles

In 1995, 44 donors provided a total of $328.1 million to the CG. Over time the number of donors grew, and the pattern of support varied. In the beginning (using 1972 figures), the private foundations provided 50.9 percent of the total; Europeans as a group provided 12.6 percent; the United States, 18.8 percent; and the World Bank, 6.3 percent.

The picture is now very different (table 2). If providing seed money and being eventually displaced was their vision, the private foundations were successful. Their funding support has fallen in nominal terms and now constitutes less than 2 percent of the total. In 1995, European nations as a group (excluding multilateral support through the EU) provided $113.1 million, 34.9 percent. In the same year, the World Bank

[6] This "global" total excludes the former Soviet Union and Eastern European countries.

provided $50 million (15.2 percent); the United States alone provided $40.5 million (12.4 percent of the total); Japan provided $37.3 million (11.4 percent of the total).

Table 2 Funding support to the CGIAR

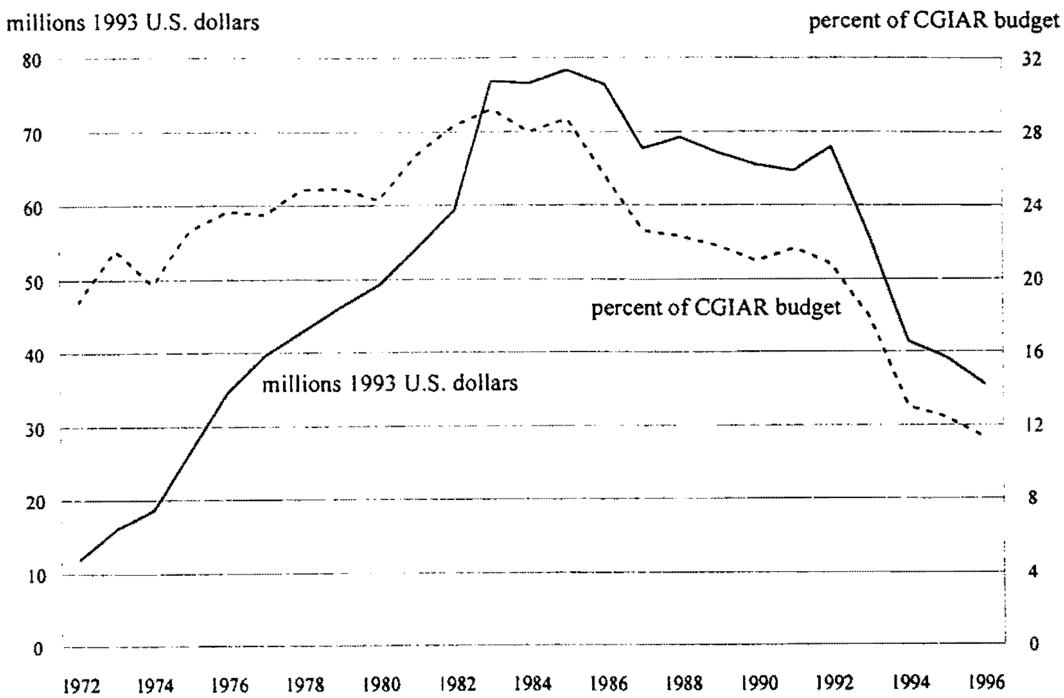
	1972-75	1981-85	1991-94	1995
	(millions 1993 dollars per annum)			
United States	18.3	69.0	57.4	39.1
Japan	0.9	13.3	31.9	36.0
Europe	19.2	53.7	98.6	109.0
Other	9.6	20.5	27.7	21.6
More-developed countries	*48.0*	*156.5*	*215.6*	*205.7*
World Bank	6.7	28.9	41.2	48.2
Foundations	22.8	4.3	6.2	6.4
Others	10.1	54.5	50.6	56.1
Total	*87.6*	*244.2*	*313.5*	*316.5*

Source: Authors' calculations based on financial reports of the CGIAR Secretariat.

The rise of support from Japan and the World Bank has been an important factor in the overall support for the system in recent years. Through institutional and government aid programs, in total the developed countries as a group contributed $322.3 million in 1995; 98 percent of the total allocation. A further $5.8 million was provided by a group of 10 developing countries. Their support represents a small (two percent) share of CG funding. Colombia and India were the largest of the LDC donors, both contributing about $1.3 million.

The U.S. government and U.S.-based foundations originally contributed two-thirds of the total. The support from the foundations has declined. The U.S. government continues to be a significant player in the system, although its position of primacy has declined, especially in recent years (figure 1). The contribution from the U.S. government grew steadily through to a peak of $60.2 million in both 1985 and 1986, after which it fluctuated around the same level until 1991, declining somewhat in

Figure 1: *U.S. Government Funding for CGIAR, 1972-96*



Source: Authors' calculations based on financial reports of the CGIAR Secretariat.

real terms. In 1992 the U.S. government contribution jumped to $66.3 million, but since then it has declined precipitously to a planned $37.2 million in 1996. Over the past several years the funding from the U.S. government has shrunk to the point where it is now equal, in real terms, to the contribution made two decades ago. This

American withdrawal of financial support has been a crucial event in the recent history of the CG. The concerns are that it represents a permanent, rather than temporary, downsizing in the U.S. support for international agricultural R&D, and that other donors may follow their example.

3. ECONOMICS OF VARIETAL IMPROVEMENT RESEARCH

To measure the economic benefits of CGIAR research in the United States, we tracked the development and release of the improved, higher-yielding varieties of rice and wheat developed by IRRI, CIMMYT, and U.S. breeders; identified the yield gains attributable to these new varieties; measured the rate and extent of their adoption by U.S. farmers during the 1970-93 period; estimated the economic value of the productivity gains from using these new varieties; and, finally, partitioned the economic benefits between CGIAR and U.S. research efforts. Comparing various streams of research benefits with corresponding streams of research costs we then identified the direct economic returns to U.S. taxpayers from investing in CG research.

MEASURING VARIETAL YIELD GAINS

Plant breeders have many objectives in breeding new cultivars, including improving yield potential, pest and disease resistance, tolerance of adverse environmental conditions (e.g., cold and drought), and a number of different grain characteristics that interact to determine quality. Apart from the determinants of quality, many genotypic characteristics have their main expression through yield. Therefore, varietal yield performance is an extremely useful summary statistic, reflecting a diversity of objectives pursued by researchers, and so varietal yield changes form the basis for the benefit calculations presented here.

In order to evaluate the impact of new varieties we need to remove the effects on yields of other factors that have not been held constant, and that may have contributed to the observed changes in yields over time. Such factors may include the year-to-year changes in weather and prices, as well as secular changes due to other changes in technology, or the evolving influence of U.S. farm bill provisions on incentives to apply variable inputs. This is not easy to do. The problem is finding an empirical counterpart to the "without new varieties" scenario.

One approach is to study experimental data on wheat and rice varieties, on the view that experimental conditions may have been more nearly constant over time than conditions in farmers' fields (with due allowance for weather and other things that clearly were not constant). Experimental yields of new varieties can be compared with yields of a numeraire variety (or basket of varieties), with the yield premium being weighted by varietal acreages to derive an overall yield gain more closely identified with the *use* of new varieties. The main problem with this approach is that it is well known that experimental yields are typically much higher than commercial yields—but it is not so well known by how much, nor whether a *gain* in experimental yields due to varietal improvement is translated one-for-one, or proportionately, or in some other way, into a gain in farmers' yields.[7]

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[7] It is widely acknowledged that there is a "yield gap" between farm and experimental conditions. Davidson and Martin (1965) compared on-farm with on-station yields for wheat, rice, tobacco, and beans, and found yield ratios ranging from 57 percent through to 95

Another approach is to use industry yields. Actual yields (or perhaps actual values with weather effects statistically removed) can be compared with yields in a base year, and the gain attributed to the new varieties. One problem with this approach is that part of the rise of the industry yields would be expected to be due to the greater use of fertilizers, since the improved varieties have been designed to be more responsive to fertilizers. It seems appropriate to correct for any additional use of variable inputs resulting from the adoption of the new varietal technologies. This can be done using either survey data or assumptions about the relationship between variable inputs and higher yields, and information on the use of variable inputs. Even still, the resulting estimate may attribute to varietal improvements benefits that arose from other changes. In the study summarized here we tried various forms of both types of approach: using experimental yields or industry yields.

VALUING INDUSTRY YIELD GAINS

An economic evaluation of wheat yield gains, and attribution to CIMMYT and other breeders, is necessarily difficult. One intuitively reasonable approach would be to calculate the gross annual research benefits (*GARB*) by multiplying the value of production of wheat, defined for the class of wheat and region of interest, by the

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percent for wheat and averaging 65 percent for rice. Whether the yield *gain* is different between the station and the farm is less certain, but it seems likely that the gains in on-farm yields will be lower than those on-station (perhaps equal in percentage terms). A narrowing yield gap in conjunction with rising farm yields—as has been observed for rice in some places—would suggest that the on-farm yield gains are greater than or equal to those on-station.

corresponding proportional gain in yield. This approach implicitly assumes that the adoption of the new varieties does not induce any change in wheat price due to either different quality or demand response to the greater quantity; a reasonable approximation given that U.S. wheat producers face world prices that are not especially responsive to changes in U.S. wheat production.[8]

While *GARB* provides a good first approximation, it is likely to overstate the benefits if input use has increased in order to capitalize on new varieties that are more responsive to fertilizers, and when supply is not perfectly inelastic. It also assumes no supply response to the changed production conditions in terms of changes in input use and changes in output in addition to those indicated by the changed yield. Thus, for wheat we have adjusted the measure of benefits by deducting the additional cost of inputs given by the change in variable costs per acre of wheat production.[9] Since variable costs have generally risen, the adjustment makes the measure lower.[10]

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[8]This approach is tantamount to using a supply and demand model in which a vertical (perfectly inelastic) supply curve shifts out against a horizontal (perfectly elastic) demand curve. Formulas for translating yield increases into supply shifts, and for evaluating those supply shifts, under various alternative specifications of the nature of technical change and of market conditions, are laid out in Alston, Norton, and Pardey (1995, chapter 5).

[9] For wheat we have not sought to distinguish changes in cost of production induced by variety changes from those induced by other changes in things such as other aspects of technology or prices. To the extent that nonvarietal factors have caused increases in costs which we have netted out from the gross benefits from new varieties, we are understating the true benefits attributable only to varietal changes.

[10] This measure is a good approximation to the total benefit regardless of the elasticities of supply and demand. Under the extreme assumption of perfectly inelastic supply and perfectly elastic demand (prices being given exogenously, as is very reasonable for most regions, if not for the United States as a whole), all benefits accrue to producers as the change in producer profit occasioned by the reduction in per bushel costs from higher-yielding varieties. Under more generally plausible assumptions about elasticities, the benefits will be

However, unlike wheat, in the case of rice we do not adjust the measure of benefits for any additional cost of inputs.[11] The reasoning is that cultural practices of rice have been relatively unresponsive to changes in varieties. While per acre input costs in rice have changed substantially over time (indeed variable costs have grown by more than the benefits from yield gains associated with new varieties of rice), much of this has been due to changes in unit costs of inputs (mainly chemicals and fuel) rather than increased quantities applied. It is difficult to attribute any real increase in variable costs per acre of rice production meaningfully to the response to new varieties.

Benefit cost analysis was conducted by converting benefits to real (1993 dollar) terms, then converting them to present values, so they could be aggregated over time, and then comparing various partitions of the benefits to various components of the costs of research undertaken in the CG centers and the United States. This analysis requires an understanding of how to partition the yield growth between U.S.-based and CG research work.

4. VARIETAL TECHNOLOGIES

VARIETAL R&D

Wheat and rice breeding became case studies of the successful application of science to the agricultural economy following a series of important advances in the

shared between producers and consumers, including foreigners, depending on elasticities of supply and demand and domestic and international shares of production and consumption.

[11] Also, the different classes of rice are largely defined by the regions where they are grown, so it becomes unnecessary to account for both class and region explicitly.

activity during the 1940s. The best-known event was the identification and application of the semidwarfing characteristic. Other improvements have also been important, however, including systematic breeding for resistance to various rust fungi, the development of broad-habitat varieties (e.g., improved drought or salinity tolerance), breeding for specific quality characteristics (such as protein content, cooking quality, grain size, shape, and color, and milling characteristics), and the development of new breeding techniques, such as "shuttle breeding."

Semidwarfing

Dwarfing refers to a characteristic of plants, where the growth of the plant's stalk is limited. Semidwarf wheats contain one of two dominant genes for dwarfness.[12] The major semidwarf gene in U.S. rice varieties is sd1.

Prior to the discovery of semidwarfism, only limited amounts of fertilizer could be applied to crops before the heavier seedhead on a longer stalk caused the head to tip over, or "lodge," making it difficult to harvest and contributing to crop losses. The semidwarfing gene makes the plant shorter. Not only is more of the plant's energy directed to the production of the edible grain, rather than inedible straw, but the plant is mechanically stronger. Otherwise, larger heads or panicles can mean reduced harvests.

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[12] These genes are labeled Rht1 and Rht2 respectively. Lines with the two genes are commonly called *dwarfs*; those with one Rht gene are called *semidwarfs*. Brennan and Fox (1995, p.1) point out that plants carrying the dominant version of these genes produce unusually high levels of the yield-promoting hormone gibberellin. Those with the recessive version of these genes produce low levels of gibberellin.

The primary source of wheat semidwarfism in spring wheats has been the *Norin 10* germplasm, a seed collected in Japan during the 1940s and brought to the United States by S.C. Salmon, a USDA Agricultural Research Service (ARS) scientist. Orville Vogel, a USDA scientist at Washington State University's Pullman station, crossed *Norin 10* with *Brevor*, a winter-wheat line with which he had been working.[13] This U.S. cross became the foundation for semidwarf varieties developed later at CIMMYT. It was used extensively in early CIMMYT breeding to create the rust-resistant, fertilizer-responsive germplasms (such as *Pitic 62* and *Sonalika*) that fueled the Green Revolution. In turn, CIMMYT varieties have been subsequently introduced into the United States for the dwarfing and other desirable characteristics, while further semidwarf varieties have been developed in the United States without any CIMMYT germplasm.

Box: DISCOVERY OF *NORIN 10*

S. C. Salmon, an Agricultural Research Service scientist helping Japan get back on her feet, observed in 1946 that Japanese farmers were growing a number of remarkably stiff, short-stemmed wheat varieties. These, when fertilized heavily, remained erect to maturity and gave excellent yields. Dr. Salmon first saw *Norin 10* at the Morioka Branch Station in northern Honshu and tells about it this way:

> "It had been seeded in rows approximately 20 inches apart in accord with the Japanese practice and on land that had been heavily fertilized and irrigated. In spite of these very favorable conditions for vegetative growth, the plants were only about 24 inches high, but stood erect. They produced so many stems and there were so many heads, a second look was necessary to verify the fact that the rows were 20 inches apart instead of the common 6 to 10 inches in the United States."

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[13]Dalrymple (1978, 1980, 1986, 1988) provides more details of the history. Brennan and Fox (1995) point out that *Brevor* was developed from crosses with Australian varieties so that, according to their parentage proportions, *Brevor* could be considered 3/8 Australian; *Norin 10/Brevor*, 3/16 Australian.

Box: Discovery of *NORIN 10 (continued)*

He brought 16 varieties of this plant type to the United States, and, through the Department's regular seed introduction and evaluation program, they were made available to breeders at seven locations in 1947-48. One called *Norin 10* is the best known and most widely used in breeding programs. Orville A. Vogel, ARS wheat breeder in Washington State, was the first to recognize its worth and to use it in a breeding program.

Norin 10 was an odd dwarf. The stems were very short, scarcely half as tall as most of our varieties, but the heads where the grains form were normal in size. On such short stems the heads appeared large indeed. The plants had as many leaves as normal plants. The straw was very strong. *Norin 10* was unsatisfactory for direct use in farms outside of Japan. However, successful use of it in crossbreeding work triggered a revolution in wheat culture which has reached clear around the earth.

The word "Norin" is an acronym made up of the first letter of each word in the romanized title of the Japanese Agricultural Experiment Station. The numerals are selection numbers; hence, we have *Norin 10*, *Norin 33*, and so on.

We have recently learned more about the pedigree of *Norin 10* from Dr. Torao Gotoh, Ministry of Agriculture and Forestry, Japan. It includes two varieties introduced from the United States: *Turkey Red* and *Fultz*. The original cross was *Fultz* x *Daruma* which hybrid in turn was crossed to *Turkey Red*. Daruma means a kind of tumbler doll in Japan, and the name was applied to a group of several varieties native to the country. The final selection from the last cross was made at the Iwate-Ken local wheat-breeding station located in the northeast section of Japan. *Norin 10* was registered in 1935.

Crossing this dwarf with the U.S. varieties posed problems. Many of the flowers were male sterile and crossed promiscuously with adjacent plants. Timing mechanism of the wheat sprout was triggered wrong; it began unfolding before it reached the surface of the warm loose soil of the Palouse area. *Norin 10* seemed susceptible to all of our diseases. Years of intensive selection and development were needed. When at last the most serious problems were solved, a new variety, *Gaines*, a winter wheat, was developed which, in its habitat of the Northwest, has set world record yields—one of 209 bushels to the acre. Fertilizer could be applied, and the plants would remain erect.

Source: Taken from Louis P. Reitz, "Short Wheats Stand Tall." USDA. *1968 Yearbook of Agriculture: Science for Better Living*, Washington D.C.: United States Department of Agriculture, pp. 236-7.

Semidwarfism did not feature in any U.S.-released rice variety until the mid 1970s—a decade after the first IRRI releases. The early IRRI success, *IR8* as well as *Taichung Native 1* (*TN1*) and *Deo-Geo-Woo-Gen* (*DGWG*)— both varieties discovered in Taiwan, but thought originally to be from southern China, and extensively used by IRRI to develop their fertilizer responsive, lodging-resistant semidwarf varieties — became the major source of semidwarfing in U.S. varieties. IRRI varieties have been used primarily as parent stock in the development of medium- and long-grain, semidwarf U.S. varieties, specifically for California and the delta states.

Box: FROM *Dee-Geo-Woo-Gen* TO *IR8*

From evidence accumulated in Japan, Taiwan, the United States, and elsewhere, we know a key factor in obtaining high yields is that the rice plant must remain erect until harvest. Indeed, there is a direct relationship between grain yield and the number of days before harvest that a rice plant lodges. The earlier the lodging, the lower the yield.

This knowledge led plant breeders at the International Rice Research Institute to seek to develop short and stiff-strawed varieties, with relatively narrow, upright leaves - plants that would resist lodging even when heavily fertilized and intensely managed.

To do this, good men were needed and luckily were at hand. The Institute's first plant breeder was Dr. Peter R. Jennings, who had served as a rice specialist in the Rockefeller Foundation's Colombian Agricultural Program. Dr. T.T. Chang, formerly with the Joint Commission for Rural Reconstruction in Taiwan, became the Institute's geneticist. And Henry M. Beachell, who for over 30 years had served the U.S. Department of Agriculture as a rice breeder at the Texas Rice-Pasture Experiment Station in Beaumont, came to play a vital role in developing the new varieties. A consultant to the Institute for 1 month in 1962, when the breeding program was being mapped out, Beachell permanently joined the Institute in 1963.

Chang, especially familiar with the rice improvement program in Taiwan, suggested that several semidwarf *indica* varieties from Taiwan might be excellent sources of short stature. Accordingly, three varieties, *Dee-geo-woo-gen*, *I-geo-tze*, and *Taichung (native) 1*, were used extensively to develop short, stiff-strawed varieties. They were crossed with such tall, vigorous, heavy-tillering (able to produce many stems on a single plant), disease resistant tropical varieties as *Peta* and *Sigadis* from Indonesia, *H-4* from Ceylon, and *BPI-76* from the Philippines.

During 1962, Jennings and his colleagues made 38 crosses, 11 of them involving either *Dee-geo-woo-gen* or *I-geo-tze* as one of the parents. Other crosses were largely between tall tropical *indica* varieties and the so-called *Ponlai* varieties from Taiwan, which are actually *japonica* varieties developed for the tropics and subtropics.

Several crosses made in 1962 were successful; others were soon discarded because of such inferior characteristics as disease susceptibility and poor plant type. The eighth cross, however, proved exceptional. From it came a variety, now named *IR8*, which has opened new vistas to rice yields and has given added hope for food sufficiency to the vast number of Asians who are dependent upon rice for their staple food.

This dramatically different rice plant was obtained by crossing *Peta*, a tall Indonesian variety that has disease resistance, heavily-tillering ability, seedling vigor, and seed dormancy, with *Dee-geo-woo-gen*, a short-statured Chinese variety. Of about 10,000 plants grown in each of the second and

Box: From *Dee-Geo-Woo-Gen* TO *IR8 (continued)*

third generations, only a few hundred were retained for further testing. In the fourth generation, plant No. 3 in row 288 was among those selected out and was appropriately designated *IR8-288-3*.

After further purification in the fifth and sixth generations, *IR8-288-3* was planted in its first yield trial. This was in March 1965, less than 3 years from the date the cross was made. In July, it surprisingly produced a computed yield of about 6,000 pounds an acre. In the cloudy monsoon season in the humid tropics when plant performance is seriously limited by insufficient solar radiation, a yield of that magnitude is excellent. Later, we found that in the dry season and under high-level management, this strain could produce over 9,000 pounds an acre and would regularly yield between 6,000 and 8,000 pounds.

Moreover, we soon learned that high yield records for the new variety were being established not only in the Philippines and Southeast Asia, but in Latin America and Africa as well. Widespread adoption of this promising new rice plant seemed assured. In recognition of its general acceptance, the International Rice Research Institute, in November 1966, announced that henceforth *IR8-288-3* would be known simply as *IR8*.

How can a new rice variety, tailored to predetermined specifications, be created so quick? Fortunately, the short stature of *Dee-geo-woo-gen* is simply inherited and can easily be incorporated into the progeny of any cross. More specifically, in this Chinese variety shortness is a simple recessive characteristic. Thus, in accordance with Mendelian laws of heredity, in the second generation, one-fourth of the plants were short and three-fourths were tall. Very quickly, therefore, a large population of short plants was obtained, from which the *IR8* variety could be selected.

The importance of *Dee-geo-woo-gen* (and of the other Chinese dwarf varieties) is comparable with that of the introduction into the United States after World War II of the Japanese wheat variety, *Norin 10*. That out of Asia came the dwarfing genes which drastically changed the yield potential of the world's two most important food grains is a dramatic coincidence.

Although we do not know the absolute origin of *Dee-geo-woo-gen*, we assume the original variety was brought to Taiwan from mainland China before the Japanese occupation. There is no clue to whether the short-stature mutation occurred in China or Taiwan. Probably, it appeared as a natural mutation and was selected by some enterprising Chinese or Taiwanese farmer before the turn of the century. (*Dee-geo-woo-gen* translates to "short legged, brown tipped," and is the sort of local descriptive name commonly used by Chinese farmers.)

If this variety was so outstanding, why had it not been used before? First of all, in Taiwan the Japanese - who preferred *japonica* rice to *indica* - concentrated their breeding efforts on development of the *Ponlai* types. Secondly, such low amounts of nitrogen were applied to farmers' fields and experimental plots that yields from *Dee-geo-woo-gen* were never exceptionally high. Happily, though, the Taiwan Agricultural Research Institute in Taipei kept the variety in its collection for many years and thus saved it for our use today. And the Chinese were the first to use it, *Dee-geo-woo-gen* being one of the parents of *Taichung (native) 1*, the first improved local variety in Taiwan.

Source: Taken from Robert F. Chandler, Jr. "Dwarf Rice - A Giant in Tropical Asia." USDA. *1968 Yearbook of Agriculture: Science for Better Living*, Washington D.C.: United States Department of Agriculture, pp. 252-5.

Rust Resistance

Rust fungi, attacking the leaves and stems of the wheat plants, have always threatened wheat yields. Since the various fungi are able to mutate, a particular control method can only work temporarily; the disease evolves in response to biological or chemical controls, and reappears in new forms. Breeding has traditionally been one of the main responses to rust infestations—new varieties are developed that resist the locally-dominant rust strains, and are replaced when new rusts appear to which those varieties are not resistant. Regional variations in the characteristics of rust strains has been one of the reasons for localizing breeding work. Such localization can be understood in both a spatial and temporal sense: high wheat yields are dependent upon the existence of wheat lines that are resistant to the rusts that are dominant in a given time and place. The rapid rate of release of wheat lines in the United States over the past few decades is in part a measure of the success of wheat breeders in keeping up with, or even ahead of, the mutations of the wheat rust fungi.[14]

Shuttle Breeding

Borlaug's early (pre-CIMMYT) work in Mexico was initially devoted to breeding rust-resistant lines. Following then-current breeding doctrine, he sought local breeding

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[14]CIMMYT's early work on rust resistance was certainly well-known to U.S. breeders of the time. While the CIMMYT introductions may not have been directly applicable to large parts of the United States, the paths already followed by CIMMYT breeders would have been noted by their colleagues in the United States. An advance in breeding technique at CIMMYT is, to some extent, an advance in breeding technique everywhere.

advances to solve local problems. However, breeding progress was limited to one cross per growing season. To speed things up Borlaug recalls

> we decided to grow two breeding cycles per year, shuttling successive breeding cycles between an irrigated, sea-level environment in Sonora in the northwest corner of the country, and the cool, rain-fed highland plateau around Toluca at 2650 meters altitude. The materials planted in November in Sonora and harvested in early May were transferred to Toluca for immediate planting. Selections at this site were in turn harvested in November and sent back to Sonora for immediate planting (1982, p.69).

Borlaug's "shuttle breeding" had two outcomes. First, it reduced the time to develop and release improved varieties from about 10 years to about 5 years. Second, the procedure yielded broadly-adapted disease-resistant varieties, which could be grown in a broad range of micro-environments. While the latter feature is likely most valuable to developing countries, with their relatively weak seed distribution and marketing systems, the demonstration of shuttle breeding, and of the possibility of successful wide-scale (if temporary) disease resistance, were important developments in wheat breeding practice.

VARIETAL RELEASES

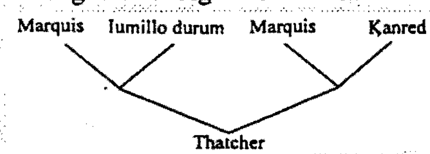
Neither wheat nor rice grew naturally in the United States; all the varieties in use today have been introduced from elsewhere, or are based on introduced varieties. In the broader sweep of history the use of scientific breeding methods to develop improved varieties is a fairly recent phenomenon. The pre-1900 U.S. releases resulted from the introduction of thousands of varieties, which, after local screening and testing, led to the release of just 35 wheat varieties and four rice varieties of any commercial significance (table 3).[15] Introduced varieties continued to be a feature of local releases during the first half of this century, although simple screening and testing techniques gave way to the development of true-to-type lines based on selections made from imported varieties, or varieties taken from the fields of U.S. farmers. Hybridization techniques, involving the crossing of parents with promising traits, were increasingly used by public R&D agencies in the United States beginning around the 1920s.

Box: THE COMPLEXITY OF PEDIGREES

A prominent feature of the recent history of varietal improvement in wheat and rice has been the increasing complexity of the family trees of planted varieties. Prior to the varietal revolution, the grain plants changed slowly through time, as the result of repeated selections, often by farmers, of plants with desirable characteristics. More radical changes resulted from the introduction of plants from other regions, followed by further selection, increasingly by breeders. During the 1950s and 1960s, the old selection method was overturned by breeders applying Mendelian genetics, who crossed different varieties, followed by purposeful selection and segregation, in order to combine desirable traits from different lines. Continued work in this tradition has contributed to detailed knowledge about the varietal origins of a large number of characteristics, including quality and protein content, responsiveness to irrigation and to fertilizers, tolerance to drought, and resistance to a variety of diseases. Breeders have exploited this knowledge by including a wide variety of ancestors in the family trees of new varieties. More recently, scientists have worked to identify the specific genes associated with various traits, so that in the future plant improvement may increasingly involve genetic-engineering techniques. The promise of the new technology rests solidly on the knowledge of traits and characteristics, that has grown out of the plant-breeding revolution.

The old tradition of plant selection is represented well by the *Thatcher* line. *Thatcher* is a hard red spring wheat, released in 1934 by the Minnesota Agricultural Experiment Station. This variety was one of the two or three most widely planted wheat varieties in the United States into the mid-1960s. Its pedigree is very simple: one parent is a cross of *Marquis* and *Iumillo Durum*, the other a cross of *Marquis* and *Kanred*. *Marquis* is a 1911 cross of landraces from outside North America, while *Kanred* is a selection from the Russian landrace *Turkey Red*. *Thatcher* illustrates two important features of the old methods of plant improvement: first, it combines a small number of well-established and widely planted varieties. Second, both it, and its progenitors, continued to be used by farmers for a very long time.

Figure: Pedigree of *Thatcher*



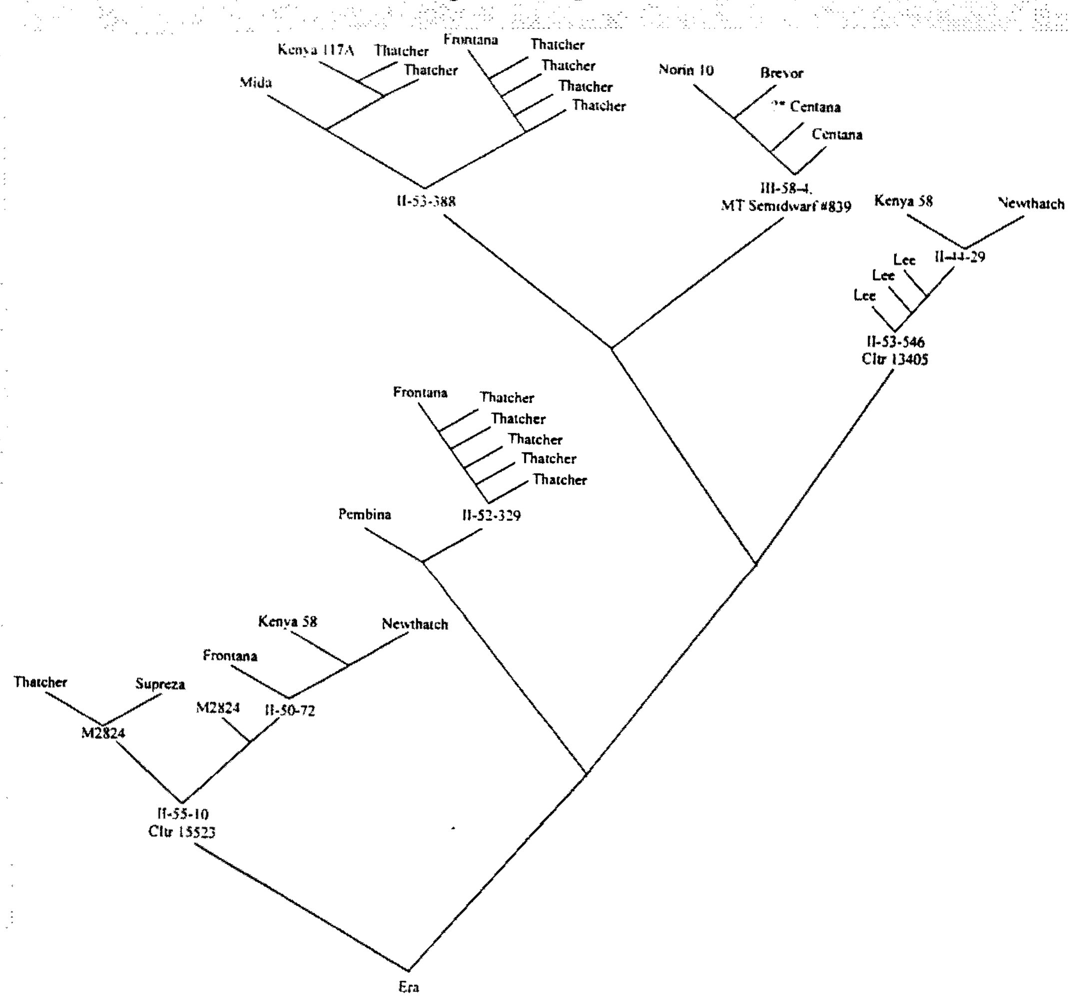
[15]Different germplasms may be different varieties, or different selections or releases of the same variety, with different performance characteristics.

Box: The Complexity of Pedigrees *(continued)*

A good contrast with the old method is provided by the *Era* variety, released by the Minnesota AES in 1970. *Era* entered widespread production in the United States in 1973, was the second most widely planted hard red spring wheat in 1974, and continued to be one of the top three varieties in that class until 1983. There has been no recorded *Era* acreage since 1984.

The change in breeding practices is obvious from a comparison of the two pedigree charts. *Era* brings together genetic material from around the world, in an effort to enhance the basic characteristics found in the *Thatcher* line. The *Norin-10/Brevor* cross contributes semidwarf stature, and consequently high responsiveness to fertilizers. Kenyan and Brazilian lines contribute resistance to rusts and other diseases. *Era* combines 12 distinct ancestors, but they are crossed and recrossed through a wide variety of experimental lines and selection, representing the work of breeders at many different sites, before the release of the final seed line.

Figure: Pedigree of *Era*



Wheat and rice breeding have been accelerating. Since 1901, the rate of release of new wheat varieties in the United States has averaged 8.8 varieties per annum; a release rate of 5.1 varieties per year for the 1901 to 1970 period, which increased to 21.6 new varieties per year after 1970. In total, 824 wheat varieties and 136 rice varieties have been planted by farmers. Although the total number of rice varieties is only one-fifth as large, the pattern of accelerating rates of varietal releases noted for wheat is mirrored in the rice release data presented in Table 3.

Table 3 Varietal releases in the United States

Period	Wheat	Rice
	(number of varieties)	
Pre-1900	35	4
1901-40	106	38
1941-50	62	8
1951-60	76	6
1961-70	113	12
1971-80	210	29
1981-90	222	39
Total	*824*	*136*
Average annual rate of release	*(varieties per year)*	
1901-90	8.8	1.5
1901-70	5.1	0.9
1971-91	21.6	3.4

Source: Authors' calculations based on data obtained online from Grain Genes databank and various issues of *Crop Science* and *The Rice Journal*.

VARIETAL ADOPTION

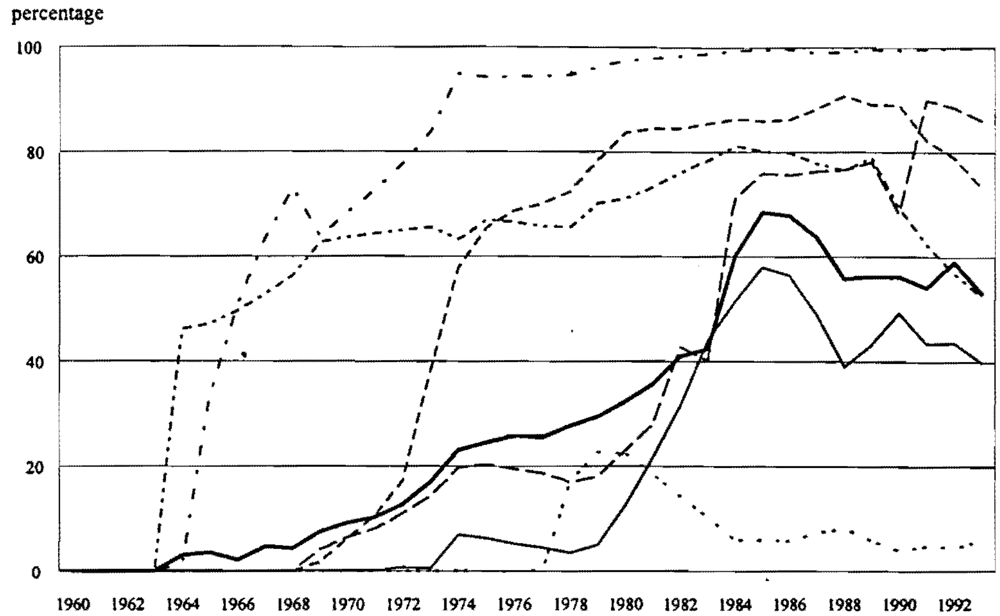
Semidwarf Varieties

A key part of the story for varietal innovation in U.S. wheat and rice production has been the introduction and spread of semidwarf varieties. Figures 2 and 3 summarize trends in the proportion of U.S. wheat and rice acreages sown to these short-statured varieties. Almost all spring wheat grown in California is now semidwarf varieties. Semidwarf varieties have also become widespread in other regions, although they are less important for winter wheat, and there are very few semidwarf durum varieties. In 1993, 53.1 percent of the U.S. wheat acreage was sown to semidwarfs; the corresponding share for rice is 75 percent. For rice too, the pattern of change has distinct geographical differences. California now grows semidwarf rice almost exclusively, a pattern that emerged shortly after the first introduction of short-statured rice varieties to the state in 1978. Now most of the production in Texas and Mississippi is also semidwarf rice. In contrast, Arkansas, the largest rice-producing state, introduced semidwarf rice much later, in 1985. While the semidwarf share of Arkansas acreage has grown steadily, in 1993 it was still only 59 percent.

CGIAR Varieties

The CGIAR contributes to U.S. varieties both directly, through transfers, and indirectly, through providing parent material. The area of "CGIAR varieties" is computed as the area sown to any varieties with any CGIAR ancestors. Figures 4 and 5 identify the U.S. wheat and rice acreages sown to varieties with CIMMYT and IRRI germplasm in their pedigrees.

Figure 2. *Semidwarf Wheat Acreages in the United States, 1960-93*



Source: Compiled by authors from data obtained from Grain Genes databank, as well as USDA and state statistical agencies on area sown to varieties.

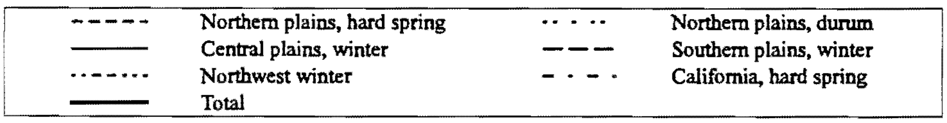
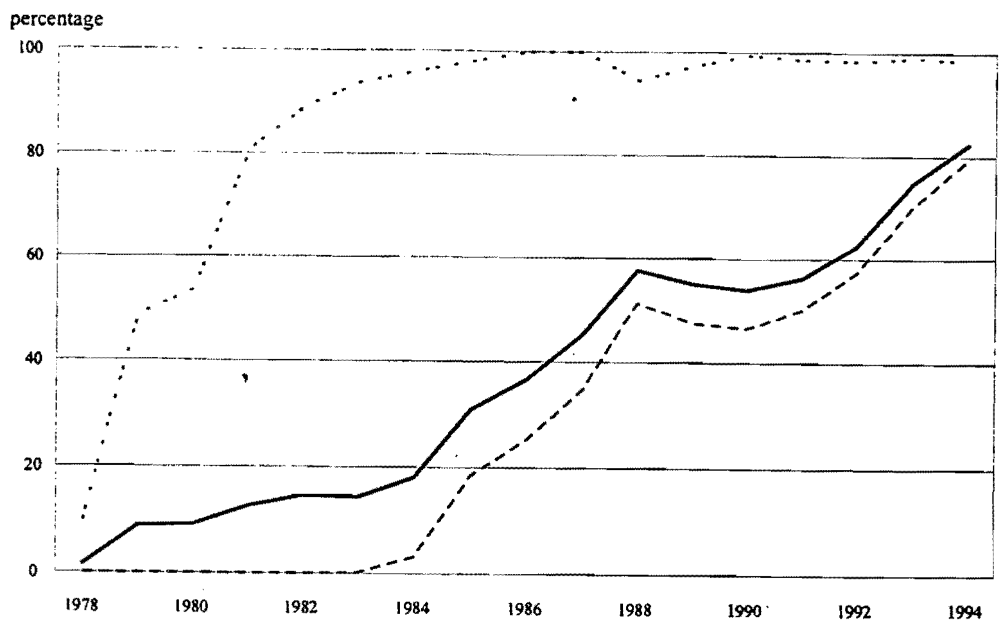


Figure 3. *Semidwarf Rice Acreages in the United States, 1978-94*



Source: Compiled by authors from pedigree and varietal data obtained from *Crop Science* and *The Rice Journal*.

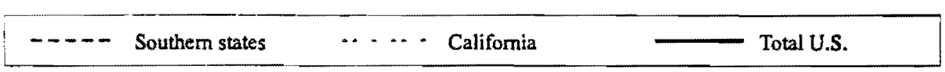
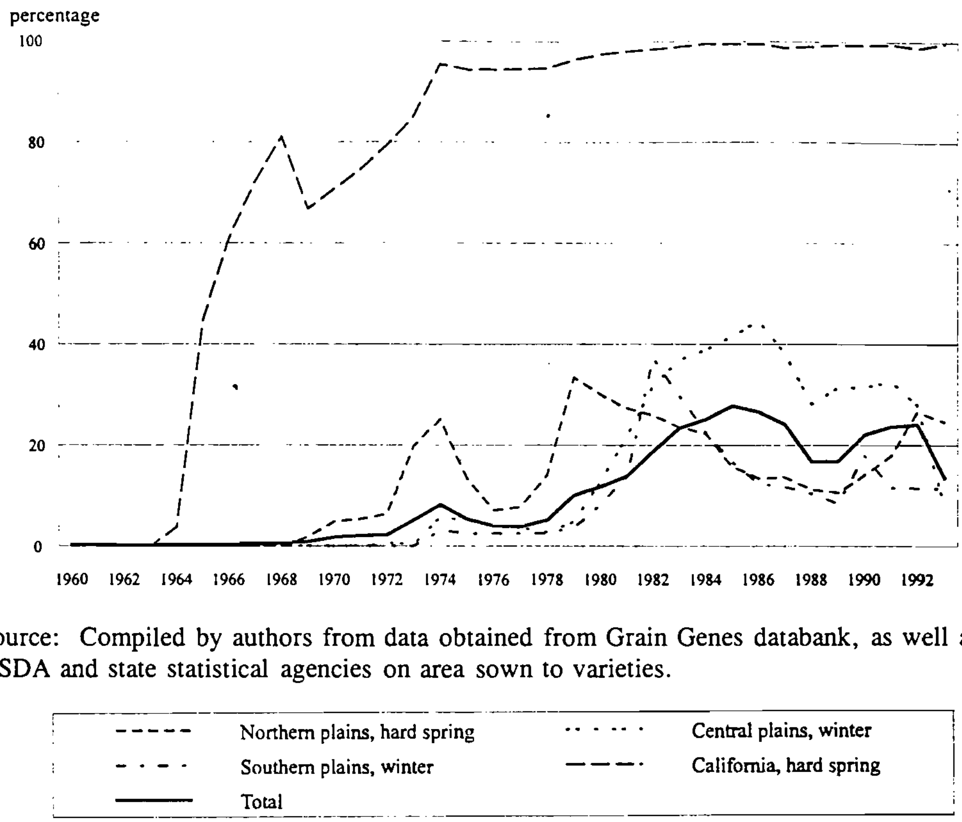
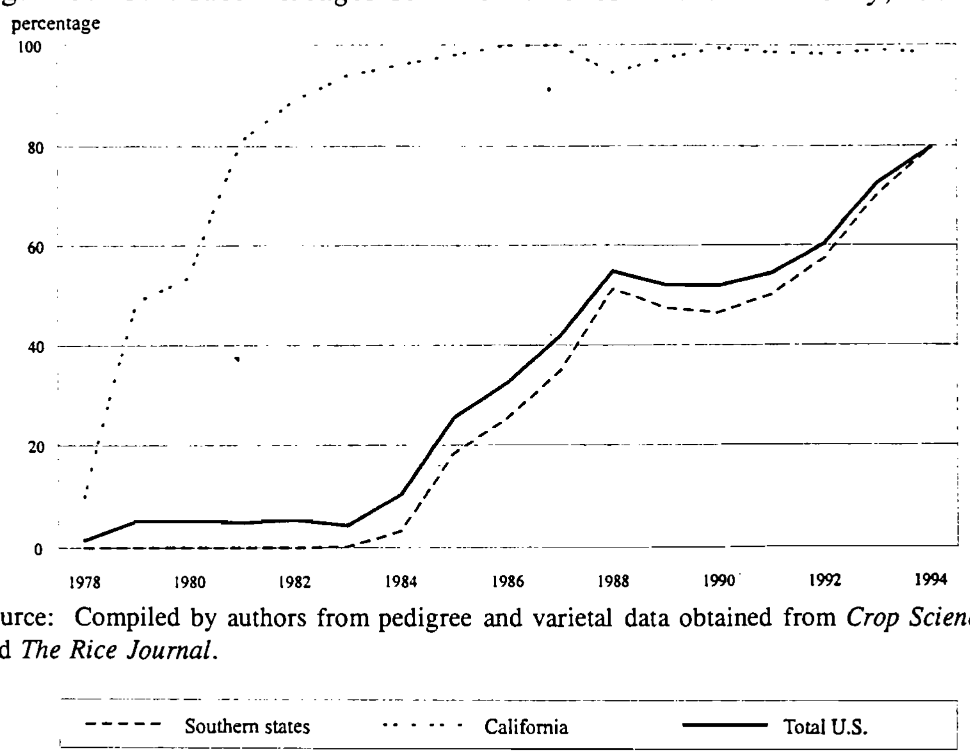


Figure 4: *U.S. Wheat Acreages Sown to Varieties with CIMMYT Ancestry, 1960-93*



Source: Compiled by authors from data obtained from Grain Genes databank, as well as USDA and state statistical agencies on area sown to varieties.

Figure 5: *U.S. Rice Acreages Sown to Varieties with IRRI Ancestry, 1978-94*



Source: Compiled by authors from pedigree and varietal data obtained from *Crop Science* and *The Rice Journal*.

By the early 1990s, about one fifth of the total U.S. wheat acreage was sown to varieties with CIMMYT ancestry. CIMMYT material first featured in California spring wheat acreages in 1964; by 1974 over 90 percent (and in 1993 virtually all) of this crop was grown with CIMMYT based or bred varieties. Beginning in 1969, CIMMYT germplasm also appeared in the spring wheats grown in the Northern plains states of Minnesota, North Dakota, South Dakota, and Montana; by 1993, about one quarter of this acreage was sown to varieties with CIMMYT ancestry. Beginning in the mid- to late 1970s, about a decade after CIMMYT varieties were first used by California farmers, the winter wheats grown in the Central and Southern plains states (Nebraska, Iowa, Kansas, Colorado, Oklahoma and Texas) involved varieties that began to draw on CIMMYT germplasm. CIMMYT material appeared later, and was never as widely incorporated into the winter wheats grown throughout these plains states as it was in spring wheats grown elsewhere in the United States, but these CG varieties had a sizeable influence nonetheless. U.S. breeders have incorporated desirable traits in CIMMYT germplasm into locally bred varieties, and so CIMMYT wheats have had a significant indirect impact on these more northerly regions in recent years.

Around 73 percent of the total U.S. rice acreage in 1993 was sown to varieties with IRRI ancestry. Very few U.S. acres have been sown directly to IRRI varieties; much of this varietal transfer has occurred as IRRI germplasm has gradually found its way into locally bred varieties. Unlike the case of wheat, where a number of CIMMYT varieties were widely used in California, few IRRI varieties have been locally released or gained any commercial significance in the United States. Indeed, only two IRRI varieties have been released locally—*Jasmine 85* in 1991 and *Jasmine* in 1994. Both these long-grain varieties have yet to be planted on any significant acreage; *Jasmine 85* peaked at just one percent of Texan acreage in its year of release and only 75 acres were planted to *Jasmine* in Louisiana in 1994. Yet while few U.S. acres have been planted directly to IRRI varieties, a substantial amount of IRRI material does feature in the pedigrees of many contemporary U.S.-bred rice varieties (figure 5).

5. U.S. BENEFITS FROM CGIAR RESEARCH

In this section we draw together the varietal yield performance, uptake, and pedigree data for U.S. wheat and rice and use these data, in conjunction with relevant market data, to estimate the overall economic benefits to the United States from varietal improvement research. This is a measure of the *total* benefits from varietal research, be it from U.S., CGIAR, or other sources of varietal improvement. We then identify the CGIAR contribution to the total benefits and compare these benefit streams with various streams of research costs to calculate various cost-benefit ratios.

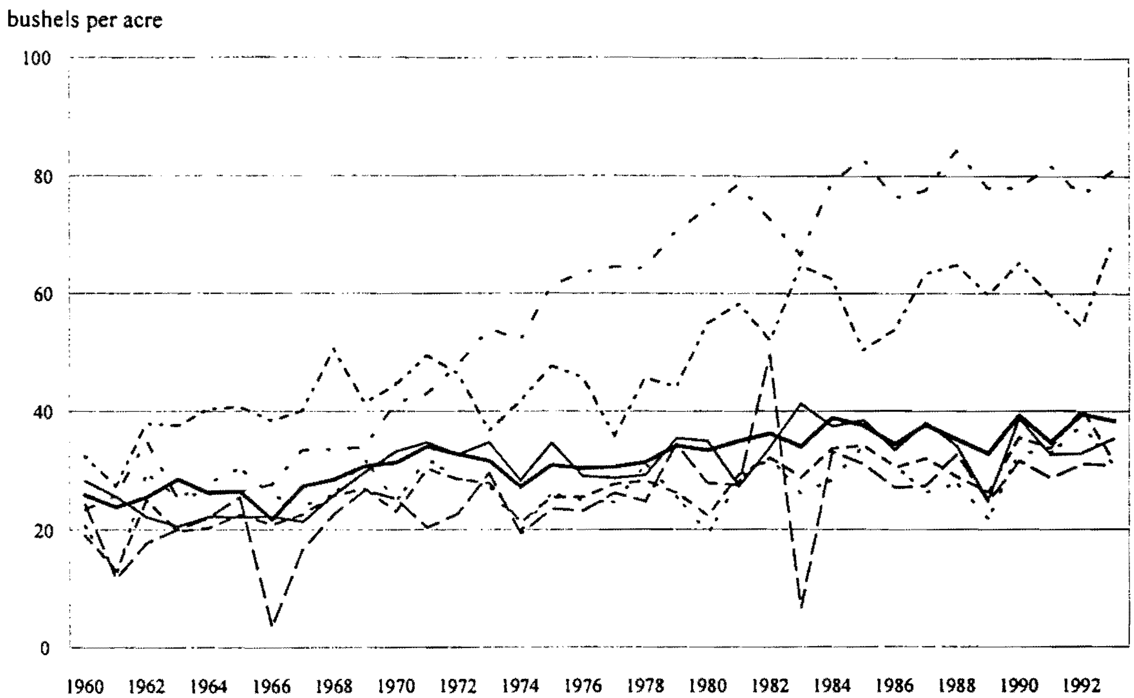
INDUSTRY YIELD PERFORMANCE

To place the varietal yield performance of the U.S. wheat and rice sectors in proper perspective it is helpful to have some understanding of the overall pattern of industry yield gains during the past three decades.

Wheat

The data on industry yields confirm a number of points (figure 6).[16] First, yields grew substantially in all regions, particularly in the 1960s and early 1970s. Second, the

Figure 6. *National Average and Regional Wheat Yields, 1960-93*



Source: USDA, U.S. Crop Reporting Board and National Agricultural Statistical Service.

- - - - -	Northern plains, hard spring	·· · ··	Northern plains, durum
———	Central plains, winter	— — —	Southern plains, winter
·· - - - ··	Northwest winter	- · - ·	California, hard spring
━━━	Total		

[16]To compute aggregated experimental yields, the regional average (across all experimental sites) of experimental yields for each variety in each year were multiplied by the corresponding acreage planted. Planted acreage data were built up from state-level acreage-by-variety data obtained from USDA through 1984 and thereafter from state statistical agencies.

most dramatic growth in yields has been in California and in the Pacific Northwest, both of which were early centers of introduction of semidwarf wheat varieties.[17] In California, yields doubled between 1955 and 1971, and have approximately doubled again since. Presumably, this resulted not only from the introduction of new varieties, but also from the irrigation and intensive fertilizer applications that the new varieties made possible. In the Northwest, driven by the early spread of two semidwarf varieties, *Gaines* and *Nugaines*, industry yields grew by 81 percent between 1955 and 1968; in recent years, yields in the Northwest have been around 60 bushels per acre, or about 20 percent higher than their late-1960s peak.

Rice

National average rice yields in the United States have also risen dramatically in conjunction with the progressive adoption of improved (semidwarf) varieties since the 1970s (figure 7). Yields have grown from a national average of 3,423 lbs per acre in 1960 to a three-year (1992-4) average of 5,738 lbs per acre;[18] an increase of almost

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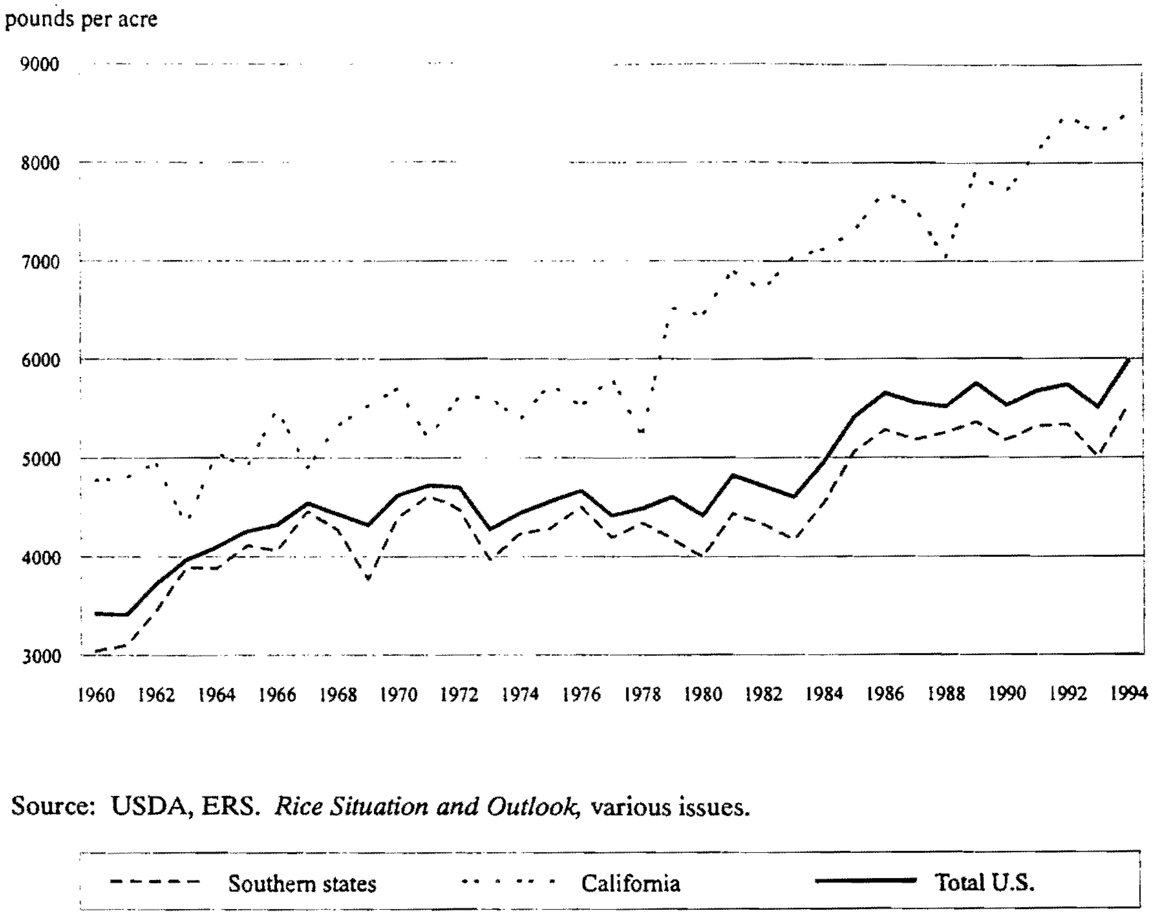
[17] Wheat produced in different locales has different end-uses. In the Northern Plains states (Montana, Minnesota and the Dakotas), spring wheats are grown, including the hard (high protein) red wheats used for bread-making, and durum wheats used for pasta. In the Central plains (Nebraska, Colorado, Iowa, and Kansas) and Southern plains (Oklahoma and Texas), winter wheats dominate, primarily hard red and white wheat. The Northwest (Washington, Oregon, and Idaho) also grow winter wheats which are soft wheats useful for biscuits and noodles. California, like the Northern Plains states, grows high-quality (and value) hard red spring and durum wheats.

[18] Using 1993 as the basis of comparison is problematic: it was a particularly poor year given the exceptionally heavy rains (and flooding) in April that delayed plantings throughout much of the south.

Figure 7: *National Average and Regional Rice Yields, 1960-1994*



Source: USDA, ERS. *Rice Situation and Outlook*, various issues.

70 percent, or an average rate of gain of 1.6 percent per annum. Over the same period the proportion of rice acreage sown to semidwarf varieties grew from zero to 75 percent. The yield growth has not been uniform across the nation; nor are the levels of yields. Rice yields are relatively high in California and lowest of all in Louisiana. These yield differences across regions, and the growth in yields over time, are attributable to a number of different factors, including new varieties.[19]

[19] Its is also worth pointing out there are geographical differences to the types of rice grown in the United States. Indica varieties are native to and widely grown throughout South and Southeast Asia: their sensitivity to cool temperatures and daylength limits their range of adaptability to the humid tropics but means they are suited to the delta region of the United

BENEFITS FROM RESEARCH

In this section we report the total U.S. benefits from wheat and rice variety yield improvements, and the portions of those benefits attributable to the work of the CG centers, with those portions computed according to different rules. First we discuss the attribution problem. Then we discuss the measures of benefits.

Attribution of Benefits

There is no accepted procedure for determining how much of the desirable qualities of a particular semidwarf wheat available today in the United States is due to work of the U.S. breeder who produced the last cross; nor how much is due to the breeders beforehand who produced its parents, and grandparents?[20] Our approach was to use a set of plausible rules to attribute benefits between breeders in the United States and elsewhere. One way is to share the *genetic* content of a variety equally between its parents, and by serial division, among all its antecedents. But the contribution of the parents, grandparents, and so on, to performance of the offspring

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States. Japonica varieties were first grown in China and then spread to Japan. They are tolerant of cool temperatures and thrive in sub-tropical to temperate climates making them ideally suited to the growing conditions found in the swampy areas of the Sacramento Valley in northern California. Through modern breeding efforts the short-grained varieties that once dominated California production (69 percent of production in 1960) have been largely replaced with medium-grain varieties that now account for 97 percent of California production.

[20]It is useful to keep these issues about attributing scientific credit for varietal improvement separate from issues about rights to shares of any benefits, since the economic issues about compensation and so on involve additional considerations—such as important implications for incentives to invent. A key point is that the fact that breeders have used farmers' varieties as nursery stock does not diminish in any way the continued availability of those varieties to the farmers (Wright 1996).

in a particular dimension, say yield or quality, cannot be attributed accurately in this fashion. *Norin 10/Brevor* provided only 15/64th of the *genetic content* of the variety *Yolo*, but may be owed a greater share of its *value* than that.

Thus the question remains how do we use this pedigree evidence to isolate the effects of CIMMYT and IRRI—indirect though some of these effects may be—on the U.S. wheat and rice industries?[21] A multiplicity of rules have been used in the past to attribute benefits from variety improvement across stages of varietal development. In essence, these rules vary in terms of the benefits they ascribe on the basis of breeders' efforts (i.e., using crosses as the basis of attribution) and on the basis of various views on genetic content (i.e, using heritability of important traits as the basis of attribution), and also vary in terms of the weight given to recent versus distant past aspects of the development of the new variety. Plausible arguments could be made in support of any one of these rules—which has major implications for the attribution of benefits—but the choice of a particular rule is essentially arbitrary.

A reasonable approach, and the one we adopt here, is to provide a lower and upper bound on the likely CG share of U.S. benefits. To generate the upper bound we used an **any ancestor rule** that takes a value of 1 for a variety that has *any* CG germplasm in its pedigree, and 0 otherwise. Corresponding "CGness" indexes for wheat and rice varieties grown in various regions and the United States as a whole are obtained by multiplying the respective regional or national acreage shares of each

[21] And, conversely, identifying the impact of the United States on the CG is also difficult. This is even more so if we go beyond simply tracking the flow and exchange of germplasm to also identify the flow and impact of ideas, knowledge, scientists, and so on.

variety by the appropriate CGness measure obtained for each variety using this zero-one attribution rule. This approach attributes all the benefit to the CG for any U.S. variety that contains CG germplasm, irrespective of the importance of that germplasm in the overall genetic makeup of the variety.

The most conservative estimate of the CG share of the overall benefits from improved varieties was obtained with a **geometric rule** that gives geometrically declining weights with the highest weight assigned to the most recent breeding work. Here we assign weights back to the level of great-grandparents, beginning with 50 percent of the benefits from a variety being attributed to its breeder, 1/8 to the breeder of each of its parents, 1/32 to the breeder of its grandparents, and 1/64 to each great grandparent.[22]

Total Benefits

Total U.S. benefits from varietal improvements were estimated for each year of the 1970-1993 period, and reported in real 1993 dollars. This total, along with the portion attributable to wheat and rice varieties from CIMMYT and IRRI, and the corresponding U.S. values of production for each crop are summarized in table 4. In present value (1993 dollar) terms the economic benefit to the United States from improved wheat varieties totaled $42.9 billion from 1970-93, equivalent to 10.6 percent

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[22] Other partitioning rules are possible and were estimated and included in the longer, more technical version of this report.

of the total value of U.S. production. The overall benefit from improved rice varieties was $5.4 billion, or about 8.0 percent of the total value of U.S. output since 1970.

The benefit figures in table 4 are based on measures of varietal yield gains relative to a set of numeraire varieties, combining information on experimental yield relativities with actual industry yields. In consequence, sometimes the yield "gain" for a variety is negative (when the variety does not do as well as the numeraire in the trial), and the values vary from year to year, reflecting weather effects on the industry yields

Table 4 U.S. value of production and benefits from varietal improvements in wheat and rice

	Production value	Benefits		
		Total	Any ancestor	Geometric
		(millions 1993 dollars)		
Wheat				
1970	6,411.9	135.0	32.7	28.6
1975	18,333.6	1,899.5	120.8	106.4
1980	15,690.3	2,088.8	320.7	212.2
1985	10,225.9	1,418.6	1,121.9	169.9
1990	8,430.2	581.2	228.8	47.2
1993	7,756.3	1,482.7	602.4	54.8
Rice				
1970	1,596.1	92.3	0	0
1975	2,655.1	166.5	0	0
1980	3,176.8	220.0	18.8	0
1985	1,146.2	138.4	50.2	2.1
1990	1,139.5	170.2	95.3	4.3
1993	1,231.6	217.8	163.3	3.6

Source: Authors' calculations.

that are used to scale the measures of gains. An additional feature of our estimation approach is that the benefits of maintenance research -- research that restores the past yield gains "lost" to the effects of new pests and diseases -- are included, along with research that improves upon past yield potentials.

The national level benefit streams reported in table 4 mask some interesting and significant differences in the pattern of benefits across states and regions within the U.S. Major wheat producing regions, such as the Northern Plains for spring wheats, and the Central Plains for winter wheats, have realized large benefits from yield gains. This is particularly clear in the Northern Plains; annual production of bread wheat is now 234 million bushels greater than it would have been in the absence of yield improvements. Even in the Central Plains, where yield gains have been about half as great, annual production is 166 million bushels greater than it would have been using the older varieties. In California, where yield gains have been larger, and have appeared earlier, the gain has been applied to a much smaller acreage, so that overall production gains have been less than one tenth as great as in the Northern Plains.

For rice too, there are significant differences in the spatial distribution of benefits from varietal improvements that reflect differences in the rates of adoption of the new varieties, the yield performance of new versus old varieties, and differences in the size of the industry affected by these new technologies. About 15 percent of the total U.S. benefits accrued to California and the rest to the delta states; Arkansas accounted for 42 percent of the total, Louisiana 24 percent, and Texas about 13 percent.

CG Share of U.S. Benefits

The total benefits represent gains to the United States from the use of improved wheat and rice varieties since 1970, irrespective of the source of those varietal improvements. Table 4 also reports upper- and lower-bound estimates of the share of those total gains attributable to CIMMYT and IRRI varieties. Using the "any ancestor" approach to attributing benefits, about 32 percent (or $13.6 billion) of the total wheat benefits can be attributed to CIMMYT varieties, and about 19 percent (or $1.0 billion) of the overall rice benefits can be attributed to IRRI varieties. The CG share is clearly sensitive to the choice of attribution rule used to form this estimate. Taking the most conservative view, and using the geometric attribution rule, about $3.4 billion of wheat improvement benefits can be attributed to CIMMYT varieties; for rice the corresponding lower-bound estimate is $36.7 million attributable to IRRI varieties.

COSTS OF RESEARCH

Constructing the cost data required for this study meant dealing with three main issues: matching the estimated benefit stream with an appropriate stream of costs, deciding on the appropriate coverage in terms of U.S. and CG R&D institutions and activities, and distinguishing funding from the United States from other sources of funds for the CG.

Matching Costs and Benefits

Ideally, a cost-benefit analysis of varietal-improvement research would compare the benefits from a particular variety to the costs of developing that variety, or the benefits from a set of new varieties (perhaps all new varieties), to all varietal-development costs. The two value streams are not contemporaneous: research costs occur first, with benefits occurring only after some period of time. Not only is there a lag between research and the first release of a new variety, but there are lags between release and first adoption, and between first adoption and widespread use. These lags can be quite long. For instance, the lag between the initiation of research investments and the availability of new wheat and rice varieties is often around 7 to 10 years. The adoption process could span another decade, or more. Further, since some benefits from one cross can be achieved through planting its offspring, as well as by adopting the variety itself, the effects of a particular varietal innovation can persist for a very long time, even after the first variety becomes displaced. These dynamics make the inter-temporal matching of streams of benefits and costs of variety innovations tricky.

Institutional and Activity Coverage

In our efforts to evaluate the economic benefits to the United States from U.S. investments in CG research we found it expedient to first evaluate the joint effects of CG and public-sector agricultural R&D in the United States and subsequently compare various research benefit streams against corresponding cost streams. The costs of U.S. wheat and rice research includes research performed by the State Agricultural Experiment Stations and federal facilities operated by the USDA.

There is some privately conducted wheat-breeding research in the United States. While these private programs have led to a number of commercial introductions, there is very limited test-plot data, so it has been impossible to compute the yield gains, and resulting benefits, due to the direct introduction of privately-bred varieties. Private efforts may also have contributed to the benefits measured here through contributions of germplasm. However, in very few cases has private germplasm been found in the genealogies of the public varieties, so only a small share of the benefits measured here could be attributed to unmeasured private breeding efforts.

CG costs include wheat and rice research undertaken by CIMMYT and IRRI, respectively. Wheat research by the CG is also undertaken by the International Center for Dryland Agriculture (ICARDA) in Aleppo, Syria while the Centro Internacional de Agricultura Tropical (CIAT) in Cali, Colombia, the West Africa Rice Development Association (WARDA) in Bouaké, Côte d'Ivoire, and, in past years, the International Institute of Tropical Agriculture in Ibadan, Nigeria also develop and diffuse new rice varieties. But CIMMYT and IRRI account for the lion's share of wheat and rice breeding research in the CG and are the centers with the longest histories of such research.

Because the stream of benefits reported here relates only to the gains from varietal improvements, the most direct comparison is with the costs of varietal improvement research. Developing improved varieties involves input from more than plant breeders. The costs of all associated work undertaken by agronomists, plant pathologists, entomologists, and so on were included in our estimates of CIMMYT, IRRI, and U.S. crop improvement research costs. Indirect or overhead costs relating to physical capital and the management and support costs required to undertake the research were also included. The intent was to develop a crop-improvement cost series for each agency that was as comprehensive as possible.

U.S. Share of CG Research Expenditures

The wheat and rice improvement research done by CIMMYT and IRRI are funded by a number of donor countries and organizations. To identify the U.S.-funded component of this research is difficult. The United States provides some of its CG funding for specific research projects and programs. But much of its support is in the form of "core" funding earmarked for particular centers within the CG rather than specific aspects of work within a CG center. Moreover, the U.S. support includes private funds provided by the Ford and Rockefeller foundations as well as government support administered by the United States Agency for International Development.

In this study a variety of cost measures were identified and used as a basis against which to compare the U.S. benefits. With regard to the source of funds, it was possible to identify the U.S. support to CIMMYT and IRRI separately from that of other donors, and to distinguish between public (i.e., taxpayer) and private (i.e., Ford and Rockefeller Foundations) components of that support.

Wheat and Rice Research

In 1993, the United States spent $74 million on wheat research, over six times the corresponding costs for CIMMYT. For rice the relative sizes of the investment in U.S. and CG research are reversed; IRRI spent $48 million, more than double the investment in U.S. rice research. These various research investment relativities reflect the importance of wheat and rice production in U.S. and world agriculture. The United States is an important wheat producer in global terms. Wheat is among the top ten agricultural commodities by value in 26 states of the U.S. It is grown in states stretching from California, across the northern plains and mid-western region of the country, to northeastern states such as New York and Pennsylvania. In 1993 the United States produced 65 million metric tons of wheat, about 11.6 percent of the world's total output of 564 million metric tons.

While rice is an important crop in California and the delta states of Arkansas, Texas, Louisiana, Mississippi, and Missouri, total U.S. production in 1993 was less than two percent of world output of 527 million metric tons of paddy (i.e., rough) rice. Asian countries such as China, Indonesia, India, and Thailand account for a majority of the world's rice production and a sizable share of rice consumption, where the crop is the staple foodstuff of many of the world's poor people. But rice consumption is on the rise in richer countries too. The premium quality of U.S. rice varieties means that, in contrast to its small share of global production, the United States is a major exporter, accounting for nearly 18 percent of internationally traded rice. Total wheat and rice research costs for CIMMYT, IRRI, and the United States are summarized in table 5.

Varietal Improvement Research

Wheat-Improvement Research. The wheat-breeding program was one of the original activities at CIMMYT, with a budget of $436,000 in 1967, about one half of the center's total research budget.[23] Since the 1970s the breeding program has generally increased its share of total CIMMYT wheat research. Both the breeding and non-breeding wheat

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[23]The term breeding is used in the text as a shorthand for the more comprehensive, and for our purposes more appropriate, set of activities called crop improvement research.

Table 5: Total wheat and rice research costs

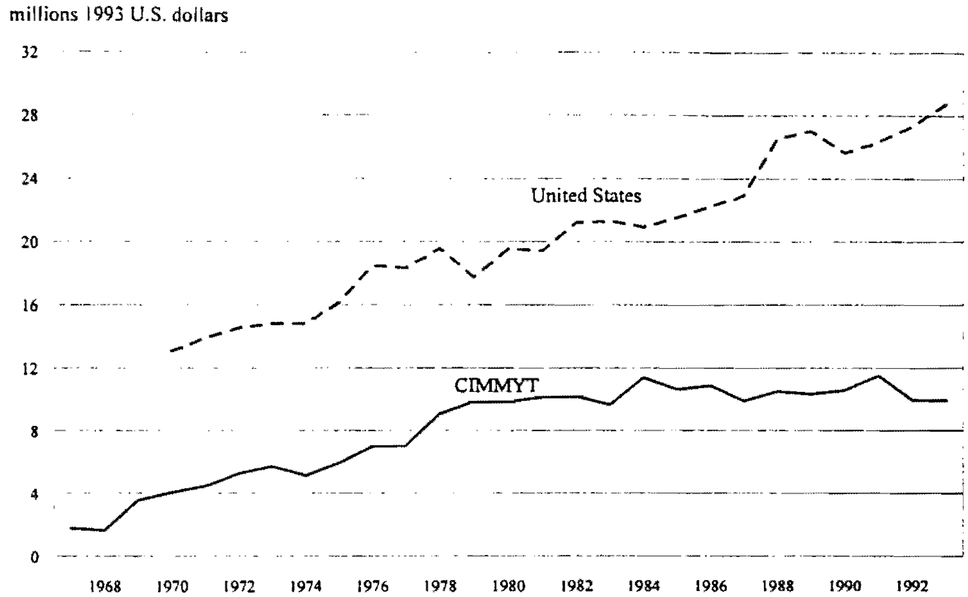
	Wheat			Rice		
	U.S.	CIMMYT	Total	U.S.	IRRI	Total
			(millions current dollars per annum)			
1970	12.2	1.5	13.7	2.4	2.8	5.1
1980	28.0	6.9	34.9	7.4	21.1	28.5
1990	67.6	11.0	78.7	18.9	40.4	59.3
1993	73.8	11.8	85.6	22.2	48.2	70.4
			(millions 1993 dollars per annum)			
1970	42.9	5.3	48.2	8.4	9.7	18.1
1980	47.9	11.7	59.6	12.6	36.1	48.7
1990	73.6	12.0	85.7	20.6	44.0	64.5
1993	73.8	11.8	85.6	22.2	48.2	70.4

Source: U.S. data are principally from unpublished USDA Current Research Information System data files. CIMMYT and IRRI costs were compiled by the authors from unpublished financial records of the respective institutes with the assistance of the senior financial officers from both institutes.

research programs continued to grow through 1984, when the breeding budget was over \$11.4 million (1993 dollars) and the budget for other wheat research was about \$2.5 million. Since the mid-1980s the breeding budget has remained reasonably constant in real terms. It declined in the last two years of our sample, as did CIMMYT's overall expenditures on wheat research. By 1993 wheat-breeding costs were \$9.9 million, out of a total wheat research budget of \$11.8 million.

Although U.S. public-sector wheat research is performed by both state and federal agencies, the federal government has typically provided around two-thirds of the funding to support this research. In 1993 the federal government share was 69 percent, with 19.5 percent funded by state governments, and the remainder from industry and other sources. Historically the non-breeding aspects of this program accounted for a substantially larger share of the total wheat research budget but breeding research has grown at a much faster pace over the past few decades.[24] In 1970, wheat-oriented public-sector research, including all disciplines and activities cost, $43.0 million (1993 dollars), one third of which went to breeding research. By 1993, total wheat R&D spending had increased to $73.8 million, 39 percent (or $28.8 million) of which went to breeding. Figure 8 shows the evolution of wheat-improvement research costs for CIMMYT since 1967 and the United States since 1970.

Figure 8: *Wheat-Improvement R&D Costs, 1967-94*



Source: Unpublished data provided by CIMMYT and USDA Current Research Information System.

Rice-Improvement Research. The annual costs of IRRI's varietal improvement research grew by 10.8% per annum from 1961 to 1993, marginally faster than the growth in

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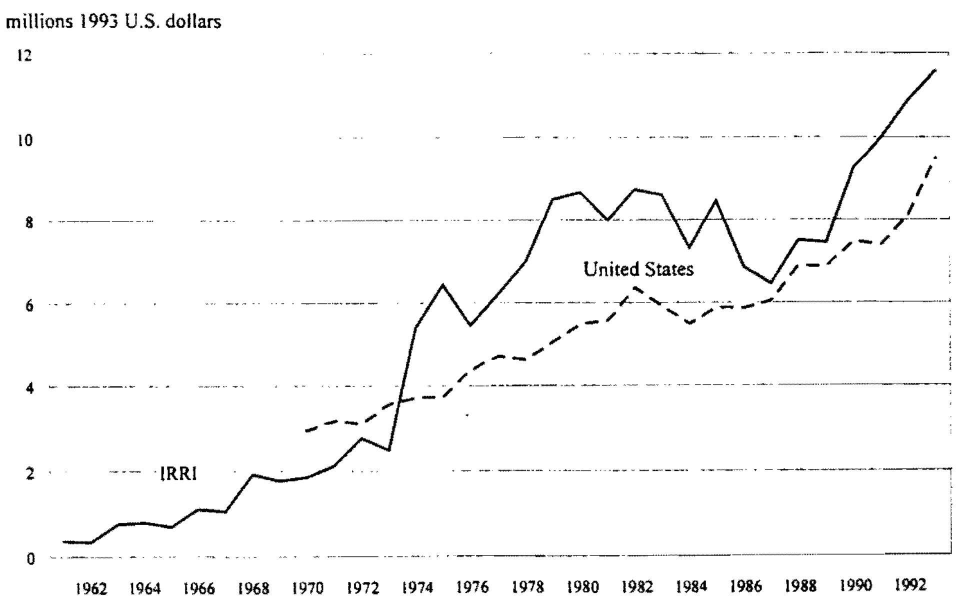
[24]The basis of our calculation of the U.S. costs of varietal improvement in wheat and rice are the research expenditures reported by public-sector research performers, and other performers of government-funded research. The research agencies of the USDA—including, in particular, the Agricultural Research Service (ARS) and the State Agricultural Experiment Stations (SAESs)—provide programmatic and budgetary information on all of their research and development activities to the USDA's Current Research Information System. In addition, other research performers, primarily universities, also report details on projects funded by the USDA. Among the programmatic information available is the commodity orientation and discipline. We identified all projects containing a wheat or rice orientation, and divided them into "breeding" and "other." This database covers budgetary obligations back to 1970.

IRRI's overall real expenditures. By 1993, IRRI's rice breeding program was costing $11.6 million per annum. This was about 24% of the institute's total annual budget, up from the 19% experienced in 1970 and the corresponding share that was common for IRRI during its pre-CG years.

Breeding research in the United States has grown substantially too; from $3 million in 1970 to $9.5 million in 1993 (1993 dollars). While both federal government support for rice research and state government and other support have increased, the most rapid growth has been in state and other funding. In 1970, 58.6 percent of SAES rice research was federally funded, 11.9 percent was state funded, and 29.5 percent was funded by other sources, including private industry. In 1993, federal government funding was 39.3 percent of total funds, state sources accounted for 27.1 percent of the funding, with industry and other sources accounting for the remaining 33.6 percent. Rice breeding costs since 1960 for IRRI and 1970 for the United States are plotted in figure 9.

Figure 9: *Rice-Improvement R&D Costs, 1961-94*

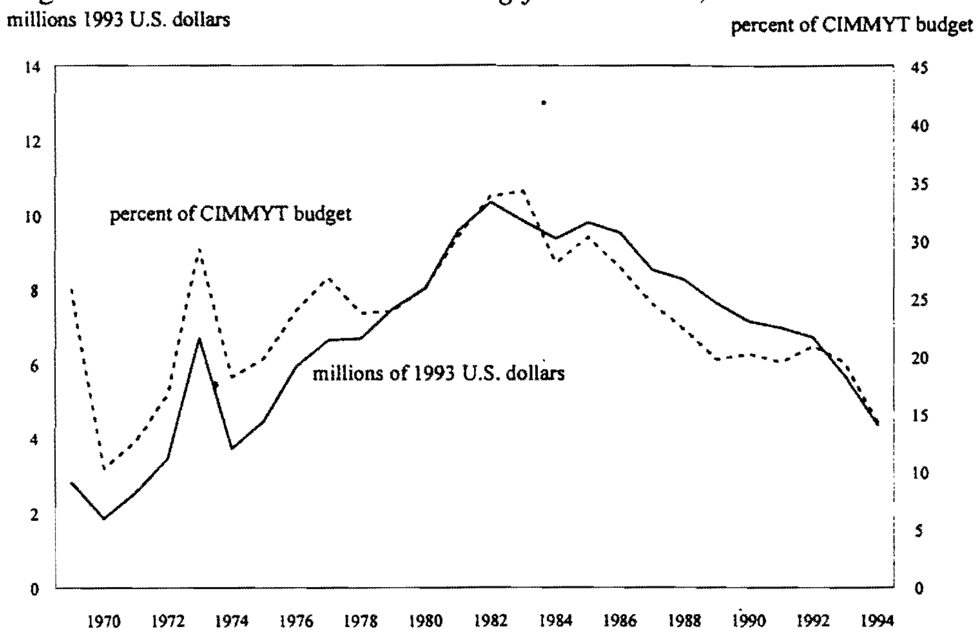


Source: Unpublished data provided by IRRI and USDA Current Research Information System.

U.S. Contributions to CIMMYT and IRRI

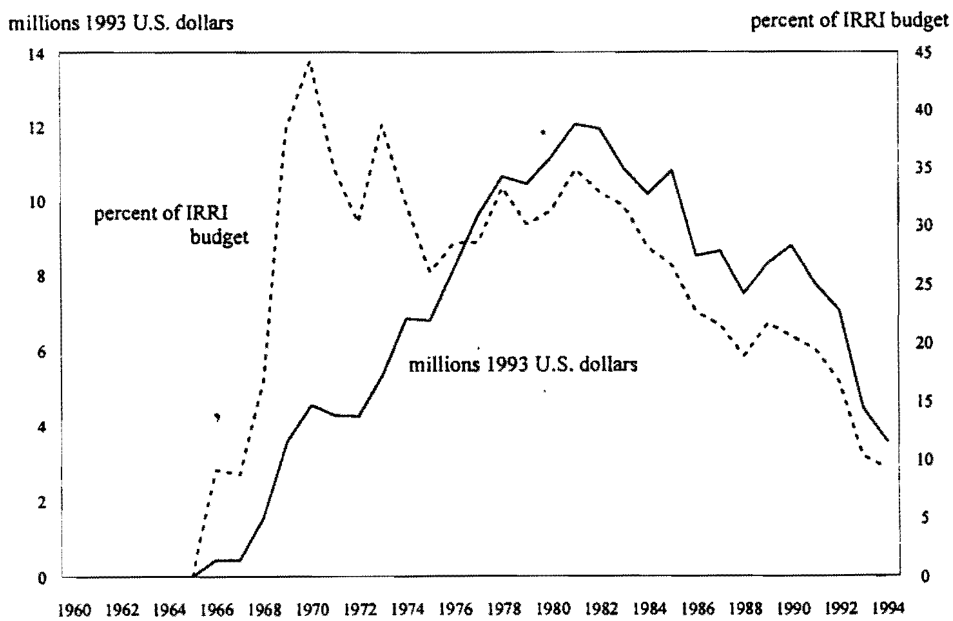
The pattern of U.S. government support to CIMMYT and IRRI has paralleled U.S. support to the CG as a whole. During the period of CIMMYT and IRRI's pre-CG operations (i.e., prior to 1971) the United States accounted for a sizeable share of each

Figure 10: *U.S. Government Funding for CIMMYT, 1969-94*



Source: Authors calculations based on unpublished data provided by CIMMYT.

Figure 11: *U.S. Government Funding for IRRI, 1960-94*



Source: Authors calculations based on unpublished data provided by IRRI.

center's total costs (figures 10 and 11). After 1971, U.S. contributions continued to climb in real terms, peaking at $10.3 million (1993 dollars) for CIMMYT in 1982 and $12.0 million for IRRI in 1981. As a share of total spending, the U.S. contribution peaked at 34.2% percent for CIMMYT in 1983 and 34.7% for IRRI in 1981. Since then, the U.S. contribution has fallen dramatically in both absolute and relative terms for both centers. By 1994, the United States contributed only $5.7 million (1993 dollars) to CIMMYT's research and $4.5 million to IRRI; about half the amount given to CIMMYT during the early 1980s and one third of the corresponding IRRI figure. As a share of total support to each center the United States now constitutes just 14.4% of CIMMYT's total costs and 9.2% of IRRI's.

BENEFIT-COST COMPARISONS

Both the costs and benefits of research programs are realized over time. Research and breeding teams are assembled, materials are gathered, experimental crosses are made, and selection, segregation, and field trials proceed. After a number of breeding cycles, varieties are released to farmers, who may use them for a number of years. Some breeding endeavors may, in retrospect, be seen as failures, while others may be extraordinarily successful. In evaluating research programs, it is appropriate to consider their overall effects for the entire life of the associated activities. To do so, we reduce the streams of both benefits and costs of the varietal improvement programs to present value terms. The real flows in past years are compounded at a real annual rate of 3 percent.

Overall Costs and Benefits

Varietal improvement activities in rice and wheat over the past thirty years have produced major benefits in the United States. The additional wheat production resulting from the introduction of new varieties since 1970 was worth (in present value terms) about $43 billion (table 6). In part, this large gain reflects the large size of the U.S. wheat crop: wheat production between 1970 and 1993 was worth over $405 billion. Thus, about 1/9th of the total value of wheat production may be attributed to increases in yields due to the introduction of new varieties. While the rice industry is much smaller, large benefits were still realized: rice production has a present value of $67 billion, of which $5.4 billion is the value of extra production from new varieties.

Table 6: U.S. benefits and costs of varietal improvement in the United States

	Wheat	Rice
	(millions 1993 dollars)	
Present value of benefits	42,913	5,388
Present value of costs	1,293	511
Benefit-to-cost ratio	33:1	11:1
Present value of production	405,026	66,621

Source: Authors' calculations.

Note: Benefits and value of production are expressed in present value terms for the 1970-93 period. Present value of costs are for the 1960-93 period.

We match these total benefits against total expenditures on varietal improvement in these industries, including both total expenses within CIMMYT and IRRI, and expenses within the public agricultural R&D sector in the United States. The CG expenses include a share of overhead and other non-programmatic expenses; the costs in the United States include all expenditures on wheat and rice breeding in the institutions reporting to the USDA's Current Research Information System, with an additional allowance to account for the activity of scientists other than breeders, such as plant pathologists and agronomists, who contribute directly to the development and introduction of new grain varieties. We have no data prior to 1970 for the United States costs, nor prior to 1967 for CIMMYT. Wanting to account for earlier activities whose benefits were realized in part during the 1970s, we calculated the average of the real costs for the earliest three years (1967-69 for CIMMYT, 1970-72 for U.S. institutions), and calculated present values as if this level of real expenditures had been maintained since 1960. The present value of the costs of the entire varietal improvement endeavor for wheat, in both the United States and at CIMMYT, between 1960 and 1993, is a little over $1.2 billion. The present value of varietal improvement efforts for rice, computed on the same basis, is about half that.

Research intensities in the two industries are modest. For every $100 of U.S. wheat production, less than 70 cents is devoted to varietal improvement at CIMMYT and at public research institutions in the United States. The investment in rice research at IRRI and in the United States, relative to the size of the industry, is higher, at a little over $1.40 per hundred dollars of production. Given the quite small size of the research intensities, in these industries, it is not surprising that the realized benefit is very high, relative to the size of the investment. The ratio of benefits to costs for varietal-improvement research in wheat is 33 to 1, while in rice it is about 11 to 1. A benefit-cost ratio in excess of 1 implies that the investment is profitable. Thus, the total investments in varietal improvement in rice and wheat have been very profitable indeed.

U.S. Costs and Benefits

The evaluation of the U.S. taxpayer's investment in the CG varietal-improvement improvements is more complicated. Ideally, a first step would be to identify the objectives of the investment. U.S. support of the CG centers has probably been motivated primarily by a combination of humanitarian desires (to abolish hunger), economic interest in the health of actual and potential trading partners, a desire to correct for global underinvestment in agricultural R&D, and the political need to encourage stability in the less-developed countries. The focus of a full evaluation of U.S. support of the CG centers would be the degree of success of the CG centers in meeting the primary objectives of the support. Such an evaluation is not undertaken here; instead, we measure the contributions of the CG to U.S. farm production, a secondary benefit. It happens that, particularly for wheat, these secondary benefits are sufficiently large to justify, on narrow economic grounds, the *entire* U.S. investment in the CG programs. However, this does not mean that the support should not be measured in terms of the primary objectives.

A second task, which applies to the evaluation on narrow economic grounds undertaken here, is to identify the U.S. benefits that occur because of the CG activities, and because of U.S. taxpayer support of these activities. The partitioning, between CG centers and other sources, of the U.S. benefits from varietal improvement is an effort to quantify the specific contribution of the breeders and other scientists at the CG centers. For each center, two partitioning rules are applied and reported here, which give a range of benefits in the U.S. attributable to the activities of CIMMYT and IRRI.

A third task is to identify the costs against which these benefits should be set. It is possible that some of the new varieties that have been used in the United States would have been developed even in the absence of the U.S. contributions; thus, the U.S. contributions might not, strictly speaking, have been the costs of the benefits received. Two factors suggest that the U.S. contributions are, in fact the appropriate cost stream. First, it is unlikely that free-riding on the international agricultural research centers is or has been a serious option for U.S. policy. Second, especially in the early years, the U.S. contribution has been of vital importance to the centers, and especially to CIMMYT and IRRI. It is not at all clear that these centers would have survived and prospered without U.S. government support.

In retrospect, U.S. support of the CG varietal improvement programs appears to have been an extraordinarily successful investment. Even using the conservative geometric-weights rule to allocate the benefits of enhanced yields, CIMMYT's contribution to U.S. wheat production since 1970 generated benefits worth at least $3.3 billion (table 7). Using an "any ancestor" attribution rule, the gain in wheat production was worth over $13 billion. For rice, the benefits from additional production attributable to IRRI varietal-improvement activities is between $36.6 million and $1.0

Table 7: U.S. benefits and U.S. government costs of CG varietal improvement programs

	Wheat	Rice
	(millions 1993 dollars)	
Present value of benefits		
Upper bound	13,598	1,042
Lower bound	3,354	37
Present value of costs	68	62
Benefit-to-cost ratio		
Upper bound	199:1	17:1
Lower bound	49:1	0.6:1

Source: Authors' calculations.

Note: Benefits are expressed in present value terms for the 1970-93 period; costs cover the 1960-93 period.

billion. These benefits are set against a quite modest U.S. contribution to the CG varietal-improvement programs: since 1960, U.S. government support of wheat varietal-improvement activities at CIMMYT (and its predecessor institutions) has amounted to 68 million (in present value terms, as of the end of 1993). That is less than two cents for every $100 of U.S. wheat production. The benefit-cost ratio for U.S. government support of CIMMYT is between 49 to 1 and 199 to 1. U.S. government support of IRRI, computed on the same basis, has cost about $62 million, or about nine cents per hundred dollars of U.S. rice production. The benefit-cost ratio of that contribution is between 0.6 to 1 and 17 to 1.

The lower bound for the benefit-cost ratio for rice research is less than one, raising the possibility that the rice program has not been profitable (in terms of the very narrow measure of economic benefit used here). There are at least two reasons why this interpretation is probably incorrect. First, almost all rice production in the United States now uses semidwarf varieties, and semidwarf technology in rice was largely developed at IRRI. Without IRRI commercially significant semidwarf rice may not have appeared in the United States but certainly would have appeared much later than it did. Thus, the "any ancestor" rule, with its associated 17 to 1 benefit-cost ratio, seems a more accurate reflection of reality in rice than does, for example, the geometric rule. Second, all of the measures of IRRI-attributed yield gain in rice have been increasing in recent years, suggesting that many years of work adapting IRRI-origin lines to U.S. conditions is beginning to pay off. The measures of benefits used here necessarily ignore benefits that will be realized in the future.

Finally, the U.S. benefits from CIMMYT wheat and IRRI rice varieties can be compared with the costs of the *total* U.S. contribution to the CG. Such a comparison ignores all of the benefits from other programs at those institutes and other CG centers, and ignores all of the benefits besides the narrowest economic benefit from enhanced yields in the United States. Even still, using the smallest measure, the benefits in the U.S. from the CIMMYT wheat and IRRI rice breeding programs is worth more than twice the total U.S. government contribution *to the entire CG* since 1961. The hidden harvest from the seeds developed at El Batán and Los Baños has been rich indeed.

6. CONCLUSION

The success of the CGIAR institutes at achieving their primary goal—the expansion, through enhanced yields, of global food supplies, and the consequent alleviation of hunger, especially in the less-developed countries—is well known and widely acclaimed. The adaptation of semidwarf technology in wheat and rice to growing conditions in LDCs, in particular the incorporation of disease resistance and other beneficial traits, set off a Green Revolution, and liberated many millions of people from the threat of famine. All those who participated in this achievement are justified in taking great pride in their contributions, including the CG scientists and other workers at the breeding and testing facilities, their colleagues in the national agricultural research systems around the world, who contributed genetic resources, expertise, and facilities, and participated in the rapid and wide diffusion of the new technologies, and the farmers and other workers in the food production system whose husbandry brought forth the rich harvests.

The pride ought also to be shared by those whose financial investment made the research program possible, including in particular the taxpayers in the United States and other donor countries. Great successes offer much credit to be shared.

It must be remembered that the CG was not formed for the benefit of the United States. CGIAR varietal improvement research is geared to making new seedlines available to national agricultural research systems and farmers in LDCs. In this they have been demonstrably productive. The spread of semidwarf wheat and rice varieties throughout the developing world has been dramatic since suitable varieties were first made available, largely through the efforts of CIMMYT and IRRI. Byerlee (1994) reports that 74 percent of developing-country rice acreage is now planted to semidwarf varieties, up from 30 percent in 1970, while 70 percent of wheat acreage is planted to semidwarf varieties, as against 20 percent in 1970. The initial spread of improved (mainly semidwarf) plant varieties was a central element of the Green Revolution that got under way in the 1960s. Subsequently, newer varieties replaced the original semidwarfs. For instance, Byerlee and Moya (1993) calculated that 34 percent of the production increase in 1990 due to international wheat breeding research was due to the first introduction of semidwarfs. Most of the gain is attributable to post-Green Revolution technology, adopted from 1977 to 1990, which they estimated added $3 billion to spring wheat production in developing countries, in the year 1990. They attributed about half this amount to CIMMYT.

Our main task, however, has not been to evaluate the U.S. support of the CG varietal improvement programs in terms of the primary rationales for that support. Rather, we have shown that the investments in CIMMYT and IRRI have also yielded important direct economic benefits to the United States, quite apart from the indirect benefits associated with a healthier international political and economic environment. First, the breeding programs have been vital and integral parts of an international selecting, testing, and breeding system, which has made major contributions to food supplies in the United States. The varietal-improvement programs in rice and wheat in the United States have been funded at very modest levels, but have produced substantial benefits to U.S. producers and consumers. The international flow of germplasm, trait information, and gene information has been formally and informally encouraged and facilitated by the CGIAR institutions; even in the absence of direct releases of varieties, or of the transfer of yield-enhancing germplasm, CIMMYT and IRRI have earned credit for their participation in the vigorous wheat and rice breeding programs in and for the United States. With a total benefit, through 1993, of over $42 billion from varietal improvement in wheat, and over $5 billion in rice, against a public investment of about $1.2 billion in wheat and $511 million in rice, there is a lot of credit to be shared.

In fact, the contributions of the CG facilities extend far beyond general contributions to the scientific infrastructure. In rice, the basic semidwarfing genes were taken by workers at IRRI, and worked into breeding lines that were useful to workers in the United States. In wheat, critical advances in breeding technologies were developed at CIMMYT and its predecessor institutions, and important work was carried out to identify and incorporate disease-resistance traits. Substantial direct releases of CIMMYT-bred varieties were made in California, with subsequent breeding upon a foundation with strong roots in the CIMMYT programs. In other parts of the country climate conditions do not permit direct varietal transfers; yet traits isolated through the CIMMYT programs now find themselves incorporated into varieties widely planted around the United States. As a result, we identify benefits attributable to CIMMYT breeding achievements in upwards of 199 times the total U.S. contribution to the CIMMYT wheat improvement budgets. The results are less spectacular in rice, taking into account the central contribution IRRI has made, and continues to make, to rice breeding, the small U.S. contribution to IRRI has been repaid many times.

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